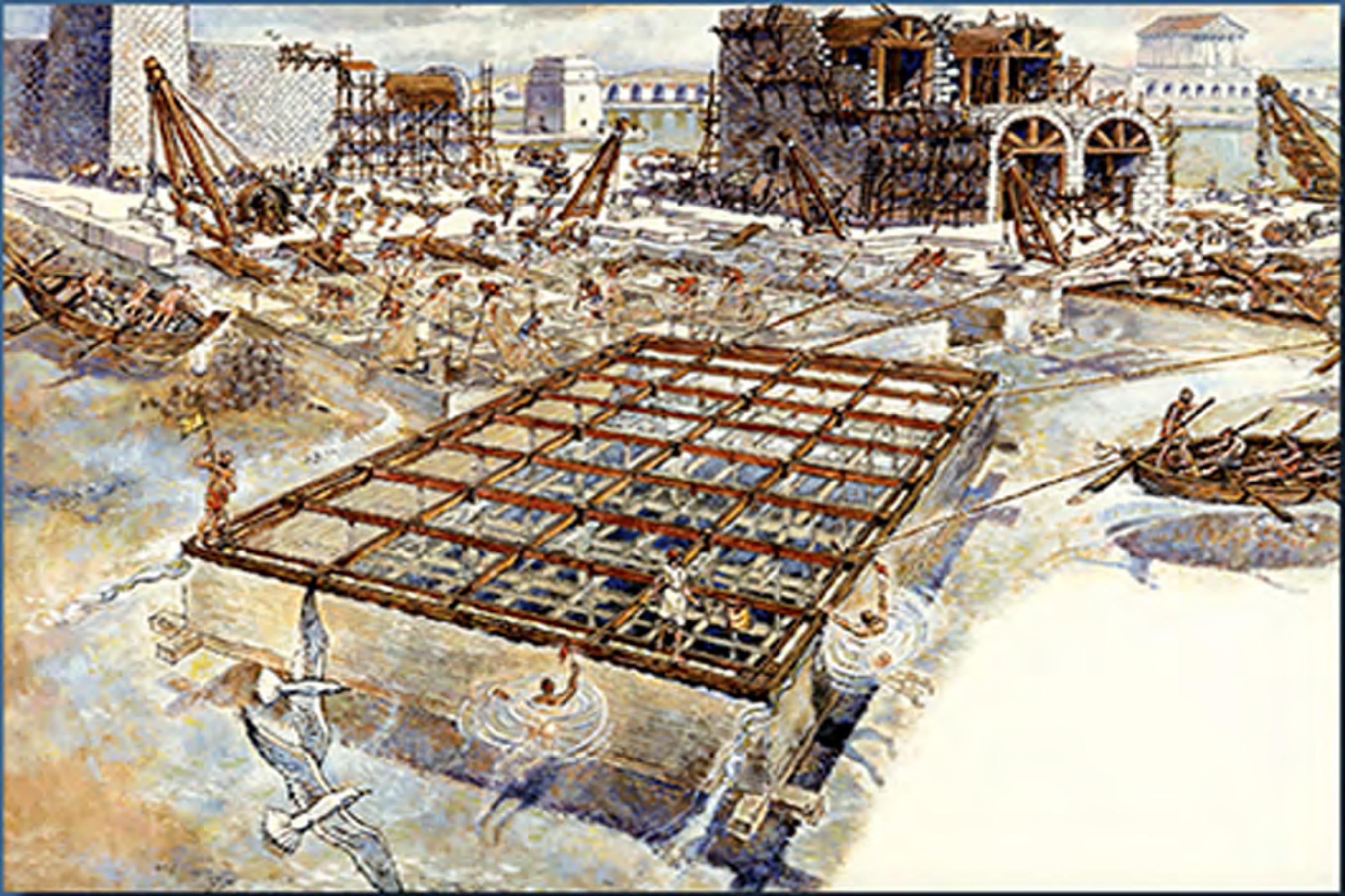
# BUILDING FOR ETERNITY

## THE HISTORY AND TECHNOLOGY OF ROMAN CONCRETE ENGINEERING IN THE SEA



*by*

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*With contributions by*

L. BOTTALICO, S. CRAMER, R. CUCITORE, E. GOTTI, C.R. STERN AND G. VOLA

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J. P. OLESON

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*Front cover: Reconstruction of workers lowering mortar into formwork at Sebastos (Hohlfelder 1987: 264–65) (National Geographic Society, used with permission).*

To the unknown master builders of ancient Rome who challenged and tamed the sea,
and to the CTG Italcementi Group for unwavering support from the inception
of the Roman Maritime Concrete Study through the publication of this volume.
Their embrace of our vision made this book possible.

# CONTENTS

# PREFACE AND ACKNOWLEDGEMENTS

In a project of this nature, in which the four participants all contributed their special skills while at the same time sharing the many collective tasks and interweaving their knowledge into the final publication, the only just way to acknowledge everyone's contribution is to list the principal authors alphabetically on the title page.

Since this project has lasted for over a decade and has involved numerous countries and archaeological sites, we naturally have been helped by a great number of individuals, institutions, laboratories, and agencies. If we have inadvertently missed anyone here, we express our apologies.

Our greatest debt of gratitude is to the CTG Italcementi Group. We remain indebted to Dr. Luigi Cassar of Italcementi who supported our research in so many ways at its inception. Dr. Enrico Borgarello continued this enlightened patronage and provided a generous subvention towards the cost of publishing this book. We also thank Mr. Dario Belotti, Ms. Isabella Mazza, Mr. Piero Gandini, and Mr. Massimo Borsa for their invaluable assistance in surmounting numerous logistical and practical problems at every stage of our project. We especially thank Mr. Bruno Zanga for his very precise and nuanced mineralogical descriptions of the concretes. Dr. Gabriele Vola, Mr. Zanga, and Dr. Emanuele Gotti, the principal CTG Italcementi scientific staff who carried out analytical investigations of the concretes, appear in the book as contributors.

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In Istanbul, Dr Ismail Karamut and Metin Gökçay very kindly arranged access to the excavations at Yenikapı.

In the text of the book, dates are AD unless labelled BC. Place names in Latin or other foreign languages are not italicized.

# LIST OF ABBREVIATIONS

| | |
|---|---|
| *AE* | *L'Année Épigraphique*. Paris: CNRS. 1888– |
| *Aed*. | Procopius, *De aedificiis* |
| *Aen*. | Virgil, *Aeneid* |
| *Ag*. | Palladius, *Opus Agriculturae* |
| *Agr*. | Cato, *De re rustica* |
| *AJ* | Josephus, *Jewish Antiquities* |
| *Ann*. | Tacitus, *Annales* |
| asl | above mean sea level. |
| *Att*. | Cicero, *Epistulae ad Atticum* |
| *Aug*. | Suetonius, *Divus Augustus* |
| *B civ*. | Caesar, *Bellum civile* |
| *BJ* | Josephus, *Jewish War* |
| bsl | below mean sea level |
| C | Celsius or centigrade temperature measurement |
| *Caes*. | Suetonius, *Divus Iulius* |
| *Carm*. | Horace, *Carmina* |
| *CIL* | *Corpus Inscriptionum Latinarum*. Berlin: Reimer, 1893– |
| *Claud*. | Suetonius, *Divus Claudius* |
| cum | cubic metre |
| *De arch*. | Vitruvius, *De architectura* |
| *Ep*. | Pliny the Younger or Seneca, *Epistulae* |
| H | height |
| *HN* | Pliny, *Historia Naturalis* |
| *ILS* | H. Dessau, *Inscriptiones Latinae Selectae*. Berlin: Weidmann, 1892–1916 |
| L | length |
| *Mete*. | Aristotle, *Meteorologica* |
| *Mil*. | Vegetius, *De re militari* |
| *Ner*. | Suetonius, *Nero* |
| nm | nanometre, one-billionth of a metre |
| *Pan*. | Pliny the Younger, *Panegyricus* |
| *Phorm*. | Demosthenes, *Against Phormio* |
| *QFr*. | Cicero, *Epistulae ad Quintum fratrem* |
| *QNat*. | Seneca, *Quaestiones Naturales* |
| *Rust*. | Varro or Columella, *De re rustica* |
| SEM | scanning electron microscope, or scanning electron microscopy |
| *Silv*. | Statius, *Silvae* |
| UTM | Universal Transverse Mercator coordinate system, a grid-based method of mapping locations on the surface of the Earth, usually associated with GPS systems |
| W | width |

# LIST OF FIGURES

Unless otherwise indicated, the photographs were taken by members of the ROMACONS team.

All maps and plans in Chapter 6 are by Will Foster Illustration.

All figures in Chapter 7 are by M. D. Jackson and Bronze Black Design, unless otherwise noted.

Appendix 3. In these figures the upper part of the core is always at the left side of the photograph. Images of individual cores progress from more general to more detailed views.

# LIST OF TABLES

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# Chapter 1

# The Technology of Roman Maritime Concrete

*J. P. Oleson and M. D. Jackson*

## 1.1. Introduction

The central purpose of this book is to present literary, archaeological, and analytical data concerning Roman concrete structures built in the sea, with particular focus on the highly specialized marine concrete developed for that purpose. We have brought together and translated all the Greek and Latin literary sources that describe maritime concrete and its applications, the materials, formwork, and tools used to produce it, and, to an extent, the ancient interpretations of the geological origins of those materials. Careful interpretation of these texts in combination with results of archaeological, experimental and analytical investigations provides important information on Roman practical knowledge and engineering procedures for building in the sea. We have also put together catalogues of known Roman concrete structures constructed in the sea (Chapter 6) and of the remains of the formwork used to create these structures (Chapter 8). Although these catalogues undoubtedly are incomplete, the first provides a general idea of the geographical spread of the technology of maritime concrete construction, while the second documents both widespread uniformity and local innovation in the design of Roman concrete formwork. While the materials used in Roman concrete bridge footings and lakeshore structures are undoubtedly relevant to the topics discussed in this book, with the exception of the bridge at Chalon-sur-Saône (pp. 219–20) and a concrete embankment at Lake Nemi (p. 127), we have chosen to focus on the marine structures that we had the opportunity to sample.

The bulk of the book, however, is a report of the activities and results of the Roman Maritime Concrete Survey (ROMACONS), directed by Brandon, Hohlfelder, and Oleson between 2002 and 2009 (Chapter 4), and of the scientific analysis of the resulting concrete cores carried out by Jackson, Vola, Gotti, Bottalico, Cucitore, and Stern, and researchers at the University of Naples (Chapter 7, Appendices 3–4). Over the seven years of fieldwork, the ROMACONS team took 36 cores (totalling 36.55 m in length) from 11 Roman harbour sites and one fish-pond in Italy, Greece, Turkey, Egypt, and Israel. The cores are described in Appendix 3. A wide variety of physical, chemical, and microstructural analyses was carried out on the cores, producing the results presented in Chapter 7. A synthesis and historical appreciation of the results of the research is presented in Chapter 8.

This book is not intended to be a general introduction to Roman concrete engineering, or a history of how continued innovation in the mixing and placing of concrete affected the evolution of Roman building design on land. Numerous surveys of these topics already exist (*e.g.* Blake 1947; Lugli 1957; MacDonald 1982; Lamprecht 1996; DeLaine 1997; Taylor 2003; Lancaster 2005).

Given the multidisciplinary character of this book, which involves ancient literature, archaeology, and the physical sciences, terminology can become problematic. A glossary of technical terms that frequently appear has been provided in Appendix 1, in the interest of avoiding repetitive explanations, or laborious periphrasis. Volcanic ash is the product of an explosive pyroclastic eruption; it is composed of glass and crystals derived from magma, or molten rock, and particles of rock, mainly lavas broken from the underground edifice of the volcano. Tuff is the rock that forms when volcanic ash lithifies and consolidates through the development of natural mineral cements. A pozzolan is a siliceous and/or aluminous material, named after ash from Pozzuoli (ancient Puteoli), which reacts with lime or lime-based compounds in the presence of moisture at ordinary temperatures to produce compounds with cementitious properties (Massazza 1988). Above all, it should be noted that the term *pozzolana* is used only rarely in this book, given its widely ambiguous meanings in both Italian and English. The term "pozzolanic additive" is also avoided in this book, since this has specific applications to modern cement technologies that do not pertain to the ancient concretes. In the modern literature concerning Roman concrete, for example, the term *pozzolana* can be used to indicate a type of powdery, pumiceous, incoherent volcanic ash erupted from the Campi Flegrei volcanic district that surrounds the Bay of Pozzuoli at the northwest sector of the Gulf of Naples (Fig. 1.1, 7.2), pumiceous volcanic ash from elsewhere along the coast of the Gulf of Naples, or scoriaceous volcanic ash found in and around the city of Rome. Instead, we use the more straightforward "pumiceous ash pozzolan" or "mortar containing pumiceous volcanic ash."

*Fig. 1.1.* Puteolanus pulvis *(*pozzolana*) from a quarry near Baia.*

Pozzolanic materials add durability and long-term strength to modern cementitious materials, even in maritime environments. In antiquity, the most common pozzolans were pyroclastic rocks – mainly poorly consolidated volcanic ash or glassy tuffs. Vegetable ash pozzolans were also sometimes used on a large scale (Lancaster 2012: 146). The altered volcanic tuffs, or trass, of the Rhine region were finely ground and used as pozzolan in the mortars of Roman concrete structures at Cologne during the first and second centuries (Lamprecht 1996: 61, 75, 87; Elsen 2006). Ground-up potsherds and brick also produce pozzolanic reactions with lime, and these were frequently used by the Romans, producing *opus signinum* for floors and cistern linings (Italian, *cocciopesto*; Blake 1947: 322–23; Lancaster 2005a: 58–59).

In Latin, Vitruvius' term for the pumiceous, poorly-consolidated volcanic ash that crops out "in the vicinity of Baiae and the territory of the municipalities around Mount Vesuvius" in the northwest sector of the Gulf of Naples was *pulvis*, "powder" or "dust" (*De arch* 2.6.1). This term refers to its finer grain size distribution, as compared with the granular scoriaceous ash or excavated sands (*harenae fossiciae*) of the region around Rome. Vitruvius thus indicates that the powdery ash used in first century BC came from either the Flegrean Fields near Puteoli or the Somma-Vesuvius volcanic districts (Fig. 7.2). The term, *Puteolanus pulvis*, or "dust (or powder) from Puteoli," occurs in two of the three passages by ancient authors that mention *pulvis* (Seneca, *Q Nat* 3.20.3; p. 26, Passage 14; Pliny, *HN* 16.202; pp. 26–27, Passage 15). In Pliny *HN* 35.167 (p. 27, Passage 16) the phrase is *a pulvere Puteolano.* Vitruvius does not attach a locative adjective, but simply states *pulvis*. The mention by Vitruvius and other Roman authors of Puteoli and the coastline of the Gulf of Naples as sources of *pulvis* for marine concrete has led many modern scholars to assume that all the pumiceous volcanic ash used in Roman marine concrete was sourced from this region. While the new literary, archaeological, and geological investigations described here have led the authors of this book to regard this as a reasonable hypothesis, our analytical results and those of previous studies are seldom perfectly conclusive. As a result, the association of the pyroclastic materials in the ancient concretes – mainly pumice and tuff – with the Gulf of Naples volcanic deposits is often expressed in a tentative manner. This approach may surprise readers accustomed to the confident attributions seen in many archaeological publications (see below pp. 2–5), but the reasons for this caution are explained in Chapter 7.

We refer to the material that is the focus of this book as "Roman maritime concrete" or "Roman marine concrete," rather than "Roman hydraulic concrete." The latter is a general, generic term that refers to concretes that harden by reacting with water and form a water-resistant product. Romans did not use kiln-fired cements as we know them. Instead they relied on the reaction of hydrated lime with volcanic ash to produce stable binding cementitious hydrates. Most ancient Roman concretes used on land, as well as that in the sea, remain intact when saturated in water, and even develop new cementitious phases.

## 1.2. The unique character of Roman maritime concrete

The earliest synthetic lime mortars, simple mixes of slaked lime and quartz sand, appear in the archaeological record in the Near East as early as 12,000 BC, and these were applied to architectural uses by 10,000 BC (Gourdin and Kingery 1975; Kingery *et al.* 1988). Probably not by accident, and possibly in connection with early ceramic production or metallurgy, it was discovered that heating limestone to 800–900° C produced a caustic alkaline powder, calcium oxide (CaO). The principal component of most limestone is calcite, or crystalline calcium carbonate ($CaCO_3$). During calcination in kilns, calcium carbonate releases $CO_2$ gas and decomposes to calcium oxide (CaO), called lime (or quicklime). When quicklime is mixed with water, or "slaked," an exothermic hydration reaction takes place that produces hydrated lime ($Ca(OH)_2$), or portlandite. Vitruvius described this reaction as it occurred during the slaking of lime with fresh water to form putty for the volcanic ash mortars of architectural concrete structures (*De arch* 2.6.3; pp. 17–19, Passage 7).

When slaked lime putty is mixed with quartz sand, the portlandite carbonates in the presence of atmospheric $CO_2$ to form a calcite cement binder. The resulting mortar develops some compressive strength and resistance to shrinking and cracking. This type of mortar is non-hydraulic, and it may deteriorate during long term saturation in water after having set. Nevertheless, simple lime mortars provided adequate strength and water resistance to serve as plaster on floors, walls, and roofs, and for the lining of cisterns throughout the Mediterranean area for many centuries. Plasters were widely used during the Bronze Age (Shaw 2009). By the Hellenistic period, similar mortars were also used in the Aegean world to bind rubble walls and to provide a smooth joint between dimensioned stone blocks (Theophrastus, *On Stones* 65; Martin 1965: 422–33; Hellman 2002: 94). By the late Republican era, Romans had developed careful techniques regarding both the design of their limekilns and the selection of limestone for calcination (Cato, *Agr.* 38; Vitruvius, *De arch.* 2.5.1–3, pp. 16–17, Passage 6; Adam 1994: 65–76; DeLaine 1997: 88–89, 111–14).

Several authors have stated that hydraulic mortars in certain Classical and Hellenistic Greek structures at Santorini (Thera), Athens, and Rhodes were formulated deliberately with volcanic pozzolans (Martin 1965: 424, 432: Koui and Ftikos 1998; Stamatopoulos and Kotzias 1991). The pozzolan is usually said to be the siliceous volcanic ash of the Santorini eruption of approximately 1600 BC. The chronology of some of the structures involved, however, is poorly established, and the components of the mortar, as far as can be determined, have not been subjected to thorough analysis. It is clear that the local pumiceous ash on Santorini was used by local island builders in mortars and plasters from the Archaic through the early modern period. The ash may have improved cementitious properties, and it was applied to both structures meant to contain water and those that were not. This suggested to early archaeologists that local and Roman builders alike did not understand that Santorini ash could produce a hydraulic mortar, that the ash may have been added as inexpensive bulk filler, and that it was thus unlikely to have been exported (Wilski 1909). This perspective underestimates the empirical expertise of both the local builders and the Imperial age Roman builders, who began to develop their great technological expertise with high performance concretes in Rome during the late first century BC (Jackson *et al*. 2009, 2010, 2011; Jackson and Kosso 2013). Siddall (2000: 340) believes there is no evidence for the export of pumiceous volcanic pozzolans from Santorini or Melos during the pre-Roman period. Although the ROMACONS project has not detected pumiceous volcanic ash from Santorini or Melos in the Roman harbour structures that were cored, further research is needed on the proposed use of Santorini ash at Athens and Rhodes, and on the possibility that there was a modest export trade to other Aegean sites during the Imperial period. The new results from mineralogical studies and trace element signatures of pumices in the Roman maritime concretes presented here provide new insights into Roman builders' selections of volcanic ash pozzolans for the maritime concretes (Chapter 7).

From the fourth century BC onwards at some sites in the Aegean world, crushed brick was added to mortars used to line cisterns (Martin 1965: 432). The large-scale production of pozzolanic mortars for applications in water-saturated environments, however, began at some point in the third or second century BC, most likely in the landscape of the Campi Flegrei volcanic district (Latin: *Campi Phlegraei* = Phlegraean Fields), whose central crater forms the Bay of Pozzuoli in the northern sector of the Gulf of Naples. Most of the ancient literary sources that mention pozzolanic mortar concern this region, and the highly valued pumiceous ash pozzolan, *Puteolanus pulvis,* was and is still excavated in the volcanic craters near ancient Puteoli and Baiae (see Strabo and Pliny, below; also Maffei 1949; Lugli 1957: vol. 1, 394–401; Lancaster 2005a: 54–58). Blake (1947: 346) dates the beginning of harbour construction at Puteoli to 199 BC, but the remains of the arcuated pier visible until the early twentieth century probably belong to the Augustan period (Döring 2003: 47). The history of the earliest concrete, therefore, remains fraught with uncertainty. Although Blake (1947: 328–30) mentions literary evidence for various construction projects in Rome in the third or second century BC that might have used concrete, she states that the Temple of Concord erected in Rome in 121 BC "furnishes the earliest concrete of which the date is sure." Controversy now surrounds the identification, function, and age of the so-called Porticus Aemilia, on the left bank of the Tiber River near the Aventine Hill (Lancaster 2005a: 5). Lugli (1957: vol. 1, 409; *cf*. also pp. 375–85) uses the traditional date of 193 or 174 BC, but new analyses by Tucci (2012) suggest a later date for the *opus incertum* construction, perhaps in mid-second century BC. Geochemical and petrographic investigations of the mortars of late Republican concrete structures indicate that builders experimented with various ash deposits of the Roman landscape through the late first century BC, until they standardized a specific scoriaceous ash formulation during the Augustan era (Van Deman 1912a; Jackson *et al*. 2010, 2011). Many aspects of the earliest concrete structures must have been experimental, resulting in early failure, or repairs, replacement, and incorporation in later structures, and further analytical studies of Late Republican concrete structures, such as those described in Jackson and Kosso (2013) are needed. Vitruvius states (*De arch.* 7, preface 18) that he wrote the *De architectura* to fill the gap left by earlier Roman architects who had not written down the principles of their work. It seems, however, that the most important advances in concrete construction in architectural settings occurred in Rome in the mid- to late first-century BC, based on both observations of structures (Van Deman 1912a) and analytical investigations of concrete materials (Jackson *et al.* 2010, 2011), and this may be true of maritime concrete construction as well (Jackson *et al.* 2012).

In Rome, volcanic pozzolans were excavated first from alluvial deposits in the city, and then from the mid-Pleistocene Pozzolane Rosse pyroclastic flow erupted from the nearby Alban Hills volcano (Jackson *et al*. 2010). The granular scoriaceous ash has a grain size distribution with a large proportion of sand-sized ash particles, described by Vitruvius as *harena fossicia*, or "excavated sands" (pp. 15–16). At Portus, for example, the pozzolanic mortars of the marine structures in the harbour proper appear to have been made with *pulvis* imported from the Gulf of Naples (see Figs 7.10, 13), while associated structures on land were made with local dark gray and reddened scoriaceous *harena fossicia* (Delaine 2001: 248). Vitruvius described the characteristics of both materials and distinguished their different functions in structures on land and in the sea (*De arch.* 2.6.6; Passage 7; pp. 17–18). These descriptions undoubtedly were based on the practical experience of first-century BC builders (Jackson and Kosso 2013). In fact, *pulvis* and *harenae fossiciae* in the ancient mortars have quite different chemical and mineralogical compositions, particle size distributions, and microstructural characteristics (Jackson *et al.* 2007, 2010, 2012). Roman builders apparently recognized these differences and, by the late first century BC, selected the appropriate ash pozzolan for specific construction demands. In addition, they observed natural cementitious processes in specific volcanic products (*cf.* Seneca, *Q Nat.* 3.20.3; Passage 14, p. 26) and hypothesized that similar processes might occur in the hydrated lime-pyroclastic rock concretes. Recent analyses of Vitruvius' comments on the development of construction technologies coupled with analytical investigations of the construction materials themselves indicate that Republican era builders integrated a long-standing tradition of thoughtful reasoning and invention with skilled workmanship to develop highly sustainable masonry materials, construction technologies, and engineering solutions, as described in *De architectura* 1.1.1, 2.1.2 (Jackson *et al.* 2005, 2007, 2011; Jackson and Kosso 2013).

Roman engineers evidently had excellent empirical skills. Their observations of natural cementitious processes in volcanic ash deposits around the Bay of Pozzuoli were recorded, for example, by Seneca (*Q Nat.* 3.20.3; p. 26, Passage 14). Vitruvius used various theories to explain the consolidation of concretes produced by the calcination of limestone, hydration of the resulting lime, and its incorporation with volcanic ash. The concrete in the cores from the Roman harbours that we sampled varies in its fine compositional details, but every structure investigated makes use of pumiceous volcanic ash pozzolan that resembles poorly consolidated volcanic ash deposits erupted from the Campi Flegrei or wider Gulf of Naples volcanic districts, even those in the far distant harbour of Pompeiopolis in Turkey (Stanislao *et al.* 2011). The more precise origins of the pumiceous components of the maritime mortars are explored in Chapter 7. The very innovative aspect of Roman maritime concrete that developed in the first century BC was that the lime-pyroclastic rock mix would set and cure in sea-water, out of contact with atmospheric $CO_2$, so that concrete could be placed in partially inundated, or even completely submerged, forms to create massive harbour structures and breakwaters. The volcanic pozzolan evidently also contributed to the long-term stability and durability of the concrete structures in sea-water, through various processes (see Chapter 7).

## 1.3. Recent research on Roman concrete

The bibliography concerning ancient Roman concrete is enormous. Some of the most important secondary sources include Blake 1947: 21–69, 308–52; Lugli 1957: I, 363–436; Blake 1959; MacDonald 1982; DeLaine 1997; Felici 1993, 1998; Rowland *et al.* 1999; Gazda 2001; Massazza 2004; Lancaster 2005a. Furthermore, Gazda (2001) has discussed the main contributions to the topic of Roman maritime concrete up to the year 2000, and has provided insightful highlights of the major issues. As she notes, the use of hydraulic concrete in harbour engineering represented a major step forward for ancient technology, but until recently the construction material itself has not received the scholarly attention it deserves (Gazda 2001: 153). Most studies of ancient Roman concrete naturally have focused on terrestrial rather than maritime structures, and they have tended to address either site-specific questions or general historical surveys of architectural development. Gazda emphasizes the need for collaboration between archaeologists and scientists, anticipating the need for the approach taken by the ROMACONS Project. Nevertheless, like other scholars, she poses questions as to why Roman mortar was so "hard and strong," and she assumes that the longevity of Roman hydraulic concrete is tied to such characteristics (Gazda 2001: 148–49). DeLaine (2001: 230) also asserts that the Romans produced "a hydraulic mortar of great strength, easily comparable with the best of modern mortars." In fact, as our research has shown, concrete of the Roman maritime structures is neither particularly hard nor strong: it has relatively low compressive strength compared with Portland cement-based concretes, and its pyroclastic rock components often disaggregate in subaerial environments. The reasons for its extraordinary longevity in sea-water are complex, and recent advanced analyses of its cementitious components have begun to elucidate why this is so (Jackson *et al.* 2013a–b).

Many important archaeological and technical studies concerning ancient Roman maritime concrete have appeared since Gazda's survey. A sample of archaeological studies, omitting the specifically ROMACONS research cited throughout this book, includes Felici 2001a–b; Gianfrotta 2007a–b; Votruba 2007; Gazda 2008; Scognamiglio 2008; and Gianfrotta 2010, 2011. A sample of the technical studies includes Bakos *et al.* 1992, 1994; Chiari *et al.* 1992, 1996; Samuelli Ferretti 1997; Giuliani 1997; Perno 1997; Siddall 2000; Branda *et al.* 2001; Degryse *et al.* 2002; Bonora *et al.* 2003; Casadio *et al.* 2005; Gavarini *et al*. 2006; Jackson and Marra 2006; Pavía and Caro 2008; Goldsworthy and Zhu 2009; Jackson *et al.* 2007, 2009, 2010, 2011; Miriello *et al.* 2010; Vola *et al.* 2011; Stanislao *et al.* 2011.

The collection of samples of ancient Roman plaster, mortar, and concrete from monuments within and outside Italy for study of their chemical and material properties has tended to be opportunistic rather than systematic, overall, and in only a few cases were samples obtained by coring deep into concrete structures (Lamprecht 1996: 54–87; Samuelli Ferretti 1997; Gavarini *et al.* 2006; Jackson *et al.* 2009). The collection of chunks of ancient concrete partially disaggregated by weathering or chipped away with a rock hammer can result in compromised samples, and it is difficult to reconcile the disparate laboratory results of some tests. Research focussed specifically on the material characteristics of Roman cementitious materials in water-saturated environments has been even more limited in scope and number (*e.g.* Langton and Roy 1984; Roy and Langton 1989) and has been focused mainly on mortars and plasters (Branton and Oleson 1992a–b).

In response to this paucity of information Brandon, Hohlfelder, and Oleson founded the Roman Maritime Concrete Study (ROMACONS) in 2001, a comprehensive research program focused on the collection and analysis of large cores of hydraulic concrete from carefully selected, well-dated maritime structures (Hohlfelder *et al.* 2008, 2011; Oleson *et al*. 2008). Between 2002 and 2009, 36 cores were taken from 12 different maritime sites around the Mediterranean, supplemented by smaller samples taken from several dozen more sites from a variety of maritime concrete structures in Italy and elsewhere in the Mediterranean. Subsequently Jackson, Vola, and several other scientists performed extensive analytical investigations of cores recovered in a standard and repeatable fashion based on consistent and comprehensive microscopy techniques, chemical analysis, and mechanical testing. The results of these scientific endeavours are presented throughout this book. The significant remaining portions of the core samples are being kept for the moment at the Italcementi headquarters near Bergamo. We hope that they will continue to serve as a resource for further scientific analysis.

Since 2010, several new advances have been made in understanding the fine-scale structures and material properties of the volcanic ash-hydrated lime mortars of the ancient concretes through multi-disciplinary collaborations with civil and mechanical engineers, mineralogists, and archaeologists. The results of these studies provide a firm analytical base for investigating the reasons for the very long service lives of the ancient concrete structures. In addition, they provide an experimental and analytical foundation for developing new perspectives towards improving the chemical and mechanical durability of environmentally friendly concretes formulated with volcanic pozzolans.

An innovative experimental testing program in the Department of Civil and Environmental Engineering at Cornell University in collaboration with Professor A. R. Ingraffea has produced a highly accurate reproduction of the mortar of the Great Hall of the Markets of Trajan, with the intent of understanding the resistance to fracture that the mortar develops over time (Brune 2011; Brune *et al*. 2013). This is particularly relevant to the eventual design of modern pozzolanic concretes with heightened fracture toughness and mechanical durability in seismically active environments – as in the City of Rome. The testing program required the development of an unusual arc-shaped specimen geometry and inverse data reduction procedure, implemented by P. Brune. The initial results suggest a relatively long curing process that increases resistance to failure by fracture over about 90 days. At that point, the mortar reproduction has Young's modulus and uniaxial tensile strength around one-tenth those of a modern concrete, but with fracture energy about half. This means that the young mortar develops a resistance to fracture propagation that is far greater than conventional concretes composed of fine cement paste and inert sand and gravel aggregate. These properties indicate a relatively ductile cementitious material, and are a first step in explaining the enduring mechanical stability of the ancient Roman vaulted monuments.

Recent nanoscale investigations of the cementitious components of the ancient sea-water concrete by M. D. Jackson in collaboration with Professor P. J. M Monteiro and Professor H.-R. Wenk at the Department of Civil Engineering and Department of Earth and Planetary Science at University of California at Berkeley have provided new perspectives on the long term stability of ancient Roman syntheses of crystalline Al-tobermorite and poorly crystalline calcium-aluminium-silicate-hydrate (C-A-S-H) binder. These aluminious cementitious hydrates hold great potential as binders for environmentally-sustainable concretes and concrete encapsulations of hazardous and nuclear wastes. The crystal structure and composition of tobermorite form the model basis of C-S-H in Portland-cement concretes, but the crystals can be produced only in small quantities in laboratory syntheses and they do not occur in conventional concretes; the long-term performance of C-A-S-H is unknown. A comprehensive analytical program using synchroton radiation applications at the Advanced Light Source at Lawrence Berkeley Laboratories has yielded new information about the bonding environments of aluminium and silica in both the Al-tobermorite and C-A-S-H in the concrete of the Baianus Sinus *pila* from the Gulf of Pozzuoli (Jackson *et al.* 2013b), as well as the bulk modulus and crystallographic properties of the Al-tobermorite (Jackson *et al.* 2013a). An adiabatic thermal model of the 10 square metre by 5.7 m thick Baianus Sinus block from heat evolved through hydration of lime and formation of C-A-S-H suggests relatively low crystallization temperatures, <100 ºC. Cooling to sea-water temperatures occurred in about two years. These slightly elevated temperatures and the mineralizing effects of sea-water and alkali-and alumina-rich volcanic ash appear to be critical to Al-tobermorite crystallization in the ancient maritime concrete. The properties of the crystals synthesized by the Romans are being compared with those in young hydrothermal environments, such as Surtsey volcano in Iceland, to provide new perspectives for modern syntheses of Al-tobermorite for high performance concretes using volcanic pozzolans, and geological analogs of these processes. Ongoing mineralogical studies of the cementitious fabrics of the Markets of Trajan concretes and ancient sea-water concretes continue to validate Roman builders' practical ingenuity and provide valuable principles to improve the durability and service life of modern environmentally friendly concretes.

## 1.4. ROMACONS research questions

The ROMACONS team of specialists from both the humanities and the sciences was formed to address many of the unanswered questions concerning the history of Roman maritime concrete, the technology of its production and use in harbour structures, and its composition, material characteristics, and engineering properties. The pioneering application to ancient concrete structures of a sampling technique that allows the collection of long cores from the interior of the concrete mass has opened up new opportunities for testing and analysis, and the results have provided new perspectives regarding the unique properties of the ancient materials and the expertise of the Roman builders.

The handbook of architecture that Vitruvius wrote in the later first century BC contains several passages with unparalleled information relevant to Roman marine concrete (see pp. 14–23). These are the passages usually cited in discussions of this Roman technology. But how closely do the Vitruvian formulas and procedures for marine concrete and formwork correspond to actual engineering practice in Italy and the rest of the Mediterranean world during the Republic and Empire as recorded by the ancient structures? Vitruvius did not invent hydraulic mortar or pioneer its application, nor did he present a comprehensive manual of procedures then in use. Nevertheless, it is important to determine to what degree his information was based on contemporary practice in the late first century BC, and when, where, and why builders in the first and second centuries AD deviated from the procedures he outlined. A deeper question is when the volcanic ash-hydrated lime formula was discovered. Evidence uncovered during the underwater excavations at Sebastos, the port of Caesarea Palaestinae, for example, indicate that the engineers of Herod's harbour were probably Italians familiar with contemporary practices in the Gulf of Naples. They apparently went to enormous trouble to import what appears to be pumiceous ash pozzolan from that same region (Branton and Oleson 1992; pp. 164–66). Nevertheless, the engineers at Sebastos employed some formwork very differently from that described by Vitruvius, and they occasionally employed in a single structural unit mortars both with and without pumiceous volcanic ash as an ingredient. The single-use barge forms are a particularly original Roman innovation (Brandon 1997a–b; Goddio *et al*. 1998; Brandon 1999; Hohlfelder 2000: 249–50; Brandon 2001; below pp. 208–21) (Figs 8.51–52). At the harbour of Kenchreai in Greece, which was still under construction when the *De architectura* was completed, the building program bears little resemblance to the procedures specified by Vitruvius (Hohlfelder 1985: 84–85). There are, so far, no known archaeological examples that follow Vitruvius' laborious and time-consuming method for constructing a concrete breakwater into the open sea by building on a succession of platforms concrete blocks that, after curing, were allowed to be undermined and to fall into position (*De architectura* 5.12.3–5, pp. 20–23, Passage 9; Oleson 1988: 150; Brandon 1996: 27) (Fig. 2.1c). Horace and Virgil may allude to this practice in their poems (pp. 23–24). Although *De architectura* was not a canon for marine concrete construction, Vitruvius displays a detailed knowledge as a practising engineer of the ideal materials and procedures that were needed for building in the sea.

Evidently, the natural challenges posed by a particular harbour site required some creative expansion and modification of existing technology to facilitate construction. The building programme at Herod's harbour, which departed in dramatic fashion from the Vitruvian model, was not an isolated case. If Vitruvius' text was not a general guide or *canon*, was some other written handbook of Roman harbour design and construction ever produced, and did it affect projects across the empire? Were the engineers skilled in the use of concrete materials for marine structures few in number and always associated in some way with the Imperial court, or did the knowledge of the materials and procedures spread widely by some other method of transmission? Hohlfelder (1996: 95) has suggested that at Paphos the builders who assisted in the repairs of that strategic harbour facility may have been the same individuals who had worked at Sebastos, dispatched to both projects by Augustus or Agrippa. Alternatively, were there also sub-literary harbour engineering manuals that circulated independently of the military and the royal house (pp. 229–33; *cf.* Oleson 2004, 2005)?

The formwork or shuttering into which the marine concrete was placed requires detailed study as well, since both the surviving wooden structures and the casts they have left in the concrete are relatively common. A catalogue and some of the primary observations are presented here (see Chapter 8). At Caesarea, Antium, Cosa, Laurons, Carthage, and many other sites around the Roman Empire significant remains of formwork have been found that document a remarkable variety in design (Felici 1993; Blackman 1996; Brandon 1997a–b; Felici 2001a–b). The use of mortise and tenon joints at Caesarea, Carthage, and Chalon-sur-Saône provides a tantalizing glimpse of a cross-over of technology between civil engineering and ship construction and hints at the complexity of the formwork designs (Hurst 1976: 189; Brandon 2001). Nevertheless, our observation of the bewildering variety of formwork design does suggest some normative procedures. This one aspect of harbour concrete technology, when better known, will move us closer to understanding how a standardized construction protocol might have evolved for building or repairing maritime installations.

Another major research question involves the use of pumiceous ash pozzolan and glassy tuff *caementa* from the Campi Flegrei volcanic district in harbours along the central Italian coast, the use of pumiceous volcanic ash from the Gulf of Naples, in general, in construction projects far beyond the central Italian coast, and the logistics of its transport over long distances. The chemical analyses carried out by Oleson and Branton on samples of mortar taken from the harbour at Caesarea Palaestinae were the first suggestion that the geographical source of the mortar pozzolan and occasional tuff coarse aggregate could have been the Gulf of Naples, 2,000 km to the west (Branton *et al*. 1992a–b). This startling proposal raised many questions regarding the trade in these bulky and voluminous volcanic materials. Analysis of smaller samples taken by different means, including samples from Quarteira in Portugal, outside the Straits of Gibraltar in the Atlantic world, may possibly show the same result (pp. 123–24). New mineralogical, microstructural, and chemical analyses of pumice clasts in the mortars from the diverse ROMACONS harbour concrete sites (see Chapter 7), suggest that the most reasonable working hypothesis is that the ash pozzolan may indeed originate from pumiceous ash deposits of the Gulf of Naples volcanic districts. The question remains as to whether Roman harbour engineers discovered that other Mediterranean sources of pumiceous volcanic ash outside Central Italy, for example at Santorini or Melos, could also perform as effective pozzolanic aggregate in the marine concretes.

An estimated 20,000 metric tons of pumiceous volcanic ash were used to produce the mortars for the concrete structures of the harbour of Caesarea Palaestinae (revised from Hohlfelder *et al.* 2007: 414; see pp. 75–76). If the bulk of this ash came from the Gulf of Naples, then transport may be explained, in part, by the opportunistic use of grain freighters that ran from Alexandria to Rome. When emptied of their cargo of grain, the freighters on the major return route to Alexandria from Rome required ballast, and it would have made more sense to fill the hold with pozzolanic ash ballast that could be sold upon arrival, rather than with more-or-less useless sand or river stones (pp. 223–26, *cf.* Gianfrotta 1996, 75; Hohlfelder 2000a: 251; Galili *et al.* 2010). After unloading the cargo of Egyptian wheat at Ostia or Puteoli, these ships could conceivably have taken on a cargo of the local *pozzolana* at Puteoli, then set a course for Caesarea Palaestinae – or any other major harbour project within striking distance of a source of bulk food exports needed for Rome. After unloading the ash and loading new ballast of local stone, or other opportunistic cargo, they could then continue on to Alexandria to pick up grain. Pliny (*Pan.* 31.4), in the early second century, alludes to the futility of long voyages by the grain ships from Rome back to Alexandria without cargo, in the context of a hypothetical fall in exports from Alexandria itself: *nisi ut inde navigia inania et vacua et similia redeuntibus…mittantur* ("except that empty ships would now leave [Alexandria] without cargo, like those once returning [empty from Rome to Alexandria]"). Pliny may have been unaware of the use of volcanic ash as ballast by these ships, or he may have suppressed this knowledge to facilitate his mannered rhetorical contrast. A trade guild of *saburrarii*, who specialised in the ballasting of ships, is documented at Portus in the second century (*CIL* 14.102, 448). These were labourers who dredged gravel or sand from the harbour basin for use as ballast for ships leaving port, or they possibly supplied the ballast from deposits further inland. At Puteoli individuals such as these could conceivably have been detailed to load cargoes of pumiceous ash pozzolan as ballast on ships departing for eastern Mediterranean ports.

While this explanation works well for major state harbour projects such as Sebastos, it is more difficult to explain how pumiceous ash and tuff might have been brought from the Gulf of Naples to the minor harbour of Chersonesos. Here, the pumice in the harbour concrete has a very different composition than that of Minoan eruption pumice deposits on Santorini (Chapter 7). How large were the transport ships, and who conducted the trade? Several Roman ships that sank off the coast of France were carrying partial cargoes of volcanoclastic sand – possibly volcanic pozzolan to be used for concrete constructions – as ballast that also helped prop up and protect the cargoes of amphorae (Parker 1992: 250; Joncheray *et al*. 2002: 85; see p. 224). The excavators of the Madrague de Giens freighter of *c.* 75–60 BC, for example, interpret the layer of *sable volcanique* as intended only to support the 6,000–7,000 amphorae, but it may have also been intended for sale at the end of the voyage (Liou and Pomey 1985: 562–63; Wilson 2011a: 38). Pomey (oral communication 2005) reports that "analyses" have shown this to be pumiceous volcanic ash from the Baiae area, but the actual source remains poorly documented. One of the many Roman shipwrecks found at Pisa has been reported as having carried "*pozzolana*" of Campanian origin stored in amphorae (Giachi and Pallecchi 2000: 350), but the material has also been identified as originating near Vulsini (Marra and D'Ambrosio 2013a). A 5 m × 6 m area covered with a thick layer of "le ciment à de la pouzzolane" was found on the first-century Wreck M at La Chrétienne (Joncheray and Joncheray 2002: 85); this wreck carried some pumice and "volcanic stones" as well. Since many merchant ships in the Roman Mediterranean, both large and small, carried mixed cargoes rather than a single bulk cargo moving directly from producer to consumer (Wilson 2011a: 53–54), could it have been this kind of ship that brought pumiceous volcanic ash from the Gulf of Naples to smaller Mediterranean ports, such as Chersonesos? The large-scale transport of volcanic pozzolan across the Mediterranean could have been profitable, or at least advantageous in the terms of concrete engineering, but what about the transport of smaller amounts, for smaller projects? More data are required concerning the compositions of concrete used in the smaller Roman harbours in the Mediterranean.

The study of maritime concrete technology must also address the expertise of the management and the labour force that built the Roman harbours. Were there separate *collegia*, unknown from our epigraphical evidence, that specialised in this type of structure? Did seasonal labourers, for example the *saccarii* (grain handlers and stevedores), *urinatores* (salvage divers), or *saburrarii* (providers of ballast) at Ostia, also work on the harbour construction at Portus during the reign of Claudius (Oleson 1976; Thornton 1989: 89; Martelli 2013)? Did similar groups of workers build other harbours far distant from Rome? Valerius Maximus (8.1.1) reports that the enterprising C. Sergius Orata used a contractor (*publicanus*) to build fish-pools near Puteoli in the 90s BC, and the fashion among the elite throughout the first century BC for marine concrete fish-pools must have kept numerous teams of contractors busy (see pp. 227–29). The *saburrarii* and *urinatores*, in particular, would already have been skilled in moving construction materials in the water. Were there civilian contractors (*redemptores*) who specialized in this kind of work (DeLaine 1997: 205, 2000; Lancaster 2005a: 18–20), or was most of the organization handled by military engineers? Was slave labour used in conjunction with free labourers, and how were the workers organised and sustained during construction? How were the enormous labour costs of harbour construction projects borne? Claudius's engineers, for example, were reluctant even to supply him with an estimate of the potential costs of the harbour of Portus (Cassius Dio, p. 33, Passage 27). Was Imperial largesse for harbour construction ever augmented by local euergetism, and if so, under what circumstances? In the chapters that follow we try to answer at least some of these questions.

Regarding the marine concrete itself, did the formulae for mixing the mortar, and the proportion of *caementa* vary according to location or chronology, and, if so, what were the motivations for the variation? Systematic analytical investigations of the ROMACONS drill cores analyses reveals a rather uniform chemical and mineralogical composition across time and space in the maritime mortars, and in the volumetric ratio of this mortar to the volcanic tuff (or local rock) coarse aggregate, or *caementa* (see Chapter 7). Did the function of a maritime structure – pier, fish-pond, *pila*, foundation – determine the builder's selection of the type of coarse rock aggregate, as it did to a certain extent for terrestrial structures (Adam 1994: 183–85; DeLaine 1997: 85; Lancaster 2005a, 2011)? The answer appears to be negative for marine structures. The engineers seem to have mainly used the same type of *caementa* for all the structures of a given harbour, and they constrained the composition of these large aggregate chunks to be either glassy volcanic tuff, mainly along the Italian coast, and carbonate rock in the eastern Mediterranean concretes, with some exceptions (see Chapter 7, Appendix 3). Nevertheless, at certain sites, the mortar and the *caementa* used in a single structure could vary according to whether they were placed above or below sea level, for example, at Cosa (pp. 248–53) and Sapri (Sconamiglio 2008) (map, Fig. 6.1). How did the Romans compact their concrete during construction underwater to ensure that it filled completely the forms into which it had been placed? How did they prevent separation of the lime and pumiceous ash pozzolan or of the mortar and *caementa* during placement and setting? The reproduction of a *pila* in the harbour of Brindisi (Chapter 5) answered some of these practical questions.

## 1.5. Summary of the archaeological and engineering significance of the analyses of the ROMACONS samples (M. D. Jackson)

The results of the analyses of the ROMACONS core samples presented in Chapter 7 are reflected throughout the text of this book. A summary of the archaeological implications of these results is given here. The analytical investigations reveal that the sea-water harbour concretes sampled by ROMACONS have strong resemblances, overall, in terms of their macro- and micro-scale compositions, material characteristics, and physical properties. Although variations do exist, the similarities of the concrete fabrics over the wide ranging geography of the harbour sites indicate that Roman builders took a methodical, reasoned, and consistent approach to constructing the maritime structures. In sum, the analytical results suggest that builders evidently adhered to a rather rigorous compositional mix and installation procedure for the sea-water mortars. It was the impressive achievement of the Roman harbour engineers to have produced over several centuries around the coastline of the entire Mediterranean Sea an essentially uniform building material ideally suited for the construction of harbours and other marine structures.

### *1.5.1. Uniformities among the concrete samples.*

1. All of the concretes show similarities in the selection of their raw materials. These include lime, pumiceous volcanic ash, and volcanic tuff or limestone rock rubble.
2. All of the concretes show a similar lime-pumiceous volcanic ash mortar mix. The macroscale fabric contains pumice particles and white inclusions of relict lime.
3. All of the marine mortars show similar cementing components. A rare mineral, Al-tobermorite, crystallized in all the concretes, and its poorly crystalline analog, calcium-aluminum-silicate-hydrate, is the principal binder throughout.
4. All of the concretes show hydration of the concrete mix in sea-water. Particles of lime dissolved *in situ*, and sulfate and chloride ions were sequestered in distinct crystalline microstructures.
5. All of the concretes show roughly similar mechanical properties. The compressive strength is low, overall, but the structures are highly resistant to erosion by wave action and the force of impact of large waves.

### *1.5.2. Inferences concerning engineering procedures.*

Certain guiding principles regarding Roman procedures for building in the sea can be inferred from the results of the ROMACONS analytical investigations. Nine such principles are summarized here, with their basis in analytical results and inductive reasoning briefly stated in generalized terms. These form the underlying foundation for recognizing builders' skill and expertise in creating the maritime concrete structures.

1. Our most reasonable working hypothesis is that Romans imported pumiceous volcanic ash from the Gulf of Naples to all the concrete harbour installations drilled by the ROMACONS project. The macro- and micro-scale characteristics of the pumiceous ash pozzolan in the maritime mortars and the assemblage of crystalline

components in the pumice clasts identified through mineralogical analyses have the greatest similarities to Campi Flegrei and Somma-Vesuvius pumice deposits (pp. 153–59). The presumably immobile ratios of trace elements in pumice clasts removed from the mortar fall in the range of the Campi Flegrei and Somma-Vesuvius compositional fields. They cannot, however, be assigned to any particular eruptive unit. Pumice of the Aeolian Islands, the Minoan eruptions of Thera volcano on Santorini island, and the Aegean Islands have different crystal assemblages and immobile trace element ratios. Between about 30 BC and AD 79, Vitruvius, Strabo, and Pliny all emphasized the importance of *pulvis* from the Bay of Pozzuoli or Gulf of Naples region in the setting and hardening of maritime concretes in sea-water (see Passages 7–9, 16, pp. 17–23, 27). None of the mineralogical or geochemical studies of the pumiceous ash presented here contradict the statements recorded in these ancient texts.

2. Vitruvius and Pliny the Elder mention the use of volcanic tuff *caementa* in the maritime concretes (Passages 7, 16; pp. 17–19), and glassy tuff does indeed form the bulk of the *caementa* in the concretes of the central Italian coast. Romans did, however substitute decicentimetre-sized chunks of local rock, mainly limestones, for tuff *caementa* in the eastern Mediterranean concrete harbour installations (pp. 147–53). The tuff and/or carbonate rock rubble apparently form a clast-supported framework that reinforces the concrete, and the massive size and weight of the harbour structures provides resistance to strong wave forces at the structural scale.
3. Roman engineers maintained a rather consistent ratio of pumiceous mortar to rock *caementa* in the formulation of the concretes (p. 161). Estimates of the ratio of mortar to *caementa* along the surfaces of the drill cores of the concretes suggest a volumetric ratio mainly of 35 to 45 volume % *caementa* and 55 to 65 volume % mortar. This suggests that there was a standardized formulation for the concrete mix, and that the proportion of ash for the mortar would have been calculated and its transport to the harbour site planned well in advance of the concrete construction.
4. Romans seem to have selected limestones to be calcined for lime from diverse sources. These range from nearly pure calcite, with only traces of magnesium, for the mortars of many of the central Italian coast concretes to more dolomitic, or magnesium rich compositions for the mortars of some of the eastern Mediterranean harbour concretes (pp. 170–75). Discrete microstructures indicative of dissolution of lime particles suggest that builders could have assembled a more or less dry mixture of pebble lime and pumiceous ash pozzolan in a mortar trough, for at least some of the concretes, and then dumped this mixture into the submarine form (pp. 164–65). Although variations in the hydration and placement procedures of the ancient concretes remain unclear, it seems that builders preferred matured, slaked pebble lime for at least some of the harbour concretes. They would have calcined the limestone and then hydrated the resulting quicklime in a $CO_2$-free environment, perhaps for about two to three years based on ancient sources (pp. 163–64). Modern mortars fabricated with aged slaked lime show improvements in workability and material characteristics. Lime production and preparation would have required substantial planning several years before the actual installation of the concretes, given the large size of certain harbour structures.
5. All the maritime mortars have a similar but highly heterogeneous fabric at the macroscale. This includes volcanic ash pozzolan composed of sand- to gravel-sized, mainly yellowish-gray, pale orangish-gray, and, occasionally, greenish-gray pumice and glass particles, crystals, particles of vitric tuff, lava lithic fragments, and dull white inclusions of relict lime enclosed in a translucent to dull white cementitious matrix (p. 153). There are also occasional ceramics, limestone particles, and a small proportion of scoriaceous ash in the Claudian and Trajanic structures at Portus. Some mortars also contain centimetre-sized clots of lime putty. The pumiceous ash particles seem to produce a very fine capillary pore size distribution in the mortars, in the range of about 10 to 100 nanometres. Although the overall porosity of the mortars is quite high, 40 to 60 volume %, the vesicular nature of the pumiceous ash may have improved durability by decreasing permeability and the mobility of fluids in the concretes.
6. The fundamental binding substance of the concretes, calcium-aluminium-silicate-hydrate (C-A-S-H), is a highly stable poorly crystalline cementing binder (pp. 167–70). Aluminium substitution for silica is an important factor in its chemical durability, although its overall character remains poorly understood. The ancient C-A-S-H encloses the relicts of silt- and sand-sized pumiceous ash pozzolan particles to form a complex cementitious matrix that binds the ancient concretes. Modern environmentally-friendly concretes that replace Portland cement with aluminous supplemental materials also develop a C-A-S-H binder, which improves concrete durability and resistance to decay in alkaline environments. Modern durability studies commonly last a few years and, at most, twenty years. This is, perhaps, the time scale that Romans used to evaluate the performance of the sea-water concretes formulated with the pyroclastic deposits from the Gulf of Naples that are described by Vitruvius (Passages 7, 9, pp. 17–23).
7. A rare cementitious mineral, Al-tobermorite, occurs in the mortars of all the harbour concretes. Most commonly, particles of sand- to pebble-sized lime hydrated in the sea-water environment to produce Al-tobermorite and C-A-S-H in dull white inclusions. The crystals do not form in conventional cement-based concretes, however, and instead must be produced at high temperatures in

laboratory syntheses. The ubiquitous *in situ* crystallization of Al-tobermorite evidently relies on exothermic heat produced through hydration of cementitious phases in the massive structures. That it occurs in all the mortars is a testament to the expertise of the Roman builders in creating a highly durable cementitious fabric in the sea-water concrete structures. They must have followed systemized mortar formulations and installation procedures, but the details of these remain unclear. Al-tobermorite has not yet crystallized in the Brindisi concrete pila reproduction.

8. Roman engineers' selection of pumiceous volcanic ash pozzolan for all the sea-water mortars may have provided local alumina-rich microenvironments that encouraged the development of crystalline microstructures containing chloride and sulphate derived from sea-water (pp. 168–70). These are commonly associated with the relict lime clasts and may contribute to the long-term durability of the concrete. In modern Portland cement concretes, migration of sulphate ions produces damaging expansions, and chloride ions cause corrosion of steel reinforcements. The discrete crystalline structures of hydrocalumite and ettringite, for example, in the ancient concretes may have sequestered and immobilized chloride and sulphate that are associated with corrosion of steel reinforcements and damaging expansion in Portland cement concretes.
9. Roman builders did not apparently make large structural demands on the maritime concretes structures in terms of their weight-bearing strength; loads generated by modest, overlying buildings and warehouses, would have been distributed over the surface area of a pier or mole (pp. 175–180). They did, however, rely on the harbour structures to remain anchored on the seafloor, resist the impact force of strong waves, and remain cohesive when subjected to wave erosion or earthquake ground shaking. This seems to indicate that the low compressive strengths measured through laboratory testing of the 9 cm diameter concrete drill cores may not represent the actual behaviour of the concretes in most of the harbour structures. Concretes of the central Italian coast with glassy tuff *caementa* have comparable values of uniaxial compressive strength, about 5 MPa to 8.5 MPa. The unpredictable behaviour and low strength of some of the Egnazia, Chersonesos, Caesarea Palaestinae, and Alexandria concretes seems to reflect debonding of their carbonate rock *caementa* with the pumiceous mortar in the laboratory. The limestone *caementa* evidently did not detract from the long durability of the harbour structures, and their incorporation in the concrete mix greatly reduced the volume of pyroclastic rock that would possibly have been shipped from the Gulf of Naples to far distant ports.

# Chapter 2

# Ancient Literary Sources Concerned with Roman Concrete Technology

## *J. P. Oleson*

The standard generic term in Latin for concrete structural work was probably something like *opus caementicium* ("rubble work" or "aggregate work"). This precise phrase, however, only seems to occur once in the surviving written sources, in a later first-century BC inscription from Philippi in Macedonia that mentions a patron who built an *opus caementic*(*ium*) (concrete structure"; *CIL* 3.633) in front of the temple. Instead, there is routinely mention of a type of wall or structure associated with the adjective, for example *fornice*(*m*?) *et parietes caementicios* ("an arch [or "arches"] and walls built of concrete"; *CIL* 1.1801), *in caementiciis…structuris* ("in concrete walls"; Vitruvius, *De arch* 2.4.1, 7.5). Clearly the Romans focused on the large aggregate (*caementa*) rather than the mortar, which was termed *materia* ("stuff"), *materies*, or *calx harenatus* ("a mix of lime and sand"; see Passage 3 below). This might seem odd to us, but the distinction between mortared rubble and concrete is one of degree; historians of Roman architecture tend to distinguish between the two by assuming that a concrete wall should show some distinction between the facing and the mortar and rubble core. The Latin terminology does not seem to show the same sensitivity, and in poetry such as the passages from Horace cited below, the term *caementa* alone can stand for a marine concrete structure. In any case, by the early Empire Roman builders understood that it was much faster and cheaper to use fist-sized *caementa* in the core of the concrete wall than either larger or smaller sizes, and that this factor was more important for economy than the type of facing (DeLaine 2001: 236–39).

Although large-scale construction using *opus caementicium* was a constant feature of Roman urban centres from the later Republic through the fourth century AD, particularly in Italy and the western Mediterranean provinces, there are surprisingly few literary descriptions or visual representations of the actual building process on land. Most of the literary texts relevant to terrestrial construction are collected in Humphrey *et al.* 1998: 235–81. MacDonald (1982: 122–66) could find only a few ancient texts, while Lugli (1957: 363–74) only assembles and comments on the terminology for the various materials and their preparation and application. For visual representations see Adam 1994: 33, 44–47, 53, 76, 82–83; Rea 2004; Lugli 1957: vol. 2, pl. 30. In his handbook of architecture Vitruvius describes many materials, designs, and types of construction, and he occasionally turns to the process itself, but he is the exception. Furthermore, Vitruvius does not discuss the actual process of *opus caementicium* construction on land, only the materials and their behaviour. There are a few passages with instructions about construction materials or procedures in the handbooks on agriculture by Cato and Varro. Since so many descriptions and contemporary representations of finished structures survive (Pollitt 1966; Coulston 1990), it has been suggested that the procedures involved in constructing them were apparently so commonplace as to be unworthy of frequent or detailed comment (Wilson Jones 2000: 49–68, 248–49). Alternatively, perhaps the individuals most familiar with the concrete construction process were not learned enough to write about their expertise or, if they had developed a particularly useful method or technique, were reluctant to share their innovations with competitors or the general public in writing. A further possibility is the existence of sub-literary technical manuals for concrete construction that circulated among military engineers or even the general public, but which have now been lost (pp. 230–33; *cf.* Oleson 2004, 2005). The few descriptions of construction that we have are for the most part poetic in character (*e.g.* Virgil, *Aen.* 1.418–29), or accounts by satisfied or unsatisfied villa owners (*e.g.* Cicero, *Q Fr.* 3.1.1–2; Pliny the Younger, *Ep.* 2.17). Ironically, descriptions of the catastrophic collapse of structures are common (Oleson 2011b).

In contrast, several very useful literary descriptions of construction below water level with maritime concrete have survived, along with evaluations of the materials involved – particularly the pozzolanic components of the concrete mixes. Although this type of construction was less common than construction on land, and restricted to sea coasts, river banks, and lake shores, the procedures involved were perhaps more interesting to engineers and the general public because of the counterintuitive dumping of expensive materials into submerged formwork or on prepared foundations hidden from view. The single-use barge forms employed at Caesarea, Alexandria, and other sites would have made a particularly striking impression, since they were laboriously constructed on shore but then filled with mortar and intentionally sunk on the construction site within sight of observers on land (see pp. 208–21). Nevertheless, this type of formwork does not appear in the surviving literary tradition, except for the confused accounts of the sinking of Caligula's obelisk barge at Portus for use as formwork (see below Passages 15, 17, 24).

The long passage in Vitruvius concerning the construction of harbours (5.12.1–5; Passage 9 below) is our most important source for submarine construction, but a number of other, less well-known comments on the topic survive and contribute to our understanding of the approach Roman engineers took to this type of construction. Some passages not directly concerned with marine concrete are included in our discussion as well, since they contribute to our knowledge of the technologies and procedures involved. In particular, several passages have a bearing on the pozzolanic reactions in concrete and provide insights into what individuals such as Pliny or Cassius Dio or their sources thought about the material characteristics of volcanic ash pozzolan or volcanic tuff, why the hydration of quicklime and the wet mortar mix gave off heat during setting, and why the resulting concrete developed strength and durability. Although published translations exist for most of these passages, it was necessary to provide here both the original texts and fairly literal, new translations of all the relevant passages, both for the convenience of the reader and to clarify misunderstandings in previous translations. For example, many of the published translations of the passages retranslated here misinterpret the text because of ignorance of the chemistry or of the procedures involved in preparing and placing marine concrete. Oleson has prepared the translations, which are informed by the ROMACONS research on maritime concrete. The modern editions of the Greek or Latin text are indicated.

The ancient authors are arranged in approximate chronological sequence, but with all the inscriptions at the end of the collection, and for each literary work the passages are presented in the order in which they appear in the modern editions (Table 2.1). Any attempt to present the passages in order of perceived importance or by topic would have both introduced confusion and obscured the viewpoint and contribution of particular authors. For the benefit of the reader without these languages, important Latin and Greek terms are provided within the translations in parentheses (in the cases in which they occur, rather than in the nominative or infinitive), and sections of the Greek or Latin text follow the translation of particularly important or ambiguous phrases or passages. Where the translation is uncertain, the Latin or Greek phrase is given in parentheses and preceded by a question mark. Parentheses within the translation enclose explanatory material added by Oleson. Each passage is provided with a catalogue number, to allow easier cross-reference within this book. The texts are accompanied by analysis of the content and a short discussion of their relevance to Roman hydraulic concrete.

## 2.1. Theophrastus

Theophrastus (*ca.* 382–287 BC), head of the Lyceum in Athens after the retirement of Aristotle, continued his predecessor's strategy of collecting and commenting on data concerning the natural world. Most of his surviving works concern botany, but there are a few short works and fragments relevant to Roman concrete technology. In the first passage quoted here, Theophrastus comments on the caustic heat produced when slaking lime, necessitating the use of a stick for mixing it. This passage not only makes explicit the observation of the chemical reaction involved in slaking lime, but it also implies that other mortar mixes were sometimes worked by hand rather than with tools.

[1] *On Stones* 66. Procedures for slaking lime.

> κόψαντες δὲ καὶ ὕδωρ ἐπιχέοντες ταράττουσι ξύλοις, τῇ χειρὶ γὰρ οὐ δύναται διὰ τὴν θερμότητα. (Caley and Richards 1956: 29).
>
> Having broken up (the hydrated lime) and poured water on it, they mix it with wooden sticks, for it cannot be mixed with the hand because of the heat.

Pollux (*Nomenclature* 10.149) quotes a comment in Theophrastus *On Metals* about the equipment used by miners. The heavy sieve (*salax*) Theophrastus mentions, probably used to sift ore in the form of sand or gravel-sized particles, is a tool also used by Roman engineers to remove particles from hydrated lime or volcanic ash pozzolan in preparation for mixing with water to make mortar (see below, Cato, Passage no. 3; Apuleius, Passage no. 25; Blake 1947: 314; Jackson *et al.* 2011: 733). The particle size distribution of the volcanic ash pozzolan in some of the ROMACONS cores suggests this sort of pre-treatment, which could have been carried out either in the quarry or at the construction site.

[2] *On Metals*, frag. 198. The miner's sieve.

> …Θεόφραστος ἐν τῷ Μεταλλικῷ, περίοδον μὲν τὸ ἀγγεῖον ᾧ κατακεραννύουσι τὸν σίδηρον, σάλακα δὲ τὸ τῶν μεταλλέων κόσκινον. (Bekker 1846: 440).
>
> Theophrastus in *On Metals* (mentions) the crucible, the container in which they mix the iron ore, and the *salax*, the miner's sieve (*koskinon*).

## 2.2. M. Porcius Cato

Cato the Elder (234–149 BC) wrote a handbook on farm management – *De re rustica* – around 160 BC. His description of the construction of the floor for a pressing room mentions both the sifting of lime and the compaction of the mix of mortar and aggregate, both issues that arise in the discussion of marine concrete.

*Table 2.1: Chronological list of literary passages relevant to maritime concrete.*

| | |
|---|---|
| 1 | Theophrastus, *On Stones* 66. Procedures for slaking lime. |
| 2 | Theophrastus, *On Metals*, frag. 198. The miner's sieve. |
| 3 | Cato, *De re rustica* 18.7. Early procedures for laying a concrete foundation. |
| 4 | Vitruvius, *De architectura* 1.2.8. Economy in the selection of construction materials. |
| 5 | Vitruvius, *De architectura* 2.4.1–3. The various types of sand used in mortar. |
| 6 | Vitruvius, *De architectura* 2.5.1–3. The importance of preparing a proper lime for mortar mixes. |
| 7 | Vitruvius, *De architectura* 2.6.1–6. The origins and utility of volcanic ash pozzolans. |
| 8 | Vitruvius, *De architectura* 2.8.2. The importance of sufficient moisture for the curing of mortar. |
| 9 | Vitruvius, *De architectura* 5.12.1–6. The location and construction of various types of harbours. |
| 10 | Horace, *Odes* 3.1.33–37. Marine structures crowd the sea. |
| 11 | Virgil, *Aeneid* 9.710-714. A *pila* is tipped into the sea from the shore at Baiae. |
| 12 | Strabo, *Geography* 5.4.6. Local *pozzolana* allowed construction of the great concrete mole at Puteoli. |
| 13 | Seneca, *Quaestiones Naturales* 2.30.1. Sandy volcanic products from Mt. Aetna. |
| 14 | Seneca, *Quaestiones Naturales* 3.20.3. Pumiceous volcanic ash hardens in the presence of water. |
| 15 | Pliny, *Historia naturalis* 16.201–202. A giant ship used as a floating form for concrete. |
| 16 | Pliny, *Historia naturalis* 35.166–67. The characteristics of *pozzolana* and other volcanic sands. |
| 17 | Pliny, *Historia naturalis* 36.70. A giant ship used as a floating form for concrete. |
| 18 | Pliny, *Historia naturalis* 36.174–76. The selection of limestone and sandy volcanic products for use in mortar. |
| 19 | Statius, *Silvae* 4.3.52–53. Pumiceous volcanic ash used in the foundations for a road. |
| 20 | Josephus, *Jewish War* 1.408–414. A description of the great concrete breakwaters at Caesarea Palaestinae. |
| 21 | Josephus, *Jewish Antiquities* 15.332–38. Another description of the great concrete breakwaters at Caesarea Palaestinae. |
| 22 | Pliny, *Epistulae* 6.31.15–17. Construction of the harbour of Centum Cellae with rubble mounds and concrete. |
| 23 | Pliny, *Epistulae* 10.39.4. Inferior construction in the gymnasium at Nicaea. |
| 24 | Suetonius, *Claudius* 20.3. The engineering methods used to construct Portus. |
| 25 | Apuleius, *Metamorphoses* 8.23. A sieve for construction materials. |
| 26 | Cassius Dio, *Roman History* 48.51.3–4. The geological origins of *pozzolana* at Baiae. |
| 27 | Cassius Dio, *Roman History* 60.11.2–5. The location and construction of Portus. |
| 28 | Faventinus, *De diversis fabricis architectonicae* 4. How to mix mortar for a brick wall. |
| 29 | Faventinus, *De diversis fabricis architectonicae* 8–9. How to evaluate the quality of sand and lime. |
| 30 | Procopius, *On Buildings* 1.11.18–20. Justinian's use of box forms for a harbour at Constantinople. |
| 31 | *CIL* 10.1781. *Lex parieti faciundo Puteolana* 2.16–21, 105 BC. Specifications for the construction of a wall. |
| 32 | *CIL* 10.3414 (=*ILS* 2871), first or second century. Epitaph of L. Iulius Valens, *caementarius* with the fleet at Misenum. |

[3] *De re rustica* 18.7. Early procedures for laying a concrete foundation.

> Fundamenta primum festucato, postea caementis minutis et calce harenato semipedem unumquodque corium struito. Pavimenta ad hunc modum facito: ubi libraveris, de glarea et calce harenato primum corium facito, id pilis subigito; idem alterum corium facito; eo calcem cribro subcretam indito alte digitos duo, ibi de testa arida pavimentum struito: ubi structum erit, pavito fricatoque, uti pavimentum bonum siet. (Mazzarino 1982: 30).
>
> First tamp down the bottom (of the foundation trench), and then lay successive, half-foot thick layers of crushed gravel aggregate and a mix of sand and lime (*caementis minutis et calce harenato*). Make the pavement in the following manner. When you have levelled the site, lay a first layer of gravel and a sand-lime mix (*calce harenato*) and tamp it down, then place a second layer of the same material on top. On this place a layer two-fingers thick of lime passed through a sieve (*calcem cribro subcretam*) and lay a surface of potsherds on top. When completed, pack it down and smooth it off so as to have a good floor.

For other descriptions of the use of a sieve for construction materials, see Theophrastus, Passage 1; Vitruvius, Passage 5;

Apuleius, Passage 25. *Calx harenatus* ("a mix of lime and sand") is the early term for mortar; in Vitruvius the usual terms are *materia* or *materies*, as seen in *De architectura* 5.12.3 (Passage 9). Cato describes buildings made *ex calce et caementis* ("from lime and rubble," *Agr.* 14.1; 15; 18.7; Passage 3) or *lapide et calce* ("from stone and lime," *Agr.* 14.4), presumably *calx harenatus*. These structures might, however, have taken the form of mortared rubble rather than concrete, in which the facing and core tend to be quite different. Nevertheless, Cato is the earliest literary source for the basic materials of *opus caementicium* (Lugli 1957: vol. 1, p. 374). Cato describes the process for burning lime in *Agr.* 38 (Dix 1982).

## 2.3. Vitruvius Pollio

Vitruvius (*flor.* second half of first century BC) wrote the only surviving ancient handbook of architecture, *De architectura*, probably published between 30 and 22 BC (Rowland *et al.* 1999: 3–5). Vitruvius himself refers to it as a "handbook" meant to make up for the lack of existing handbooks of Roman architecture: *audemus institutiones novas comparare* ("…we venture to prepare a new handbook"; *De arch.* 7, *praef.* 10, 14). He ends the Preface to Book 7 with the following explanation (*De arch.* 7, *praef.* 18).

> Cum ergo et antiqui nostri inveniantur non minus quam Graeci fuisse magni architecti et nostra memoria satis multi, et ex his pauci praecepta edidissent, non putavi silendum, sed disposite singulis voluminibus de singulis exponendum. (Rose and Müller-Strübing 1867: 162).
>
> Since, therefore, our ancestors are found to have been no less great architects than the Greeks were, and-–in addition— quite a few in our recent memory, but few of these have published their principles, I thought that I should not be silent but should set out the information in order, each topic in a particular section of the book.

While Vitruvius explains that some of his work is a pastiche of borrowings from Hellenistic authors (see the list in Book 7, *praef.* 11–17), which he admits were translated into Latin with some difficulty, several books and subsections deal with materials and procedures common in Rome of the Late Republic, along with the procedures for building harbours with pozzolanic concrete. Although some scholars consider that Vitruvius generally ignores the creative engineering made possible by concrete in the second and first centuries BC in Italy (MacDonald 1982: 3–19; but *cf.* Rowland *et al.* 1999: 11–13), new analyses show how Vitruvius struggled with reconciling the empirical principles of Hellenistic science with the Empedoclean Theory of the four elements (Jackson and Kosso 2013). Literal translations of his often-convoluted Latin provide new insights into his descriptions of material characteristics, such as water absorption in earth materials, and explanations for hydration processes in the maritime concretes. Such translations also reveal his thoughts about the role of collaboration in the construction of the Late Republican era monuments (Jackson *et al.* 2011). The passages from the earlier books collected here concern materials; those from the later books, procedures. Virtually every book on Roman architecture includes long discussions of Vitruvius' work; for modern scholarship more focussed on the following passages, see in particular Dubois 1902; Jüngst and Thielscher 1936, 1939; Schramm 1936, 1938; Blake 1947; Lugli 1957; Schläger 1971; Oleson 1985; Brandon 1996; Callebat 1999; Rowland *et al.* 1999; Oleson *et al.* 2006; Jackson and Marra 2006; Jackson *et al.* 2007, 2011, 2012; Felici 2009.

The first book of the *De architectura* deals with the first principles of architecture and the layout of cities; Chapter 2, from which the following selection is taken, concerns the terms for various aspects of architecture and with architectural practice. The provision of special materials such as *Puteolanus pulvis* or *harena fossicia* would have been particularly important to engineers constructing harbours. The engineers who worked on the structures of Sebastos at Caesarea at approximately the same time the *De architecura* was composed imported *pozzolana* from 2,000 km away, and it appears they economized on its use wherever possible (see pp. 78–79).

[4] *De architectura* 1.2.8. Economy in the selection of construction materials.

> Distributio autem est copiarum locique commoda dispensatio parcaque in operibus sumptus cum ratione temperatio. Haec ita observabitur, si primum architectus ea non quaeret, quae non poterunt inveniri aut parari nisi magno. Namque non omnibus locis harenae fossiciae nec caementorum nec abietis nec sappinorum nec marmoris copia est, sed aliud alio loco nascitur, quorum comportationes difficiles sunt et sumptuosae. Utendum autem est ubi non est harena fossicia, fluviatica aut marina lota, inopiae quoque abietis aut sappinorum vitabuntur utendo cupresso populo ulmo pinu, reliquaque his similiter erunt explicanda. (Gros 1997: vol. 1, p. 30).
>
> Allocation, however, is the proper arrangement of supplies and building site, and a thrifty and well-reasoned economy in construction expenses. An appropriate standard will be kept if above all the architect does not require materials that can only be found or prepared at great expense. For not every locality has supplies of quarry sand (*harenae fossiciae*), large aggregate (*caementorum*), fir or spruce wood, or marble, but one material is found in one place, others in another. Transport of such materials to a construction site is difficult and costly. Where quarry sand does not occur, river sand or washed sea sand (*harena…fluviatica aut marina lota*) must be used, and the absence of fir or spruce wood can be remedied by the use of cypress, poplar, elm, or pine. The lack of other materials should be worked out in the same manner.

By *harenae fossiciae* ("quarry sand") Vitruvius means both pumiceous volcanic ash mainly excavated from products of the

Alban Hills volcanic district in the vicinity of Rome for use as mortar pozzolan (Jackson *et al.* 2007, 2009, 2010), and similar volcanic materials found elsewhere. See the next passage, and the discussion at the end of this section.

[5] *De architectura* 2.4.1–3. The various types of sand used in mortar.

> (1) In caementiciis autem structuris primum est de harena quaerendum, ut ea sit idonea ad materiem miscendam neque habeat terram commixtam. Genera autem harenae fossiciae sunt haec: nigra, cana, rubra, carbunculum. Ex his quae in manu confricata fecerit stridorem erit optima, quae autem terrosa fuerit, non habebit asperitatem. Item si in vestimentum candidum ea contecta fuerit, postea excussa id non inquinarit neque ibi terra subsiderit, erit idonea. (2) Sin autem non erunt harenaria unde fodiatur, tum de fluminibus aut e glarea erit excernenda, non minus etiam de litore marino. Sed ea in structuris haec habet vitia, difficulter siccescit, neque onerari se continenter paries patitur nisi intermissionibus requiescat, neque concamerationes recipit. Marina autem hoc amplius quod etiam parietes, cum in his tectoria facta fuerint, remittentes salsuginem eorum dissolvuntur. (3) Fossiciae vero celeriter in structuris siccescunt, et tectoria permanent, et concamerationes patiuntur, sed eae quae sunt de harenariis recentes. Si enim exemptae diutius iacent, ab sole et luna et pruina concoctae resolvuntur et fiunt terrosae. Ita cum in structuram coiciuntur, non possunt continere caementa, sed ea ruunt et labuntur onera quae parietes non possunt sustinere. Recentes autem fossiciae cum in structuris tantas habeant virtutes, hae in tectoriis ideo non sunt utiles quod pinguitudine eius calx palea commixta propter vehementiam non potest sine rimis inarescere. Fluviatica vero propter macritatem uti signinum liaculorum subactionibus in tectorio recipit soliditatem. (Gros *et al.* 1997: vol. 1, pp. 128–30)
>
> (1) In building with concrete, the first question concerns the sand, that it should be suitable for mixing the mortar (*materiem*) and not be contaminated with earth. These, then, are the types of quarry sand: black, white, red, and *carbunculus*. Of these, that which makes a crackling noise when rubbed in the palm is best; that which contains earth will not have the proper roughness (*asperitatem*). Similarly, if this sand is wrapped in a white garment and does not soil it or leave earthy matter behind when shaken out, it will be suitable. (2) But if there are no quarries from which to dig the sand, then it must be sifted out of rivers or gravel, or even from marine beaches. These types of sand, however, have the following faults when used in construction: the mortar sets (*siccescit*, lit. "dries") with difficulty, so the wall cannot carry a load immediately but must cure for a period of time. Also the wall cannot carry vaults (*concamerationes*). Marine sand has an additional fault in that the walls made with it, when plastered over, exude a salty florescence and crumble. (3) Concrete structures (*structuris*) made with quarry sand, however, set quickly, the plaster sticks, and they can bear vaults – as long as the sand has recently come from the quarry. For if the sand is left lying about for a while after having been dug up, it weakens, cooked by the sun and moon and frost, and takes on an earthy quality. When such sand is used in the mix for a concrete structure, it cannot bond with the large aggregate (*caementa*), these loosen, and the walls cannot sustain their load but collapse. Although recently dug quarry sand has these great advantages in building with concrete, it is not likewise useful for plastering. It has a richness (*pinguitudine*) that brings about a strong reaction when used with a lime and straw plaster, which in consequence cannot dry without cracking. River sand, however, on account of its lack of reactivity (*macritatem*, lit. "thinness") takes on strength in a plaster coating when worked with a finishing tool, as does plaster with a mix of crushed ceramics (*signinum*).

Vitruvius clearly is aware of the reactive value of excavated sands other than the fine-grained deposits from Puteoli. He recommends that they be recently dug from their quarries (*harenaria*), as such sands speed up the setting and curing of the concrete and enhance its ultimate capacity to bear loads. If quarried too long before use, the sand apparently weathers or is altered to a less useful form. Blake (1947: 313–14) suggests that the "earthy" quality of the mortars used in Rome in the second and first centuries BC indicates that builders did not at that time take sufficient care to search out quarries of "pure pozzolana." Recent geoarchaeological studies have shown that this is an erroneous perspective. Instead, builders of the second and early first centuries BC produced mortars using reworked volcanic ash from alluvial deposits, often excavated at the construction site, as at the Temple of Concord and the Temple of Castor and Pollux in the Roman Forum (Jackson *et al.* 2007). The mid- to late first century BC was a period of intensive innovation with mortar formulations in Rome, which culminated in the early Augustan age with a standard mix using the scoriaceous ash of the Pozzolane Rosse pyroclastic flow (Jackson *et al.* 2010; Jackson and Kosso 2013). The Theatre of Marcellus (44, 13–11 BC), constructed while Vitruvius was writing *De architectura*, is an excellent example of these innovations, and also contains refined barrel arches with tuff and travertine dimension stone voussoirs (Jackson *et al.* 2011). The very high quality of the concrete walls, with mortar formulated with Pozzolane Rosse pozzolan, has supported these arches for 2000 years. It is possible that the *concamerationes* mentioned in the passage above are not concrete or stone vaults, but the arches of dimensioned stone seen on the Theatre of Marcellus. Builders continued to perfect these mortars during the Imperial age, as described by Van Deman (1912a–b), and confirmed with recent analytic investigations for the Markets of Trajan concretes (Jackson *et al.* 2009).

It is interesting that Vitruvius suggests the utility of concrete in constructing buildings with vaulted roofs, which were an important part of the cityscape in the first century BC but which do not otherwise feature in his book. Vitruvius proposes simple field tests to determine the proper quality of material, appropriate to a quarry or construction site: a crackling sound when rubbed in the palm, and easy removal from a cloth without leaving an earthy trace behind.

The selection and preparation of lime is also crucial to the creation of a high-quality mortar (Lugli 1957: vol. 1, pp. 390–94). Lime paste, in fact, was the most expensive ingredient in a concrete mix (Lancaster 2005a: 16–17; Faventinus 4, Passage 28). Pliny (*HN* 36.176, Passage 18) states that "The primary cause for the collapse of buildings in Rome is cheating on the proportion of lime"; this type of fraud remains a serious problem in developing countries.

[6] *De architectura* 2.5.1–3. The importance of preparing a proper lime for mortar mixes.

> (1) De harenae copiis cum habeatur explicatum, tum etiam de calce diligentia est adhibenda uti de albo saxo aut silice coquatur. Et quae erit ex spisso et duriore, erit utilis in structura, quae autem ex fistuloso, in tectoriis. Cum ea erit extincta, tunc materia ita misceatur ut si erit fossicia, tres harenae et una calcis infundatur, si autem fluviatica aut marina duo harenae et una calcis coiciatur. Ita enim erit iusta ratio mixtionis temperaturae. Etiam in fluviatica aut marina si qui testam tunsam et succretam ex tertia parte adiecerit, efficiet materiae temperaturam ad usum meliorem. (2) Quare autem cum recipit aquam et harenam calx tunc confirmat structuram, haec esse causa videtur quod e principiis uti cetera corpora ita et saxa sunt temperata. Et quae plus habent aeris sunt tenera, quae aquae, lenta sunt ab umore, quae terrae dura, quae ignis fragiliora. Itaque ex his saxa si antequam coquantur, contusa minute mixta harenae in structuram coiciantur, non solidescunt nec eam poterunt continere. Cum vero coniecta in fornacem ignis vehementi fervore correpta amiserint pristinae soliditatis virtutem, tunc exustis atque exhaustis eorum viribus relinquuntur patentibus foraminibus et inanibus. Ergo liquor, qui est in eius lapidis corpore et aer cum exustus et ereptus fuerit, habueritque in se residuum calorem latentem, intinctus in aqua, priusquam ex ignis vim recepit, umore penetrante in foraminum raritates confervescit et ita refrigeratus reicit ex calcis corpore fervorem. (3) Ideo autem quo pondere saxa coiciuntur in fornacem, cum eximuntur non possunt ad id respondere, sed cum expenduntur, permanente ea magnitudine, excocto liquore circiter tertia parte ponderis inminuta esse inveniuntur. Igitur cum patent foramina eorum et raritates, harenae mixtionem in se corripiunt et ita cohaerescunt siccescendoque cum caementis coeunt et efficiunt structurarum soliditatem. (Gros *et al.* 1997: vol. 1, pp. 130–32).
>
> (1) Not only should we consider the proper supply of sand, but efforts must also be made concerning the lime, that it be prepared from white stone or limestone (? *de albo saxo aut silice*). The lime that is made from dense and rather hard stone will be useful in concrete work; that made from porous stone is preferable for plasterwork. Once the lime has been slaked, mix the mortar (*materia*) according to these formulae: if it is quarry sand (*harena fossicia*), mix three portions of sand to one portion of lime. If it is river or beach sand, mix two portions of sand with one of lime. These are the appropriate ratios for the mix. As concerns river or beach sand, if one adds an additional third part of crushed and sifted ceramic (*testam tunsam et succretam*), it will bring a proper temper to the mix and increase its utility. (2) But why, when slaked lime is mixed with water and sand, does it strengthen concrete (*structuram*)? This seems to be the cause, that rocks, like other entities, receive their character from their particular origin. So, limestone that has a higher proportion of air is soft, limestone with a higher proportion of water is pliable on account of the moisture, limestone with a higher proportion of earth is hard, and limestone with a higher proportion of fire is rather friable. So, if limestone of this last class is broken into small pieces before it is burned, then mixed with sand and added to the construction, it does not set and cannot support the structure. For when the stones are thrown into the kiln and are caught by the searing heat of the fire, they not only lose the advantage of their former solidity but also are left with open and empty pores, after their strength has been burned out and sucked from them. Therefore, when the moisture and air that are in the body of that stone have been burned out and snatched away, there is a hidden heat left behind in it. When plunged in water, before it takes on any strength from exterior flame, as the moisture penetrates into the slender pores it grows hot, and in the course of the reaction growing cool again it drives the latent heat out of the substance of the lime. (3) But why, then, when stones are taken out of the kiln, do they not correspond to the weight measured when they were thrown in? They are found to be the same size, but their weight has been reduced by a third on account of the moisture driven out. As a result, since their fissures and pores lie open, the sand (possibly "the pumiceous volcanic additive") takes control of the mixture as it dries and grows together in such a manner that it unites with the large aggregate (*caementis*) and produces the solid character of the concrete masses (*structurarum soliditatem*).

Vitruvius correctly emphasizes the need for care in selecting the limestone to be calcined to produce lime. The Latin word *silex* has several meanings. In most contexts it means "a hard stone," but in the context of preparing lime, it must indicate a hard, compact limestone. Pliny (*HN* 36.174; Passage 18) echoes Vitruvius' specifications, although he sets the ratio of lime to quarry sand at 1 to 4 instead of 1 to 3. According to this passage, 1 to 3 is the hydraulic mix for structures on land; for marine structures he specifies elsewhere (*De arch.* 5.12.2; Passage 9) that it was one to two (*cf.* Lancaster 2005a: 55). Although questions about the sequence of mixing often come up in discussions of Roman concrete engineering, Vitruvius here explicitly states that the lime should be slaked before it is added to the mortar mix. Unlike Pliny, however, Vitruvius does not explicitly recommend ageing the lime putty before use. Vitruvius quite reasonably assumes that the hydrated lime takes its characteristics from the original limestone, and that the loss of one-third of the weight of the original stone in the kiln leaves open "fissures and pores" (*foramina et raritates*) that allow the "sand," by which he possibly means the pumiceous volcanic additive, to drive the reaction that hardens the mix. Given the absence of modern concepts of chemical reactions, this is a reasonable analysis of the situation. In fact, limestone loses around 44 percent of its weight and one-fifth to one-tenth of its volume when calcined (Lugli 1957: vol. 1, p. 392).

[7] *De architectura* 2.6.1–6. The origins and utility of volcanic ash pozzolans.

> (1) Est etiam genus pulveris quod efficit naturaliter res admirandas. Nascitur in regionibus Baianis in agris municipiorum quae sunt circa Vesuvium montem. Quod commixtum cum calce et caemento non modo ceteris aedificiis praestat firmitates, sed etiam moles cum struuntur in mari, sub aqua solidescunt. Hoc autem fieri hac ratione videtur quod sub his montibus et terrae ferventes sunt et fontes crebri, qui non essent, si non in imo haberent aut e sulphure aut alumine aut bitumine ardentes maximos ignes. Igitur penitus ignis et flammae vapor per intervenia permanans et ardens efficit levem eam terram, et ibi quod nascitur tofus exsurgens est sine liquore. Ergo cum tres res consimili ratione ignis vehementia formatae in unam pervenerint mixtionem, repente recepto Iiquore una cohaerescunt et celeriter umore duratae solidantur, neque eas fluctus neque vis aquae potest dissolvere. (2) Ardores autem esse in his locis etiam haec res potest indicare, quod in montibus Cumanorum Baianis sunt loca sudationibus excavata, in quibus vapor fervidus ab imo nascens ignis vehementia perforat eam terram per eamque manando in his locis oritur et ita sudationum egregias efficit utilitates. Non minus etiam memorantur antiquitus crevisse ardores et abundavisse sub Vesuvio monte et inde evomuisse circa agros flammam. Ideoque tunc quae spongia sive pumex Pompeianus vocatur excocto ex alio genere lapidis in hanc redacta esse videtur generis qualitatem. (3) Id autem genus spongiae quod inde eximitur non in omnibus locis nascitur, nisi circum Aetnam et collibus Mysiae quae a Graecis κατακεκαυμένη nominatur et si quae eiusdem modi sunt locorum proprietates. Si ergo in his locis aquarum ferventes inveniuntur fontes et in omnibus excavatis calidi vapores, ipsaque loca ab antiquis memorantur pervagantes in agris habuisse ardores, videtur esse certum ab ignis vehementia ex tofo terraque, quemadmodum in fornacibus ex calce, ita ex his ereptum esse liquorem. (4) Igitur dissimilibus et disparibus rebus correptis et in udam potestatem conlatis, calida umoris ieiunitas aqua repente satiata communibus corporibus latenti calore confervescit et vehementer efficit ea coire celeriterque unam soliditatis percipere virtutem.
>
> Relinquetur desideratio, quoniam ita sunt in Etruria ex aqua calida crebri fontes, quid ita non etiam ibi nascitur pulvis, e quo eadem ratione sub aqua structura solidescat. Itaque visum est antequam desideraretur de his rebus quemadmodum esse videantur exponere. (5) Omnibus locis et regionibus non eadem genera terrae nec lapides nascuntur, sed nonnulla sunt terrena, alia sabulosa itemque glareosa aliis locis harenosa non minus materia, et omnino dissimili disparique genere in regionum varietatibus qualitates insunt in terra. Maxime autem id sic licet considerare quod qua mons Appenninus regiones Italiae Etruriaeque circa cingit, prope in omnibus locis non desunt fossicia harenaria, trans Appenninum vero, quae pars est ad Hadriaticum mare, nulla inveniuntur, item Achaia Asia omnino trans mare nec nominatur quidem. Igitur non in omnibus locis quibus effervent aquae calidae crebri fontes, eaedem opportunitates possunt similiter concurrere, sed omnia uti natura rerum constituit, non ad voluptatem hominum sed ut fortuito disparata procreantur. (6) Ergo quibus locis non sunt terrosi montes sed genere materiae, ignis vis per eius venas egrediens adurit eam. Quod est molle et tenerum exurit, quod autem asperum relinquit. Itaque uti Campania exusta terra cinis, sic in Etruria excocta materia efficitur carbunculus. Utraque autem sunt egregia in structuris, sed alia in terrenis aedificiis alia etiam in maritimis molibus habent virtutem. Est autem materiae potestas mollior quam tofus, solidior quam terra, qua penitus ab imo vehementia vaporis adusta; nonnullis locis procreatur id genus harenae quod dicitur carbunculus. (Gros 1997: vol. 1, pp. 132–36).

(1) There is a kind of powdery earth (*pulvis*) that by its nature produces wonderful results. It occurs (*nascitur*) in the neighbourhood of Baiae and the territory of the municipalities around Mount Vesuvius. This material, when mixed with lime and rubble (*calce et caemento*), not only furnishes strength to other buildings, but also, when breakwaters (*moles*) are built in the sea, they set under water. Furthermore this seems to occur for the reason that under these mountains there are both hot soils and many springs, which would not exist unless deeper down there were great fires burning with sulphur, alum, or pitch. Therefore the fire and vapour of the flame within, spreading and burning through the fissures, make this earth light; and the tuff created there rises up and is without moisture. Thus when these three substances (ash pozzolan, lime, and tuff) formed in a similar manner by the strength of fire are brought together into one mixture, and suddenly they are put in contact with [sea-]water, they cohere into a single mass, quickly solidifying, hardened by the moisture, and neither the force of the waves nor the effect of water can dissolve them. (2) The following observation also indicates that heat resides in these places: the fact that in the hills behind Baiae near Cumae there are places eroded by the exhalations, in which the hot steam coming from below, through the strength of the fire, eats through the earth here

> and spreading through it springs up in these locations and in this way generates remarkable practical applications from the exhalation. In addition, there are old records that the heat increased and overflowed beneath Mount Vesuvius and spewed out flames from it over the surrounding fields. And so, what is called Pompeian sponge stone or Pompeian pumice (*spongia sive pumex Pompeianus*) seems to have been transformed into this type of material from another kind of stone. (3) This type of sponge stone, however, which is taken from that place, does not occur everywhere, but only around Mt. Aetna and those hills in Mysia that the Greeks call "burned up" (*katakekauméne*) and in whatever locations have the same sort of qualities. If, therefore, in these locations springs of boiling water are found, and steam issues from excavations in the hills, and these same locations are mentioned in historical sources to have experienced heat distilling through the fields, it is clear that the strength of the fire has taken the fluid essence (*liquor*) from the tuff and earth in the same manner as heat takes it from limestone in the lime kiln (*quemadmodum in fornacibus ex calce*). (4) Therefore, when dissimilar and incompatible materials [lime (*calx*), ash (*pulvis*), and tuff (*tofus*)] are taken and mixed in a moist environment, the urgent need of moisture suddenly satiated by water seethes with the latent heat in these substances and vehemently causes them to combine into a unified mass and gain solidity quickly.
>
> There remains the following question: since there are numerous hot springs in Etruria, why does the same powdery earth (*pulvis*) not occur there, the substance that by the same process allows concrete work (*structura*) to cure underwater. It seems desirable to explain first how this matter seems to come about. (5) Neither the same types of earth nor the same types of stone originate in all places or all regions, but some regions are earthy, others sandy or gravelly, and elsewhere they have volcanic sands as well as a woody character (? *harenosa non minus materia*). In summary, the qualities present in the soil are dissimilar and unequal in character in the various regions. Above all one might consider the following, that where the Apennine mountains circle around (western) Italy and Etruria, sources of quarry sand (*fossicia harenaria*) occur nearly everywhere. On the other side of the Apennines, however, the region along the Adriatic Sea, none are found. And likewise in Achaea and Asia Minor and just about everywhere across the sea such quarries are not even mentioned. So the same suitability cannot present itself in the same way in all the regions in which there are numerous springs of hot water. But all things are brought about as the nature of the world (*natura rerum*) has determined, not according to the desires of humankind, but as if divided up by chance. (6) As a result, in those regions in which the landscape does not have an earthy character but is of a sort of ligneous nature (? *genere materiae*), the force of fire escaping through the veins burns it. It consumes what is soft and tender but leaves behind what is hard. So, just as in Campania the burned earth becomes ash (*cinis*), in Etruria the cooked material is transformed into *carbunculus*. Although both substances are greatly effective in concrete construction (*egregia in structuris*), some are appropriate for buildings on land (*in terrenis aedificiis*), others for structures in the sea (*in maritimis molibus*). The consistency of this material is, however, softer than tuff (*tofus*). harder than earth (*terra*), and in places deep in the earth where it has been burned up from below by the vehement strength of the gas, it produces the type of sand called *carbunculus*.

These five sections of Book 2.6 naturally have generated an enormous amount of discussion in modern scholarship concerning Roman concrete (*e.g.* Blake 1947: 312–18; Lugli 1957: vol. 1, pp. 394–401; Lancaster 2005a: 54–58; Jackson *et al.* 2007). The following discussion proceeds chapter by chapter.

The first few sentences in the first section lay out clearly the benefits for concrete construction of volcanic ash pozzolan from the area around the Bay of Pozzuoli. The term *pulvis*, literally "dust" or "powder", may not seem quite right to the modern reader, since to sight and touch the volcanic ash seems closer to a sand-sized material and, in reality, it does contain a substantial ash-sized (<2 mm) fraction (de' Gennaro *et al.* 1999: 308–9). Due to the abundance of pumice particles, it is much lighter than quartz sand, and when abraded it can be reduced to powder. The ancient *Puteolanus pulvis* apparently originated in the region around Puteoli, as the name suggests, and around the Bay of Pozzuoli in the Campi Flegrei volcanic district near Baiae, as stated by Vitruvius. This same origin is specified by Strabo, Pliny, and Seneca (Passages 12, 14, 16). Vitruvius also notes that *pulvis* originates in "the territory of the municipalities around Mount Vesuvius." This seems to be correct, as shown by the geochemical studies of pumices extracted from the ancient maritime mortars in Chapter 7. Vitruvius clearly suggests that the material properties of *pulvis* developed through the action of extreme heat deep in the earth. Section 1 concludes with an explanation of why *pulvis* is so effective in mortars used for terrestrial and marine construction. *Pulvis* and tuff are formed by geothermal heat; hydrated lime is produced by heat in a kiln. When water, the opposite of heat, is added to the mix of these three ingredients, they cohere.

Sections 2 to 4 continue this theme, explaining how geothermal heat can be recognized in this region, and elaborating on the reasons why water drives the reaction that causes *pulvis*, tuff, and lime to cohere. Vitruvius seems to suggest that all three elements lack the liquid element (*liquor*) but have a latent heat (*cf. De arch*. 2.5.2–3), which is released by contact with water. More precisely, the natural heat of the earth and the heat in a lime kiln have driven out the fluid essence of these materials, so they need moisture; when it is added, a strong exothermic reaction takes place that generates heat. It seems that Vitruvius is describing the heat that is evolved through the hydration of lime to form portlandite as well as the reaction of pozzolan in a lime mortar to produce cementitious hydrates. These processes have been recently described quantitatively in a thermal model of the Baianus Sinus *pila* in the Bay of Pozzzuoli (Jackson *et al.* 2013a; see Chapter 7). The strength of this reaction remained a source of wonder to the Romans, for example in Augustine, *City of God* 21.4.

In Sections 4–5, Vitruvius attempts to explain differences in the material characteristics of pyroclastic volcanic deposits from Mount Vesuvius and Etruria, in the Monti Sabatini and Vico volcanic districts north of Rome. If the *carbunculus* type of *harena fossicia* from Etruria gives good strength to concrete for buildings on land, then why does *pulvis* from the Gulf of Naples region preferentially give maritime concretes good durability in sea-water, if hot springs that develop from "far distant fire and heat" are associated with both deposits? If the fire element is indeed the force that causes concrete to become firm underwater (*De arch*. 2.6.1, 6.4), then Vitruvius admits that he cannot explain why *carbunculus* and *pulvis* produce mortars with different material properties. The *carbunculus* form of *harena fossicia* was probably quarried from deposits from the *Tufo Grigio a Scorie Nere* pyroclastic flow, erupted from Vico crater, which shows strong localized variations in lithification and has been used as dimension stone since Etruscan times (Jackson *et al.* 2007: 30–42). Vitruvius apparently refers to the poorly consolidated facies that may have been strongly weathered (*excocta*) on the ground surface. The pozzolanic character and material properties of this altered scoriaceous ash would have been quite different from that of glassy, zeolitized pumiceous ash from Campi Flegrei deposits.

The suggestion by Siddall (2000: 339) that Vitruvius, Pliny and others may have assumed that the origin and properties of the Phlegraean deposits were special simply because the volcanic origin of the *pulvis* around the Gulf of Naples was not recognized until after the eruption of Vesuvius in AD 79, clearly is incorrect. Certainly the reawakening of Vesuvius in AD 79 was a surprise to the inhabitants of the region, but Vitruvius describes lava flows from Vesuvius, "recalled from long ago" (2.6.2), and Strabo (5.4.8) clearly was aware of the mountain's volcanic origin. He even compares the fruitful, ashy soil around it with the *spodós* ("ash" or "dust") deposited around Catania by the on-going volcanic activity of Aetna. Vitruvius (*De arch*. 2.6.2–3) also compares a type of spongy volcanic stone found around Vesuvius with a similar stone found on the slopes of Aetna.

Section 6 sums up this challenging account. Because of the differences in the geology, as we would put it, subterranean heat produces pumiceous ash pozzolans (*cinis*) in Campania, *carbunculus* in Etruria. The substance Vitruvius terms *carbunculus* has not yet been conclusively identified, but it is most likely what is now termed *Tufo Grigio a Scorie Nere* (Jackson *et al.* 2007: 30–42; *cf.* Passage 5 above). Curtis (1913: 202–3) thought it was soft sandstone. Blake (1947: 42) identified it as possibly "the dry, porous black *pozzolana* which is still in use in the region of Viterbo." Lugli is puzzled, but suggests that it was a tufa typical of the Vulci region, now called *nenfro* (1957: vol. 1, pp. 398–99). Schofield (Schofield and Tavernor 2009: 47–48, 366–67) translates it as "lignite", which evolves from the "ligneous earth" (*materia*), but he does not propose an identification. In any case, one of these substances (*carbunculus*) is appropriate for concrete to be used on land, while the other (*cinis*) is appropriate for concrete to be used in the sea. This distinction accurately reflects the archaeologically documented use of *harenae fossiciae* found around Rome for the construction of buildings on land, and of *pulvis* for construction in the sea. Lugli's suggestion (1957: vol. I, 399) that Vitruvius simply was unaware of the volcanic ash deposits in Latium is untenable, given the use of local volcanic pozzolanic substances of varying degrees of efficacy for concrete in the region of Rome since the second century BC (Blake 1947: 317; Lancaster 2005a: 55–58; Jackson *et al.* 2007, 2010, 2011).

Neither Vitruvius nor any other ancient literary source provides specific instructions as to whether fresh water or sea-water should be used when preparing marine mortars. Vitruvius is careful to specify the source and quality of the volcanic ash pozzolan and lime to be used in both terrestrial and marine mortars, so he would certainly have indicated the preferential use of fresh water for mixing concrete intended for maritime structures if this had been an issue. Sea-water can be used for modern Portland cements as long as steel rebars are not involved (Lea and Desch 1956: 511, 553; Cornick 1962: 119; Franklin 1990: 25). The provision of large quantities of fresh water at the construction site for a harbour usually would have involved serious logistical problems (see Chapter 5), and in any case most of the maritime structures were partially or completely submerged in sea-water, which infiltrated the mortar as the concrete was placed. Analytical investigations of the ROMACONS samples indicate that sea-water was an integral component of the concrete mix design (see Chapter 7).

[8] *De architectura* 2.8.2. The importance of sufficient moisture for the curing of mortar.

> utraque autem ex minutissimis sunt instruenda, uti materia ex calce et harena crebriter parietes satiati diutius contineantur. molli enim et rara potestate cum sint, exsiccant sugendo e materia sucum. cum autem superarit et abundarit copia calcis et harenae, paries plus habens umoris non cito fiet evanidus, sed ab his continetur. simul autem umida potestas e materia per caementorum raritatem fuerit exsucta calxque ab harena discedat et dissolvatur, item caementa non possunt cum his cohaerere, sed in vetustatem parietes efficiunt ruinosos. (Rose and Müller-Strübing 1867: 46–47).
>
> Both kinds (of walling; *i.e. opus incertum* and *opus reticulatum*) must be constructed with very small facing stones (*minutissimis*), so that the walls, compactly filled with a mortar of lime and sand (*materia ex calce et harena*) might hold together longer. Since the facing stones are soft and porous by nature, they dry the concrete out by sucking the moisture from the mortar. But when the supply of lime

> and sand is abundant and takes the upper hand, the structure of the wall has more moisture and does not quickly become weak, but it is held together by the constituents of the mortar. In contrast, as soon as the strength-giving moisture has been drawn from the mortar (*materia*) by the porosity of the facing stones (*caementa*) the lime and sand separate and lose their coherence, and the facing (*caementa*) also cannot bond with them but over time makes the walls collapse.

It is not clear in this passage whether Vitruvius intends to say that the facing stones on the wall should be very small, or the coarse aggregate of the concrete, or both, since the noun is omitted in the first three sentences. In the last sentence, however, the stones in question are referred to as *caementa*. In the context of *opus caementicium* this word usually indicates the tuff coarse aggregate in the concrete wall core. The context here is the stability of concrete walls with the old-fashioned facing of irregular stones (*opus incertum*) as opposed to walls faced in the new style, with small square blocks that tapered at their inside end in order to key into the wall core (*opus reticulatum*). The clue is the clear use of *caementa* in the preceding paragraph (2.8.1) to indicate the facing stones. Lugli (1957: vol. 1, pp. 365–66) mistranslates the passage.

Vitruvius' recognition that sufficient moisture was necessary to allow the proper setting and curing of mortar suggests that Roman builders understood the importance of hydration to the formation of cementitious phases that led to strength gain in the concrete. Builders likely had a good understanding of the benefits of allowing the pozzolanic concrete to set and cure while inundated by water, during which time the mortar continued to increase in strength.

[9] *De architectura* 5.12.1–6. The location and construction of various types of harbours.

> (1) De opportunitate autem portuum non est praetermittendum, sed quibus rationibus tueantur naves in his ab tempestatibus explicandum. Hi autem naturaliter si sint bene positi habeantque acroteria sive promunturia procurrentia, ex quibus introrsus curvaturae sive versurae ex loci natura fuerint conformatae, maximas utilitates videntur habere. Circum enim porticus sive navalia sunt facienda sive ex porticibus aditus emporia, turresque ex utraque parte conlocandae, ex quibus catenae traduci per machinas possint.
>
> (2) Sin autem non naturalem locum neque idoneum ad tuendas ab tempestatibus naves habuerimus, ita videtur esse faciendum uti si nullum flumen in his locis inpedierit sed erit ex una parte statio, tunc ex altera parte structuris sive aggeribus expediantur progressus. Et ita conformandae portuum conclusiones. Hae autem structurae quae in aqua sunt futurae, videntur sic esse faciendae uti portetur pulvis a regionibus quae sunt a Cumis continuatae ad promunturium Minervae, isque misceatur uti in mortario duo ad unum respondeant. (3) Deinde tunc in eo loco, qui definitus erit, arcae stipitibus robusteis et catenis inclusae in aquam demittendae destinandaeque firmiter, deinde interea ex trastilis inferior pars sub aqua exaequanda et purganda, et caementis ex mortario, materia mixta quemadmodum supra scriptum est, ibi congerendum, denique compleatur structura spatium quod fuerit inter arcas. Hoc autem munus naturale habent ea loca, quae supra scripta sunt.
>
> Sin autem propter fluctus aut impetus aperti pelagi destinae arcas non potuerint continere, tunc ab ipsa terra sive crepidine pulvinus quam firmissime struatur, isque pulvinus exaequata struatur planitia minus quam dimidiae partis, reliquum quod est proxime litus, proclinatum latus habeat. (4) Deinde ad ipsam aquam et latera pulvino circiter sesquipedales margines struantur aequilibres ex planitia quae est supra scripta, tunc proclinatio ea impleatur harena et exaequetur cum margine et planitia pulvini. Deinde insuper eam exaequationem pila quam magna constituta fuerit ibi struatur, eaque cum erit extructa, relinquatur ne minus duos menses, ut siccescat. Tunc autem succidatur margo quae sustinet harenam. Ita harena fluctibus subruta efficiet in mare pilae praecipitationem. Hac ratione, quotienscumque opus fuerit, in aquam poterit esse progressus.
>
> (5) In quibus autem locis pulvis non nascitur, his rationibus erit faciendum uti arcae duplices relatis tabulis et catenis conligatae in eo loco qui finitus erit, constituantur, et inter destinas creta in eronibus ex ulva palustri factis calcetur. Cum ita bene calcatum et quam densissime fuerit, tunc cocleis rotis tympanis conlocatis locus qui ea septione finitus fuerit exinaniatur sicceturque, et ibi inter septiones fundamenta fodiantur. Si terrena erunt, usque ad solidum crassiora quam qui murus supra futurus erit exinaniatur sicceturque, et tunc structura ex caementis calce et harena compleatur. (6) Sin autem mollis locus erit, palis ustilatis alneis aut oleagineis configantur et carbonibus compleantur, quemadmodum in theatrorum et muri fundationibus est scriptum. Deinde tunc quadrato saxo murus ducatur iuncturis quam longissimis, uti maxime medii lapides coagmentis contineantur. Tunc qui locus erit inter murum ruderatione sive structura compleatur. Ita erit uti possit turris insuper aedificari. (Gros 1997: vol. 1, pp. 586–90).
>
> (1) …I must not omit the proper arrangement of harbours but rather explain by what techniques ships are protected in them from stormy weather. Harbours that have an advantageous natural location, with projecting headlands or promontories that naturally form curved or angled recesses, seem to be the most useful. Colonnades or shipyards are to be constructed around the circumference, or entrances from the colonnades to the markets. Towers are to be built on either side [of the entrance to the harbour], from which chains can be drawn across by means of windlasses.
>
> (2) If, however, we have no natural harbour situation suitable for protecting ships from storms, we must proceed as follows. If there is an anchorage on one side and no river mouth interferes, then a mole composed of concrete structures or rubble mounds (*structuris sive aggeribus*) is

to be built on the other side. The harbour enclosure should be constructed in the following manner. Those concrete structures that are to be in the water must be made in the following fashion. Pumiceous volcanic pozzolan (*pulvis*; lit. "dust" or "powder") is to be brought from the region that runs from Cumae to the promontory of Minerva and mixed in the trough in the proportions of two parts earth to one of lime. (3) Next, in the designated spot, formwork (*arcae*) enclosed by solid (*or* "oak") posts and tie beams (*stipitibus robusteis et catenis*) must be let down into the water and fixed firmly in position (Fig. 2.1a). Then the area within it at the bottom, below the water, must be levelled and cleared out, [working] from a platform of small crossbeams (? *ex trastilis* or *trastillis*). Afterwards, aggregate broken in the trough (*caementis ex mortario*) and mortar (*materia*) mixed as specified above is to be placed within, until the space inside the form has been filled with the concrete structure. The locations that we have described above, then, have this natural advantage.

But if because of waves or the force of the open sea the anchoring supports (*destinae*) cannot hold the forms together, then a platform must be built out from the shore itself or from the foundations of the mole, and made as firm as possible. This platform is to be built out with a level upper surface over less than half its area. The shoreward section is to have one side sloping (Fig. 2.1c). (4) Next, retaining walls one and one half feet thick are to be built at the end facing the sea and on either side of the platform, equal in height to the level surface described above. Then the sloping section is to be filled in with sand and brought up to the level of the retaining walls and platform surface. Next, a concrete block (*pila*) of the appointed size must be built there, on this levelled surface, and when it has been formed is left at least two months to cure. Then the retaining wall that holds in the sand is cut away, and in this manner erosion of the sand by the waves causes the block (*pila*) to fall into the sea. By this procedure, repeated as often as necessary, the breakwater can be carried seaward.

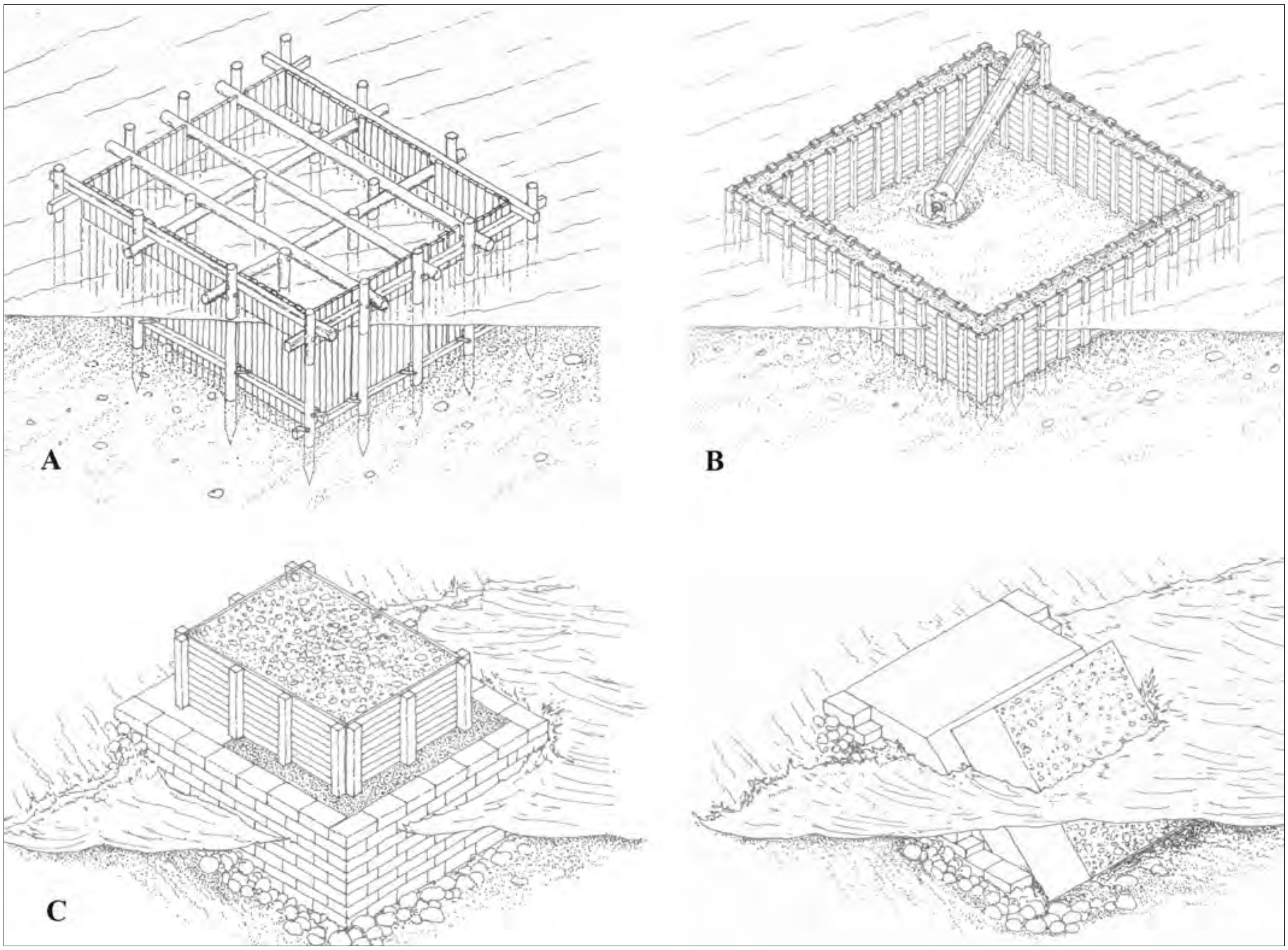


*Fig. 2.1. Reconstruction of the three types of forms mentioned by Vitruvius: A. Inundated form constructed* in situ*. B. Cofferdam constructed* in situ *and dewatered. C. Casting* pilae *sequentially on shoreline (C. J. Brandon).*

> (5) But in locations where pumiceous volcanic ash (*pulvis*) does not occur naturally, one must use the following procedure. Let double-walled formwork (*arcae duplices*) be set up in the designated spot, held together by close set planks and tie beams (*relatis tabulis et catenis conligatae*), and between the anchoring supports (*inter destinas*) have clay packed down in baskets made of swamp reeds (Fig. 2.1b). When it has been well tamped down in this manner and is as compact as possible, then have the area bounded by the cofferdam emptied and dried out by means of water-screw installations and water-wheels with compartmented rims and bodies. The foundations are to be dug there, within the cofferdam. If the foundations are to be on earth, the area to be excavated and drained must be wider than the wall that will stand above. Then fill in the form with concrete composed of aggregate, lime, and sand (*structura ex caementis calce et harena*). (6) But if the bottom is soft, the foundations should be covered with charred alder or olive wood pilings and filled in with charcoal, as described for the foundations of theatres and city walls. Then the wall must be built of squared stone with joints as long as possible, so that the stones in the middle may be well tied together by the joints. The space inside the wall is to be filled with rubble packing or concrete. Thus it will be possible to build a tower upon it.

In this enormously important and frequently cited passage Vitruvius provides the only detailed description of how Roman builders constructed concrete structures in and under the sea, in the context of a more general account of harbour construction in various circumstances. For discussion, see Dubois 1902, Choisy 1909; Jüngst and Thielscher 1936: 156–65; Schramm 1936, 1938; Schläger 1971; Oleson 1988; Felici 1993: 95–98, 1998: 298–330; Brandon 1996; Oleson *et al.* 2004a: 199–203. As noted above, it seems odd that Vitruvius does not provide similar detailed information for concrete construction on land. He frequently made use of Hellenistic architectural handbooks, such as Hermogenes' treatise on temple design (Rowland *et al.* 1999: 5), but, given the focus on hydraulic concrete, this information on the harbours most likely was condensed from a Roman engineering manual. It is also possible that Vitruvius composed them on the basis of his own experience at Massalia and elsewhere (Hesnard 2004). Analysis of the ROMACONS cores has shown that Vitruvius had a thorough, practical knowledge of the materials and procedures associated with marine concrete (see Chapter 7).

After an introduction concerning the structures appropriate for a naturally protected basin, Vitruvius outlines three techniques, with an engineer's eye for site and materials: laying maritime concrete within an inundated form (5.12.2–3; Brandon Category 1, pp. 191–205; Figs 2.1a, 8.3), prefabricating a block of maritime concrete above water then allowing controlled fall into the sea (5.12.3–4; Brandon Category 3, pp. 208–10; Figs 2.1c, 8.48–53), and laying non-hydraulic concrete made of lime and silica sand in a double-walled cofferdam from which the water had been pumped out (5.12.5–6; Brandon Category 2, pp. 207–8; Figs 2.1b, 8.43). According to Vitruvius, the first technique was suitable for situations in which pozzolanic mortar was available, the second for locations where pozzolanic mortar was available but rough sea conditions made it difficult to build formwork, and the third for situations in which pozzolanic mortar was not available. Vitruvius does not mention the technique used at Sebastos and Alexandria, where single mission barge forms were constructed, floated into position, and sunk by adding mortar and aggregate (Fig. 8.51–53). Since the various types of Vitruvian and non-Vitruvian formwork are discussed in detail in Chapter 8, commentary here will be restricted to particular problems of language or interpretation.

Book 5 concerns public buildings, so it is natural that Vitruvius should find harbour design and construction a topic "not to be passed over" (5.12.1). The construction of harbours in naturally protected bays is straightforward (5.12.1), but breakwaters are necessary in less protected locations (5.12.2). Concrete structures and rubble mounds (*structuris sive aggeribus*) are noted as possible alternative approaches, but in fact these two types of structures often were found together, since concrete *pilae* or splash walls were often placed on rubble mound foundations in Roman harbours, as at Sebastos, Centum Cellae, or Cosa. The submerged concrete structures are to be made with *pulvis* sourced from the region defined by the coastline of the Gulf of Naples (*a regionibus quae sunt a Cumis continuatae ad promunturium Minervae*). This description includes the areas of Baiae and the municipalities in the territory of Vitruvius discussed in 2.6.1 (Passage 7).

The *pulvis* is to be mixed with lime in a mixing trough (*mortario*) in the ratio of two to one (*misceatur uti in mortario duo ad unum respondeant*). The omission of *calx* ("lime") from the clause is awkward, but since the mix consists only of lime and *pulvis*, it is implicit that the two to one ratio is that of *pulvis* to lime. Since the lime is not explicitly mentioned, some translators render the clause "and let the *pozzolana* be mixed in the mortar in the ratio of two to one." As Blake (1947: 308–9) points out, there do not seem to be any occurrences in Latin of *mortarium* as "mortar." The usual terms are *materia* or *materies*, as seen in the following paragraph (5.12.3; see also *De arch* 2.8.7). Schofield (Schofield and Tavernon 2009: 161) translates the term here as "mortar," but it is not clear whether he means the lime mix or a mixing trough; the English term is ambiguous. Rowland (Rowland and Howe 1999: 73) translates this phrase "as if with a mortar and pestle," which does not suit the large scale of the operation.

In his passage about sand for the mortars of buildings on land (2.5.1), Vitruvius sets a ratio of three parts *harena fossicia* to one of lime, or two parts river or beach sand to one of lime; he does not mention *pulvis* here. The *Lex parieti faciundo Puteolana* (Passage 31) of 105 BC sets the ratio of volcanic ash (*harena, terra*) to lime at three to one. In the second half of the first century, Pliny (*HN* 36.175; Passage 18) sets the ratio at four parts *harena fossicia* to one of lime, and three parts of river or beach sand to one of lime. Around 300, Faventinus (Passage 28) states that the conventional ratio for terrestrial structures is five measures of *harena aspera* (= *harena fossicia*?) to two measures of lime, but that two measures of sand to one of lime provides a more lasting structure.

Vitruvius evidently believed that the mortar mix for underwater work should be very "fat," that is, rich in lime. Even though analyses of the ancient mortars through point counts (Chapter 7) cannot accurately determine the lime to ash *pozzolana* ratio, the Vitruvian ratio was used in mixing the mortar for the reproduction *pila* in Brindisi, and the resulting concrete appears quite similar to the ancient material.

The description of the box form described in section 3 is relatively clear (Fig. 2.1a), other than the corrupt phrase *ex trastilis* or *trastillis* ("from small crossbeams"?). Choisy (1909: 268) prefers *ex rastilis*, which makes practical sense but has not been widely accepted: "must be levelled and cleared out by means of rakes." There are numerous archaeological parallels for crossbeams in formwork just above sea level (*catenae*; see pp. 201–5). The supports for this sort of form had to be pounded into the sea floor so, as Vitruvius notes, a different approach had to be taken if the harbour was to be constructed on the open sea, where waves would disrupt the construction process. This was precisely the situation for the harbour of Sebastos at Caesarea, and here singe-use barge forms were employed (see pp. 210–21). Vitruvius, however, proposes a different solution: blocks of pozzolanic concrete were to be constructed on shore one by one on easily eroded platforms, and allowed to fall into position once initial curing was complete (Fig. 2.1c). This sounds like the impractical solution of an armchair engineer, but it would have solved the problem of constructing forms in locations unfavourable for formwork construction. It would also have allowed the deployment of very large *pilae*, the formwork for which might have been unwieldy, or exceeded the capacity of Roman divers for underwater construction. The only other literary evidence for this approach may be brief comments by Horace and Virgil (Passages 10–11 below).

Section 5, outlining construction procedures for concrete where volcanic ash pozzolan was not available, is a straightforward description of building within a sealed cofferdam (Fig. 2.1b). It is interesting that at this point (5.12.5) Vitruvius uses a phrase that serves as a generic definition of concrete construction: *structura ex caementis calce et harena*. The term *harena* is ambiguous, but since Vitruvius is describing a situation in which non-maritime concrete has to be prepared, he presumably intends silica sand rather than *harena fossicia* volcanic pozzolan. The cofferdam design sounds reasonable, and the three types of pumps specified for dewatering the work area were well known in the Hellenistic and Roman world (Oleson 1984: 108–9). ROMACONS identified only one possible form of this type (Brandon category 2; p. 208) at Istanbul (p. 136), which we were not permitted to study.

## 2.4. Q. Horatius Flaccus

Horace likely published his *Odes* (*Carmina*) at about the same time Vitruvius published his *De architectura*, the last quarter of the first century BC. Throughout the first century BC the social posturing and architectural extravagances of Roman aristocrats were a constant theme for satirists. Cicero labelled as *piscinarii* ("fish pool fanciers"; Cicero, *Att.*1.19.6, 1.20.3) wealthy Romans who ignored political responsibilities and focused their attention and fortunes on elaborate seaside villas provided with fish-pools built out into the sea. There were many luxurious villas supplied with such pools for raising desirable species along the coastline of modern Toscana, Lazio, and the Gulf of Naples (Higginbotham 1997; Lafon 2001), but the shoreline around Baiae was the most notorious area (D'Arms 1970). In this passage, Horace is mocking the attempts of a rich man to find satisfaction in extravagant building. Virgil notes the same phenomenon in Passage 11, but without satirical overtones.

> [10] *Carmina* 3.1.33–37. Marine structures crowd the sea.
> contracta pisces aequora sentiunt
> iactis in altum molibus; huc frequens
>         caementa demittit redemptor
>                 cum famulis dominusque terrae
> fastidiosus…
>         (Rudd 2004: 142).

The fish feel the seas shrink
as masses (*molibus*) are thrown into the deep. Again and again
the contractor (*redemptor*) and his team pour in rubble (*caementa*),
with the owner close at hand, too proud to live on solid ground.

A rich aristocrat is having a villa built out into the sea, probably supported by *pilae* of concrete. Although there is no explicit mention of concrete, *moles* of that material are the only masses that could be "thrown" into the sea, as in Passage 11. Despite the poetic context, there is a veneer of technical terminology: *moles, redemptor, caementa.* Both contractors and their aristocratic patrons were important factors in the early spread of the knowledge of marine concrete (see pp. 227–29). The *caementa* could simply be rubble dumped on the sea floor to serve as a foundation, but the word more often signifies the large aggregate in concrete or a mortared wall. Like Passage 9, this may be another example of the procedure described by Vitruvius in which *pilae* are cast in forms on the shore, then allowed to fall into the sea (*De arch.* 5.12.3–4). The phrase *moles iacta* also appears in a passage in Seneca's *Thyestes* (vv. 459–60) that concerns aristocratic luxury: *Non classibus piscamur et retro mare / iacta fugamus mole*… "I do not fish with a fleet of ships, nor drive back the sea by casting in a great block (*iacta…mole*)." In *Odes* 3.24.4–5 Horace mentions another nobleman, building on the Tyrrrhenian or Apulian shore, who fills the sea with *caementis*, probably alluding to casting a concrete block in the water: *caementis licet occupes / Tyrrhenum omne tuis et mare Punicum*… "Although you fill the whole Tyrrhenian and Punic Sea with your rubble work…" Horace also alludes to the crowding of the sea with marine structures in *Odes* 2.18.19–22, but in more general terms.

## 2.5. P. Virgilius Maro

[11] *Aeneid* 9.710–714. A *pila* is tipped into the sea from the shore at Baiae.

> talis in Euboico Baiarum litore quondam
> saxea pila cadit, magnis quam molibus ante
> constructam ponto iaciunt, sic illa ruinam
> prona trahit penitusque vadis inlisa recumbit;
> miscent se maria et nigrae attoluntur harenae…
> (Fairclough and Goold 1999: vol. 2, p. 164).
>
> Just as sometimes on the Euboic shore of Baiae
> a stony *pila* falls, which they build first on a great scale
> and cast into the sea; so, in its headlong fall it trails havoc
> but comes to rest with crushing impact in the watery depths.
> The sea is roiled and the black sand stirred up.

The metaphor compares the fall in battle of a great warrior in his heavy armour to the dumping of a *pila* into the sea near Baiae, presumably for the construction of a pier or fish pool. Most commentators assume that the *pila* was built of stone blocks, since it is described as *saxea* and was built *magnis... molibus* ("with great masses"). It seems impossible, however, that such a structure could fall from the shore into the sea without coming apart, so it is more likely that the *pila* was constructed of concrete. Accuracy of detail cannot always be expected of a poetic description, but *saxea* might refer to the *caementa* or simply to the stony character of hardened concrete. Furthermore, *moles* does not have to refer to large, individual stones or blocks but can also signify the overall scale of a structure.

As a result, this may be one of the few descriptions we have of the procedure described by Vitruvius (*De arch.* 5.12.3–4, Passage 9 above) in which concrete blocks are formed on the shore on special embankments, then allowed to fall into the sea once they have cured. Another possible description of the same process appears in Horace *Odes* 3.1.33–37 (Passage 10). Virgil knew the Campi Flegrei well.

## 2.6. Strabo

Like his contemporary Vitruvius, Strabo (5.4.6) praises the "natural quality of the sand-ash (*ammokonía*)" at Puteoli for the construction of breakwaters; Pliny the Elder (*HN* 35.166; Passage 16) echoes this opinion.

[12] *Geography* 5.4.6. Local *pozzolana* allowed construction of the great concrete mole at Puteoli.

> ἡ δὲ πόλις ἐμπόριον γεγένηται μέγιστον, χειροποιήτους ἔχουσα ὅρμους διὰ τὴν εὐφυΐαν τῆς ἄμμου· σύμμετρος γάρ ἐστι τῇ τιτάνῳ καὶ κόλλησιν ἰσχυρὰν καὶ πῆξιν λαμβάνει. διόπερ τῇ χάλικι καταμίξαντες τὴν ἀμμοκονίαν προβάλλουσι χώματα εἰς τὴν θάλατταν, καὶ κολποῦσι τὰς ἀναπεπταμένας ἠόνας ὥστ' ἀσφαλῶς ἐνορμίζεσθαι τὰς μεγίστας ὁλκάδας. (Meineke 1877: 338).
>
> Puteoli has become a very great emporium because it has an artificially constructed harbour, something made possible by the natural qualities of the local sand (*ámmos*), which is well suited to the lime and takes a firm set and solidity. Therefore, by mixing the sand-ash (*ammokonía*, *i.e. pozzolana* or *pulvis*) with the lime, they can run moles out into the sea and in this way make the exposed shore into a protected bay, so that the largest cargo ships can anchor there safely.

Early experimentation with pozzolanic mortar for maritime construction probably took place at Puteoli, which in the third and second centuries BC was the only important port in the vicinity of the *pozzolana* deposits of the Campi Flegrei volcano. Until completion of the Claudian and Trajanic harbours at Portus, Puteoli served as the major harbour for the city of Rome, 200 km away, particularly for grain imports (Dubois 1907). At some point between the early second and the late first centuries BC, a long breakwater composed of large, closely spaced concrete piers (*pilae*) connected by low concrete vaults was constructed to accommodate the growing sea trade serving Rome. This is the structure praised by Strabo as a "wall" or "mole" (χώματα) and mentioned by numerous other ancient authors. Antiphilus of Byzantium refers as well to the "vast χῶμα stretching out to the midst of deep sea" (*Greek Anthology* 7.379), while Philippus (*Greek Anthology* 9.708) uses the term στήριγμα ("support" or "foundation"). Neither of these later authors allude to the use of concrete.

Although there are ancient and modern representations of the harbour works at Puteoli (Figs 2.2–3), the ancient remains unfortunately now are inaccessible beneath a breakwater built in 1925. Eight surviving glass bottles, apparently souvenirs sold to tourists visiting Baiae and Puteoli in the third or fourth century, are engraved with labelled illustrations of those harbours (Fig. 2.3; Ostrow 1979; Gianfrotta 2011b). The "*pilae*" of the breakwater at Puteoli are clearly shown and labelled, linked by low concrete arches to form a long platform. The structure was apparently called by this name, and Seneca (*Ep.* 77.1) records loiterers *in pilis Puteolorum* watching for the arrival of grain ships from Alexandria. An inscription in which the town honours Antoninus Pius may refer to repairs to this breakwater (*CIL* 10.1641, *cf. CIL* 10.1640).

> [c]olonia Flav[ia Augusta Puteoli] / [quod s]uper cetera ben[eficia a divo patre promis]/[sum op]us pilarum vigi[nti vi maris conlapsum splendore] / [anti]quo et munitio[ne adiecta restituit.
>
> The Colonia Flavia Augusta Puteoli (honours the emperor) because in addition to his other favours, as promised by his divine father, he restored to its former splendour the

Fig. 2.2. The Roman pier at Pozzuoli in the mid-eighteenth century (Paoli 1768: pl. XIII) (Courtesy of the Bodleian Library, University of Oxford; Arch. Antiq. B subt. 18, pl. XIII).

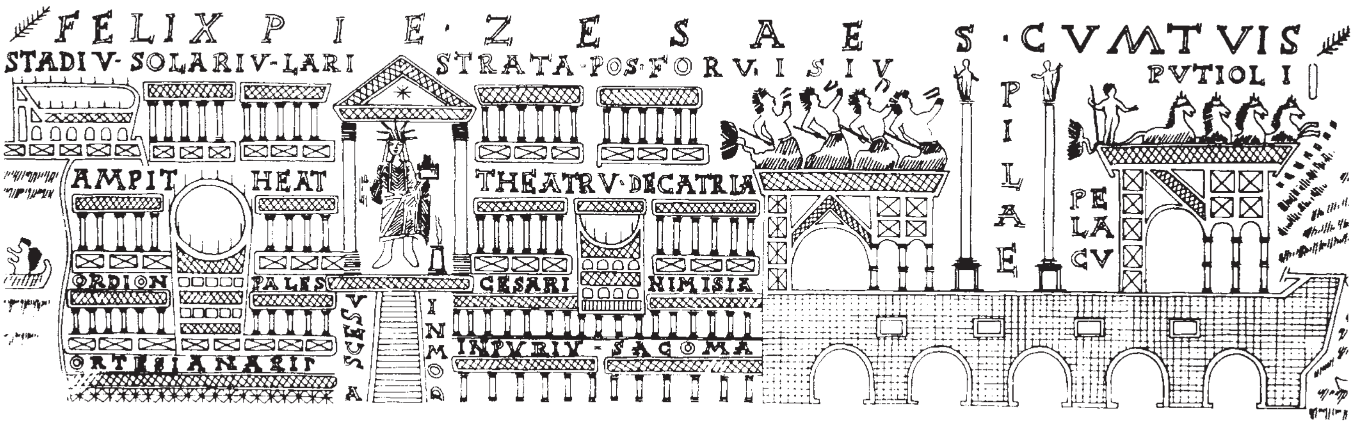


Fig. 2.3. Glass bottle with engraving of Puteoli harbour and Baiae (Courtesy of Narodny Museum, Prague).

> structure with 20 *pilae*, collapsing through the force of the sea, and added a protective embankment.

If these are the *pilae* of the main breakwater/pier at Puteoli, it is interesting to consider the fact that repairs were necessary in the mid-second century, approximately 200–150 years after they were constructed. This may not, of course, have been the first occasion for repairs, but the *pilae* and many of the flat concrete arches between them appear to be in fairly good shape in an engraving executed in 1768 (Fig. 2.2; Paoli in Blackman 1982: 195, fig. 7), after about 1,500 years with little maintenance. The engraving, however, seems to show only 14 *pilae* rather than 20, so some may have been completely lost. A late nineteenth-century engraving by Consalvo Carelli shows an *opus reticulatum* facing on one of piers down at least to sea level (Döring 2003: fig. 11), along with horizontal holes left behind by the *catenae* of the formwork. Dubois (1907: 254) and later scholars (*e.g.* Döring 2003: 47; Piromallo 2004) mention 15 *pilae*, and Beloch (1890: 133) suggests that there were originally 16. Gianfrotta (2007b) notes that an inscription from Cartagena recording the construction of concrete *pilae* probably had nothing to do with the harbour at that site.

Maintenance of concrete harbour structures must have been an important issue, and one that is difficult to assess since we have little information. One approach apparently was to dump rock rubble on or around the decaying structure, as may have happened at the harbour of Sebastos during the reign of Anastasius (Fig. 4.31; Hohlfelder 1988: 58–59, 2000b; Raban 1996: 656–57; Procopius of Gaza, *Panegyricus in Imperatorem Anastasium* 19). It is safe to assume, however, that in all ancient harbour renewals optimization of existing ruinous structures was the common approach.

## 2.7. L. Annaeus Seneca

In his *Questions about Nature* (*Quaestiones Naturales*), the mid-first century philosopher Seneca mentions *pulvis* and alludes several times to what we call pumiceous volcanic ash. His description in Passage 13 of "burning sand" and "dust" as products of a volcanic eruption probably stem from his knowledge of volcanic ash deposits evident in Passage 14. Although both Vitruvius and Strabo clearly understand the special qualities of the volcanic ash deposits of the Campi Flegrei, Seneca is the earliest preserved author to allude to the material as *Puteolanus pulvis.* Pliny uses the same term a few years later (*HN* 16.201–2; Passage 15).

[13] *Quaestiones Naturales* 2.30.1. Sandy volcanic products from Mt. Aetna.

> Aetna aliquando multo igne abundavit, ingentem vim harenae urentis effudit, involutus est dies pulvere, populosque subita nox terruit. (Corcoran 1971: 146).
>
> Once, Mt. Aetna overflowed with torrents of fire and spewed out a huge discharge of burning sand (*harenae*). The daylight was cloaked in dust (*pulvere*), and sudden darkness terrified the populace.

Mt. Aetna in eastern Sicily, known to most Romans as a very active volcano, provided many of the tropes of vulcanological speculation in the early Empire. Seneca's use of the terms *harena urens* ("burning sand") and *pulvis* ("dust," "powder") to describe the discharge of the volcano may be an echo of the terms for *pozzolana* from the Baiae area (*Puteolanus pulvis*) and *harenae fossiciae* around Rome. If so, it documents the knowledge of the volcanic origin of *pulvis* and similar pyroclastic products.

In the following passage from the same work Seneca mentions *pozzolana* ("*Puteolanus pulvis*") as a rhetorical counterpoint in a discussion of water that leaves a calcium carbonate deposit. The *pulvis* turns to stone when mixed with water. It is likely that observation of this behaviour of the natural strata composed of *pozzolana* along the shoreline near Baiae led enterprising builders to make use of this volcanic ash product for the first time as an additive in mortar.

[14] *Quaestiones Naturales* 3.20.3. Pumiceous volcanic ash hardens in the presence of water.

> Medicatum est et eius naturae habet limum ut corpora adglutinet et obduret. Quemadmodum Puteolanus pulvis, si aquam attigit, saxum est, sic e contrario haec aqua, si solidum tetigit, haeret et affigitur. (Corcoran 1971: vol. 1, p. 248).
>
> The water (of the Hebrus River) is adulterated and throws a sediment (*limus*) of such a nature that it cements and hardens objects. While the powdery earth of Puteoli (*Puteolanus pulvis*) becomes rock if it touches water, so, by contrast, if this water touches something solid it clings to it and forms concretions.

## 2.8. Pliny the Elder

Pliny's great compendium of information about the natural world and the place of humans in it, published after the author's death in AD 79, contains a rich store of miscellaneous information relevant to ancient technology.

[15] *Historia naturalis* 16.201–202. A giant ship used as a floating form for concrete.

> (201) …Abies admirationis praecipuae visa est in nave, quae ex Aegypto Gai principis iussu obeliscum in Vaticano circo statutum quattuorque truncos lapidis eiusdem ad sustinendum eum adduxit. qua nave nihil admirabilius visum in mari certum est. cxx modium lentis pro saburra ei fuere. (202) longitudo spatium obtinuit magna ex parte Ostiensis portus latere laevo. ibi namque demersa est Claudio principe cum tribus molibus turrium altitudine in ea exaedificatis obiter Puteolano pulvere advectisque. (Mayhoff 1892: 52).
>
> (201) …A fir beam of particularly astonishing size was seen in the ship which at the order of the emperor Gaius (Caligula) brought (to Rome) the obelisk set up in the Vatican circus and the four blocks of the same stone on which it was

> mounted. It is certain that nothing more amazing has ever been seen on the sea than this ship. As ballast it held 120,000 *modii* of lentils. (202) Its length took up a large part of the left side of the port facilities of Ostia, for during the reign of the emperor Claudius it was sunk there. Three great concrete masses as high as towers were built on it besides, with the dusty earth of Puteoli (*Puteolano pulvere*), and brought in (?).

In this passage Pliny mentions the importation of *Puteolanus pulvis* to Portus to make concrete for one of the breakwaters of the emperor Claudius' new harbour basin. He describes how a gigantic ship built for the emperor Caligula to carry an Egyptian obelisk to Rome, with an enormous ballast of Egyptian lentils, was sunk on site and used as a kind of caisson. The impossible suggestion that the concrete towers were built on the ship before it arrived at Portus may result from textual corruption, or from confusion with the procedures involved in using a floating ship as a caisson. Suetonius, in his *Life of Claudius* (20.3, Passage 24), states that the ship was scuttled, and then piers were built on top. See also Passage 17 below. Seneca (Passage 14) also uses the term *Puteolanus pulvis*. In all these passages, the process described most likely was as follows. The ship was towed to Ostia already loaded with a ballast of pumiceous volcanic ash. The ballast was unloaded to allow mixing with lime in the appropriate proportions, then the mortar was reloaded in the hull with aggregate, forming a marine concrete. When the ship was nearly ready to sink, it was towed outside the entrance channel to the harbour, then under construction, and sunk with the addition of more concrete to serve as the foundation of a large lighthouse. Harbour engineers under time constraints or financial pressure may have used *ad hoc* arrangements such as this in place of the purpose-built floating barge forms seen at Sebastos and Alexandria (pp. 208–21).

[16] *Historia naturalis* 35.166–67. The characteristics of *pozzolana* and other volcanic sands.

> (166) Verum et ipsius terrae sunt alia commenta. quis enim satis miretur pessumam eius partem ideoque pulverem appellatam in Puteolanis collibus opponi maris fluctibus, mersumque protinus fieri lapidem unum inexpugnabilem undis et fortiorem cotidie, utique si Cumano misceatur caemento? (167) eadem est terrae natura et in Cyzicena regione, sed ibi non pulvis, verum ipsa terra qua libeat magnitudine excisa et demersa in mare lapidea extrahitur. hoc idem circa Cassandream produnt fieri, et in fonte Cnidio dulci intra octo menses terram lapidescere. ab Oropo quidem Aulida usque quidquid attingitur mari terrae mutatur in saxa. non multum a pulvere Puteolano distat e Nilo harena tenuissima sui parte, non ad sustinenda maria fluctusque frangendos, sed ad debellanda corpora palaestrae studiis. (Mayhoff 1892: 292).
>
> (166) But other creations belong to the Earth herself. For who could marvel enough that on the hills of Puteoli there exists a powder (*pulvis*)—so named because it is the most insignificant part of the Earth—that, as soon as it comes into contact with the waves of the sea and is submerged, becomes a single stone mass impregnable to the waves and every day stronger, especially if mixed with stones quarried at Cumae. (167) An earth in the region of Cyzicus has the same characteristics, but there it is not a powder, rather whatever size block of earth one digs out and immerses in the sea, it comes out as a stone. It is said that the same thing happens around Cassandrea, and that earth placed in a fresh-water spring at Cnidus becomes stone within eight months. Furthermore, along the coastline from Oropos to Aulis, whatever soil the sea touches is transformed to stone. In its own way the very fine sediment of the Nile is not that different from the powder at Puteoli (*a pulvere Puteolano*)—not for resisting the sea and breaking waves, but for defending bodies that favour the exercise ground.

Seneca (Passage 14) and Pliny (Passage 16) both undoubtedly knew that *Puteolanus pulvis* had to be mixed with lime to make a proper mortar, so they may just be glossing over the full formula to make a rhetorical point. On the other hand, these observant natural scientists may simply be referring to natural concretes or volcanic tuffs that form through lithification of volcanic ash during alteration by ground and surface waters, or even to the secondary mineral cements formed by the alteration of coastal deposits of volcanic ash in sea-water. It is possible that builders or engineers in the late third century BC noticed this phenomenon and experimented with the substitution of this *pulvis* for beach or river sands in their mortars. Pliny also describes foreign stones and earth that harden in the sea, but which are not suitable for preparing mortar. These two passages incidentally reveal that that Roman "scientists" saw no natural impediment to the use of sea-water in mixing hydraulic mortar.

[17] *Historia naturalis* 36.70. A giant ship used as a floating form for concrete.

> Divus Claudius aliquot per annos adservatam, qua C. Caesar inportaverat, omnibus quae umquam in mari visa sunt mirabiliorem, in ipsa turribus Puteolis e pulvere exaedificatis, perductam Ostiam portus gratia mersit. (Mayhoff 1892: 332).
>
> The deified emperor Claudius kept for some years the ship on which Caius Caesar (Caligula) had imported (the obelisk) – a ship more remarkable than any that had ever been seen on the sea. After towers had been built on it at Puteoli from *pozzolana* (*Puteolis e pulvere*), he brought it to Ostia and sank it to protect the port.

As in Passage 15, the impossible suggestion that the concrete towers were built on the ship before it arrived at Portus may result from textual corruption. The emendation of *Puteolis e pulvere* to *Puteolano pulvere*, which is the standard Latin term for the material, would obviate the problem of the towers being built at Puteoli. Nevertheless, the passage would still describe construction of the towers as preceding the sinking of the ship. In Passage 24 below, Suetonius states that the ship was scuttled, and then towers were built on top. Pliny possibly confused the importation of *Puteolanus pulvis* from Puteoli in the giant ship, which was then used as a floating caisson to be filled with hydraulic mortar and then sunk in position, with the subsequent construction of the towers on top. In any case, all these passages about the great boat at Portus suggest an alternative approach to that used at Sebastos and Alexandria, where single-use barges were built as floating forms designed to be sunk in position when filled with concrete. Portus was located on the open sea and presented some of the same logistical problems as Sebastos.

[18] *Historia naturalis* 36.174–76. The selection of limestone and sandy volcanic products for use in mortar.

> (174) Calcem e vario lapide Cato censorius inprobat; ex albo melior. quae ex duro, structurae utilior; quae ex fistuloso, tectoriis; ad utrumque damnatur ex silice. utilior eadem effosso lapide quam ex ripis fluminum collecto, utilior e molari, quia est quaedam pinguior natura eius. mirum aliquid, postquam arserit, accendi aquis. (175) Harenae tria genera: fossicia, cui quarta pars calcis addi debet, fluviatili aut marinae tertia. si et testae tusae tertia pars addatur, melior materia erit. ab Appennino ad Padum non invenitur fossicia, nec trans maria. (176) Ruinarum urbis ea maxume causa, quod furto calcis sine ferumine suo caementa componuntur. intrita quoque ea quo vetustior, eo melior. in antiquorum aedium legibus invenitur, ne recentiore trima uteretur redemptor; ideo nullae tectoria eorum rimae foedavere. (Mayhoff 1892: 369–70).

> (174) Cato the Censor disapproves of lime made from various stones. Lime made from white limestone is preferable. That from hard limestone is more useful for concrete work (*structurae*), that from porous stone is better for wall plaster. For both purposes he condemns the use of lime made from *silex* (darker varieties of limestone?). The lime is more useful if made from quarried stone rather than from stone taken from riverbanks; it is more useful as well if made from the limestone used for millstones (?; *utilior e molari*), because this has a somewhat fatter character. It is a curious fact that after the stone has been burned in a kiln, the lime is slaked with water. (175) There are three types of sand (*harenae*): quarry sand (*fossicia*), to which lime should be added in the ratio of one part to four of sand. River sand and beach sand are the other two types, to which lime should be added in the ratio of one part to three of sand. If one part of pounded ceramic (*testae tusae*) is added as well, the mortar (*materia*) will be better. Quarry sand does not occur between the Apennine mountains and the Po River, nor overseas. (176) The primary cause for the collapse of buildings in Rome is cheating on the proportion of lime, such that the coarse aggregate (*caementa*) is laid without cohesive mortar (*ferumine*). Slaked lime (*intrita*) is better the older it is. In the ancient regulations concerning construction one reads that the contractor (*redemptor*) might not use lime slaked less than three years before. As a result, no cracks disfigure their buildings.

This discussion of various limestones used for producing lime and of sands used for mortar clearly are derivative, like so much of Pliny's information. The lime to sand ratios differ from those of Vitruvius, and it is instructive to see that recipies varied. The addition of crushed ceramics does in fact produce pozzolanic cementitious hydrates in mortar and increases its hydraulic characteristics.

Vitruvius also states (*De arch.* 2.6.5) that, "although excavated sand quarries (*fossicia harenaria*) are found nearly everywhere (in Etruria)" they do not occur between the Apennines and the Adriatic, in Achaea or in Asia Minor. So this assertion may represent common opinion. Pliny's comment on the dangers of skimping on lime in a mortar reflects contemporary abusive building practice in Rome (Oleson 2011). His recommendation to age slaked lime, documented by Pavía and Caro (2008: 9–10) in Roman mortar samples dating from 100 BC to AD 500, reflects a practice common in the early modern period (Lancaster 2005a: 54). In the late fifteenth century Alberti (1955: 36) emphasizes the importance of ageing lime putty, praising the quality of a chance find of this material that had apparently aged in a ditch for "above five hundred years." While excavating the second-century Villa dei Quintilii in Rome in 2004, Rita Paris found a very large quantity of Roman lime putty along with other construction materials below an *opus sectile* floor ("Discovery Channel"; http://dsc.discovery.com/news/briefs/20040112/ancientlime_print.html; March 2013). When mixed with a little water the material "worked perfectly" for reconstruction of the building. It is curious that Vitruvius (*De arch.* 2.5.1; Passage 6) does not mention ageing the lime; his epitomizer Faventinus (Passage 28) insists on the use of recently slaked lime. When ageing slaked lime, the material must be insulated from atmospheric $CO_2$, to avoid gradual absorption of the gas. The most common method was to place the lime in a pit in the ground, covered with a thin layer of water. See pp. 164–65.

## 2.9. P. Papinius Statius

Few Roman poets composed poems to commemorate roads, so Statius' praise of the Via Domitiana is notable. This branch route was built in AD 95, not long before Statius' death, to replace a poor road along the coast from Rome to Naples. Since the route of the well-built Via Appia turned inland at Sinuessa, this new road represented a considerable shortcut for those travelling straight to Naples. Statius first describes the previous poor conditions for travellers and then relates the benefits of the new road and how it was constructed. It is astonishing to note that this is the only preserved extensive description of the procedures involved in the construction of a Roman road, despite the ubiquitous nature of that technology.

As with the other forms of building on land, the procedures were probably too commonplace to elicit frequent comment. These two verses relate the preparation of the foundation with a sandy volcanic product (*pulvis*) and tuff (*tofus*), presumably omitting mention of lime for poetic reasons. The phrase *cocta pulvis* ("burnt powder") is a poetic reference to the volcanic origins of the volcanic sands such as *pozzolana*, and it echoes the common architectural terms *pulvis* and *Puteolanus pulvis*.

[19] *Silvae* 4.3.52–53. Pumiceous volcanic ash used in the foundations for a road.

> illi saxa ligant opusque texunt
> cocto pulvere sordidoque tofo… (Shackleton Bailey 2003: 258).

…these workers bind stones together and weave the work
with burnt powder (*pulvere*, pozzolan) and grimy tuff (*tofo*)…

## 2.10. Flavius Josephus

Herod the Great built the harbour facilities of Sebastos at Caesarea Palaestinae between 22 and 10/9 BC as a rival to the superb harbour of Alexandria. As a sign of loyalty to the Emperor, he named the harbour "Sebastos," the Greek version of the title "Augustus." Roman engineers and *pulvis* were brought from Italy, and the resulting harbour was both technologically modern and magnificent in design (see Oleson 1992). Although the historian Josephus (37/38–*ca.* 100) did not understand the important role concrete played in the construction, and his calculations of depth are highly inaccurate, the description nevertheless gives a vivid impression of the Roman ability to create harbours at inhospitable locations. The exposure of the site to the waves led to the use of single-use barge forms for placing the concrete used in the breakwaters. The *Jewish War* was composed around 75–79, the *Jewish Antiquities* around 93–95 (*AJ* 20.267).

[20] *Jewish War* 1.408–414. A description of the great concrete breakwaters at Caesarea Palaestinae.

> (408) Κατιδὼν δὲ κἀν τοῖς παραλίοις πόλιν ἤδη μὲν κάμνουσαν, Στράτωνος ἐκαλεῖτο πύργος, διὰ δὲ εὐφυίαν τοῦ χωρίου δέξασθαι δυναμένην τὸ φιλότιμον αὐτοῦ, πᾶσαν ἀνέκτισεν λευκῷ λίθῳ καὶ λαμπροτάτοις ἐκόσμησεν βασιλείοις, ἐν ᾗ μάλιστα τὸ φύσει μεγαλόνουν ἐπεδείξατο. (409) μεταξὺ γὰρ Δώρων καὶ Ἰόππης, ὧν ἡ πόλις μέση κεῖται, πᾶσαν εἶναι συμβέβηκεν τὴν παράλιον ἀλίμενον, ὡς πάντα τὸν τὴν Φοινίκην ἐπ᾽ Αἰγύπτου παραπλέοντα σαλεύειν ἐν πελάγει διὰ τὴν ἐκ λιβὸς ἀπειλήν, ᾧ καὶ μετρίως ἐπαυρίζοντι τηλικοῦτον ἐπεγείρεται κῦμα πρὸς ταῖς πέτραις, ὥστε τὴν ὑποστροφὴν τοῦ κύματος ἐπὶ πλεῖστον ἐξαγριοῦν τὴν θάλασσαν. (410) ἀλλ᾽ ὁ βασιλεὺς τοῖς ἀναλώμασιν καὶ τῇ φιλοτιμίᾳ νικήσας τὴν φύσιν μείζονα μὲν τοῦ Πειραιῶς λιμένα κατεσκεύασεν, ἐν δὲ τοῖς μυχοῖς αὐτοῦ βαθεῖς ὅρμους ἑτέρους.
>
> (411) Καθάπαν δ᾽ ἔχων ἀντιπράσσοντα τὸν τόπον ἐφιλονείκησεν πρὸς τὴν δυσχέρειαν, ὡς τὴν μὲν ὀχυρότητα τῆς δομήσεως δυσάλωτον εἶναι τῇ θαλάσσῃ, τὸ δὲ κάλλος ὡς ἐπὶ μηδενὶ δυσκόλῳ κεκοσμῆσθαι· συμμετρησάμενος γὰρ ὅσον εἰρήκαμεν τῷ λιμένι μέγεθος καθίει λίθους ἐπ᾽ ὀργυιὰς εἴκοσιν εἰς τὸ πέλαγος, ὧν ἦσαν οἱ πλεῖστοι μῆκος ποδῶν πεντήκοντα, βάθος ἐννέα, εὖρος δέκα, τινὲς δὲ καὶ μείζους. (412) ἐπεὶ δὲ ἀνεπληρώθη τὸ ὕφαλον, οὕτως ἤδη τὸ ὑπερέχον τοῦ πελάγους τεῖχος ἐπὶ διακοσίους πόδας ηὐρύνετο· ὧν οἱ μὲν ἑκατὸν προδεδόμηντο πρὸς τὴν ἀνακοπὴν τοῦ κύματος, προκυμία γοῦν ἐκλήθη, τὸ δὲ λοιπὸν ὑπόκειται τῷ περιθέοντι λιθίνῳ τείχει. τοῦτο δὲ πύργοις τε διείληπται μεγίστοις, ὧν ὁ προύχων καὶ περικαλλέστατος ἀπὸ τοῦ Καίσαρος προγόνου Δρούσιον κέκληται.
>
> (413) Ψαλίδες τε πυκναὶ πρὸς καταγωγὴν τῶν ἐνορμιζομένων καὶ τὸ πρὸ αὐτῶν πᾶν κύκλῳ νάγμα τοῖς ἀποβαίνουσιν πλατὺς περίπατος. ὁ δ᾽ εἴσπλους βόρειος, αἰθριώτατος γὰρ ἀνέμων τῷ τόπῳ βορέας· καὶ ἐπὶ τοῦ στόματος κολοσσοὶ τρεῖς ἑκατέρωθεν ὑπεστηριγμένοι κίοσιν, ὧν τοὺς μὲν ἐκ λαιᾶς χειρὸς εἰσπλεόντων πύργος ναστὸς ἀνέχει, τοὺς δὲ ἐκ δεξιοῦ δύο ὀρθοὶ λίθοι συνεζευγμένοι τοῦ κατὰ θάτερον χεῖλος πύργου μείζονες. (414) προσεχεῖς δ᾽ οἰκίαι τῷ λιμένι, λευκοῦ καὶ αὐταὶ λίθου, καὶ κατατείνοντες ἐπ᾽ αὐτὸν οἱ στενωποὶ τοῦ ἄστεος πρὸς ἓν διάστημα μεμετρημένοι. καὶ τοῦ στόματος ἀντικρὺ ναὸς Καίσαρος ἐπὶ γηλόφου κάλλει καὶ μεγέθει διάφορος· ἐν δ᾽ αὐτῷ κολοσσὸς Καίσαρος οὐκ ἀποδέων τοῦ Ὀλυμπίασιν Διός, ᾧ καὶ προσείκασται, Ῥώμης δὲ ἴσος Ἥρᾳ τῇ κατ᾽ Ἄργος. ἀνέθηκεν δὲ τῇ μὲν ἐπαρχίᾳ τὴν πόλιν, τοῖς ταύτῃ δὲ πλοϊζομένοις τὸν λιμένα, Καίσαρι δὲ τὴν τιμὴν τοῦ κτίσματος· Καισάρειαν γοῦν ὠνόμασεν αὐτήν. (Niese in Thackeray 1927: 192–96).

(408) Herod noticed a settlement on the coast – it was called Straton's Tower – which, although much decayed, because of its favourable location was capable of benefiting from his generosity. He rebuilt the whole city in white marble, and decorated it with the most splendid palaces, revealing here in particular his natural magnificence. (409) For the whole coastline between Dor and Joppa, midway between which the city lies, happened to lack a harbour, so that every ship coasting along Phoenicia towards Egypt had to ride out southwest head winds riding at anchor in the open sea. Even when this wind blows gently, such great waves are stirred up against the reefs that the backwash of the surge makes the sea wild far off shore. (410) But the King, through a great outlay of money and sustained by his ambition, conquered nature and built a harbour (*liména*) larger than the Piraeus, encompassing deep-water subsidiary anchorages within it.

(411) Although the location was generally unfavourable, he contended with the difficulties so well that the sea could not overcome the solidity of the construction, and its beauty seemed finished off without impediment. Having calculated the relative size of the harbour as we have stated, he let down stone blocks (*lithous*; most of these blocks were, in fact,

concrete) into the sea to a depth of 20 fathoms (*ca.* 37 m). Most of them were 50 feet long, 9 high, and 10 wide (15.2 × 2.7 × 3.05 m), some even larger. (412) When the submarine foundation (*hýphalon*) was finished, he then laid out the mole (*teíchos*) above sea level, 200 feet across (61.0 m). Of this, a 100-foot portion was built out to break the force of the waves, and consequently was called the breakwater (*prokumía*). The rest of the mole supported the stone wall that encircled the harbour. At intervals along it were great towers (*pýrgois*), the tallest and most magnificent of which was named Drusion, after Caesar's stepson.

(413) There were numerous vaulted chambers for the reception of those entering the harbour, and the whole curving structure in front of them was a wide promenade for those who disembarked. The entrance channel (*eísplous*) faced north, for in this region the north wind always brings the clearest skies. At the harbour entrance (*stómatos*) there were colossal statues, three on either side, set up on columns. A massively built tower (*pýrgos*) supported the columns on the port side of boats entering the harbour; those on the starboard side were supported by two upright blocks of stone (*orthoí líthoi*) yoked together, higher than the tower on the other side.

(414) There were buildings right next to the harbour also built of white marble, and the passageways of the city ran straight towards it, laid out at equal intervals. On a hill directly opposite the harbour entrance channel stood the temple of Caesar, set apart by its scale and beauty. In it there was a colossal statue of Caesar, not inferior to the Zeus at Olympia on which it was modelled, and one of the Goddess Roma just like that of Hera at Argos. He dedicated the city to the province, the harbour to the men who sailed in these waters, and the honour of the foundation to Caesar: he consequently named it Caesarea.

[21] Josephus, *Jewish Antiquities* 15.332–38. Another description of the great concrete breakwaters at Caesarea Palaestinae.

(332) τὸ δὲ μέγιστον καὶ πλείστην ἐργασίαν παρασχόν, ἀκλύστῳ λιμένι, μέγεθος μὲν κατὰ τὸν Πειραιᾶ, καταγωγὰς δ᾽ ἔνδον ἔχοντι καὶ δευτέρους ὑφόρμους, τῇ δὲ δομήσει περίβλεπτον ὅτι μηδ᾽ ἐκ τοῦ τόπου τὴν ἐπιτηδειότητα τῆς μεγαλουργίας εἶχεν, ἀλλ᾽ ἐπεισάκτοις καὶ πολλαῖς ἐξετελειώθη ταῖς δαπάναις. (333) κεῖται μὲν γὰρ ἡ πόλις ἐν τῇ Φοινίκῃ κατὰ τὸν εἰς Αἴγυπτον παράπλουν Ἰόππης μεταξὺ καὶ Δώρων, πολισμάτια ταῦτ᾽ ἐστὶν παράλια, δύσορμα διὰ τὰς κατὰ λίβα προσβολάς, αἳ ἀεὶ τὰς ἐκ τοῦ πόντου θῖνας ἐπὶ τὴν ᾐόνα σύρουσαι καταγωγὴν οὐ μειλίχιον διδόασιν, ἀλλ᾽ ἔστιν ἀναγκαῖον ἀποσαλεύειν τὰ πολλὰ τοὺς ἐμπόρους ἐπ᾽ ἀγκύρας.

(334) τοῦτο τὸ δύσθετον τῆς χώρας διορθούμενος καὶ περιγράψας τὸν κύκλον τοῦ λιμένος ἐφ᾽ ὅσον ἦν αὔταρκες πρὸς τῇ χέρσῳ μεγάλοις στόλοις ἐνορμεῖσθαι, λίθους ὑπερμεγέθεις καθίει τὸ βάθος εἰς ὀργυιὰς εἴκοσι. πεντήκοντα ποδῶν ἦσαν οἱ πλείους τὸ μῆκος, καὶ πλάτος οὐκ ἔλαττον δεκαοκτώ, βάθος δὲ ἐννέα, τούτων δὲ οἱ μὲν μείζους οἱ δὲ ἐλάττους. (335) ἡ δὲ ἐνδόμησις ὅσον ἐνεβάλετο κατὰ τῆς θαλάσσης διακοσίους πόδας. τούτων τὸ μὲν ἥμισυ προβέβλητο κυματωγαῖς, ὡς ἀπομάχεσθαι περικλώμενον ἐκεῖ τὸν κλύδωνα· προκυμία γοῦν ἐκαλεῖτο. (336) τὸ δὲ λοιπὸν περιεῖχεν λίθινον τεῖχος πύργοις διειλημμένον, ὧν ὁ μέγιστος Δρούσιος ὀνομάζεται, πάνυ καλόν τι χρῆμα, τὴν προσηγορίαν εἰληφὼς ἀπὸ Δρούσου τοῦ Καίσαρος προγόνου, τελευτήσαντος νέου. (337) ψαλίδες δὲ ἐμπεποίηντο συνεχεῖς καταγωγαὶ τοῖς ναυτίλοις, τὸ δὲ πρὸ αὐτῶν ἀπόβασις πλατεῖα κύκλῳ περιεστεφάνωκε τὸν πάντα λιμένα, περίπατος τοῖς ἐθέλουσιν ἥδιστος. ὁ δ᾽ εἴσπλους καὶ τὸ στόμα πεποίηται πρὸς βορρᾶν, ὃς ἀνέμων αἰθριώτατος. (338) βάσις δὲ τοῦ περιβόλου παντὸς ἐν ἀριστερᾷ μὲν εἰσπλεόντων πύργος νενασμένος ἐπὶ πολὺ στερρῶς ἀντέχειν, κατὰ δεξιὰν δὲ δύο λίθοι μεγάλοι καὶ τοῦ κατὰ θάτερα πύργου μείζους, ὀρθοὶ καὶ συνεζευγμένοι. (Niese in Marcus 1963: 416–18).

(332) He provided the greatest and most laborious work with a harbour protected from the waves, as big as the Piraeus, with landing places inside and secondary moorings. What was particularly admired was that Herod obtained the supplies for so great a project not from the place itself, but he brought it to completion with materials brought in from elsewhere at great expense. (333) This city is in Phoenicia, on the sea route down to Egypt, between Joppa and Dor. These towns are on the shoreline, but they are difficult anchorages on account of the prevailing southwest wind, which constantly deposits sea sand on the shore and does not make for a smooth landing. In consequence, most of the time the merchants have to ride at anchor offshore.

(334) To correct this drawback in the topography, he laid out a circular harbour (*kúklon toū liménos*) on a scale sufficient to allow large fleets to lie at anchor close to shore, and let down enormous blocks of stone (*líthous*) to a depth of 20 fathoms. Most were 50 feet long, not less than 18 feet wide, and 9 feet high. (335) The structure (*endómesis*) he threw up as a barrier against the sea was 200 feet wide. Half of this opposed the breaking waves, warding off the surge breaking there on all sides. Consequently it was called a breakwater (*prokumía).* (336) The rest comprised a stone wall (*teichos*) set at intervals with towers (*pýrgois*), the tallest of which, quite a beautiful thing, was called Drusion – taking its name from Drusus, the stepson of Caesar who died young. (337) A series of vaulted chambers was built into it for the reception of sailors, and in front of them a wide, curving quay (*apóbasis*) encircled the whole harbour, very pleasant for those who wished to stroll around. The entrance (*eísplous*) or mouth (*stóma*) was built towards the north, for this wind brings the clearest skies. (338) The foundation (*básis*) of the whole encircling wall on the port

> side of those sailing into the harbour was a tower (*pýrgos*) built up on a broad base to withstand the water firmly, while on the starboard side were two great stone blocks (*líthoi*), taller than the tower on the opposite side, upright and yoked together (*sunezeugménoi*).

Although the *Jewish War* was written approximately 20 years before the *Jewish Antiquities*, the two accounts of Sebastos on the whole agree with each other. There is one minor difference in the dimensions of the "stone blocks" Herod let down into the sea to form the breakwater, and the account in the *Jewish Antiquities* (15.332) comments on the importation of building materials (without specifying *pulvis*) and associates the location of the harbour with the sea route from Alexandria to Rome. As noted above, importation of pyroclastic rock from the Gulf of Naples possibly made use of grain freighters returning from Rome to Alexandria in ballast, passing right by Sebastos, so the juxtaposition of the two comments could possibly have some significance (*cf.* Galili *et al.* 2010). Josephus, however, never mentions concrete, despite its important role in the construction of Sebastos, and he may not even have understood what that material was. The descriptions of the harbour nevertheless remain important for the emphasis on the difficulty of building at this exposed location, and the details they provide about the design of the breakwaters and the structures on them. Although Josephus seems to know nothing about it, the exposed location led to the use of single-mission barge forms for placing the concrete.

## 2.11. Pliny the Younger

The type of rubble-mound breakwater Vitruvius alludes to in his description of harbour design (*De arch*. 5.12.2; Passage 9) is described by Pliny, who witnessed the construction of the great harbour at Centum Cellae, modern Civitavecchia. Concrete *pilae* finished off the breakwater, which rested on the rubble foundation. Blake provides a good description of the remains of the harbour facilities (1973: 290–92).

[22] *Epistulae* 6.31.15–17. Construction of the harbour of Centum Cellae with rubble mounds and concrete.

> (15) Villa pulcherrima cingitur viridissimis agris, imminet litori, cuius in sinu fit cum maxime portus. Huius sinistrum brachium firmissimo opere munitum est, dextrum elaboratur. (16) In ore portus insula adsurgit, quae inlatum vento mare obiacens frangat, tutumque ab utroque latere decursum navibus praestet. Adsurgit autem arte visenda: ingentia saxa latissima navis provehit contra; haec alia super alia deiecta ipso pondere manent ac sensim quodam velut aggere construuntur. (17) Eminet iam et adparet saxeum dorsum impactosque fluctus in immensum elidit et tollit; vastus illic fragor canumque circa mare. Saxis deinde pilae adicientur quae procedente tempore enatam insulam imitentur. Habebit hic portus, et iam habet nomen auctoris, eritque vel maxime salutaris; nam per longissimum spatium litus importuosum hoc receptaculo utetur. Vale. (Mynors 1963: 192–93).
>
> (15) The villa is very beautiful; it is fringed by fields of the brightest green and overlooks the seashore and a bay that at this very moment is being turned into a harbour (*portus*). The breakwater (*brachium*, lit. "arm") on the left has already been reinforced with construction of the greatest stability (*firmissimo opere*), while that on the right is in the process of being built. (16) At the harbour entrance a free-standing mole (*insula*, literally "island") rises from the sea to serve as a breakwater against seas brought in by the on-shore wind and provide safe entrance to ships on either side. The technique by which the mole is built has got to be seen. A wide barge brings enormous stones right up to it, and they are thrown in one on top of another. Their weight keeps them in position, and little by little a sort of rampart is constructed. (17) A kind of stony hump can already be seen rising above the water, breaking the waves that beat upon it and tossing the spray high in the air with a great roar; the sea all around is white with foam. Masses of concrete (*pilae*) will be laid on top of the stones, and as time passes it will come to resemble an island. This will be the harbour (*portus*) – it already carries the name of its builder – and it will bring safety to many by providing a haven on this very long stretch of harbourless coastline. Farewell.

[23] *Epistulae* 10.39.4. Inferior construction in the gymnasium at Nicaea.

While he was *Legatus Augusti* in Bithynia in 110, Pliny wrote several letters to Trajan about problems with various construction projects on land. Poor planning, poor execution, and funding difficulties were at the root of most of the situations he describes. This passage is important mainly for its exceptional use of the term *caementum*.

> Praeterea architectus, sane aemulus eius a quo opus inchoatum est, adfirmat parietes quamquam viginti et duos pedes latos imposita onera sustinere non posse, quia sint caemento medii farti nec testaceo opere praecincti. (Mynors 1963: 310).
>
> In addition, the architect, undoubtedly jealous of the man who began the project, affirms that the wall, although 22 feet thick, cannot sustain the weight placed on it because the interior fill is made of concrete (? *caemento*) but not faced with brick (*testaceo opere*).

Blake (1947: 309) interprets the last sentence as the only surviving reference to concrete construction referred to as *caementum* rather than *opus caementicium*. One would expect the instability to have been caused by the use of loose rubble (*caementa*) as the fill, but in that case the reference to the typical Imperial brick facing does not make sense. Sherwin-White (1966: 618–19) follows this interpretation.

## 2.12. C. Suetonius Tranquillus

Suetonius' biographies of the emperors from Julius Caesar to Domitian, composed in the early second century, contain numerous details concerning engineering and other technologies. The description of Portus appears in the context of an account of several of Claudius' spectacular engineering projects.

[24] *Claudius* 20.3. The engineering methods used to construct Portus.

> portum Ostiae extruxit circumducto dextra sinistraque bracchio et ad introitum profundo iam solo mole obiecta; quam quo stabilius fundaret, nauem ante demersit, qua magnus obeliscus ex Aegypto fuerat aduectus, congestisque pilis superposuit altissimam turrem in exemplum Alexandrini Phari, ut ad nocturnos ignes cursum nauigia dirigerent. (Ihm 1908: 204).
>
> At Ostia he constructed a harbour (*portum*) by building breakwaters (*bracchio*) out from shore to the right and left and placing a mole (*mole*) in front of the entrance, which was in deep water. To give this mole a more stable foundation, he first scuttled the ship in which a large obelisk had been conveyed from Egypt, then laid massive concrete blocks (*pilis*) above. He topped it off with a very tall tower modelled after the Pharos at Alexandria, so that at night ships might direct their course towards its beacon fire.

This is the most believable account of the use of the giant ship as formwork, since the *pilae* are said to have been built after the ship was sunk, rather than before, as suggested by Pliny in Passages 15 and 17.

## 2.13. Apuleius

In his *Metamorphoses*, the only Latin novel to survive in its entirety, Apuleius (*flor.* 160) describes numerous details of daily life. In the passage quoted here an auctioneer points out the defects of the hero, who has been transformed by magic into a broken-down mule with little market value. He compares the mule to a heavy-duty construction sieve that presumably has seen hard use.

[25] *Metamorphoses* 8.23. A sieve for construction materials.

> … nec quicquam amplius quam ruderarium cribrum. (Helm 1968: 195).
>
> … (he is) nothing more than a sieve (*cribrum*) for rubble.

The adjective *ruderarium* is not entirely clear, but it should be a derivative of *rudus,* meaning construction rubble or crushed stone. Roman engineers probably used heavy-duty sieves of this sort to sift the various aggregates for mortar (see above, Theophrastus, Passage 1; Cato, Passage 3; Vitruvius, Passages 5 and 6).

## 2.14. Cassius Dio

Dio's history of Rome, written in the years prior to 229, contains nuggets of information about contemporary technology and scientific thought. In the following passage he provides an explanation for the origins and properties of earthy volcanic ash very similar to the more detailed account given by Vitruvius (Passage 7).

[26] *Roman History* 48.51.3–4. The geological origins of *pozzolana* at Baiae.

> (3) ταῦτά τε οὖν τὸ ὄρος ἐκεῖνο καὶ προσέτι καὶ γῆς φύσιν τοιάνδε παρέχεται. τοῦ πυρὸς τὸ μὲν καίειν οὐκ ἔχοντος (ὑπὸ γὰρ τῆς τοῦ ὕδατος συνουσίας πᾶν τὸ φλογῶδες αὐτοῦ σβέννυται), διακρίνειν δὲ δὴ καὶ διατήκειν τὰ προστυχόντα οἱ καὶ ὣς δυναμένου, συμβαίνει τῆς γῆς τὸ μὲν λιπαρὸν ἐκτήκεσθαι ὑπ᾽ αὐτοῦ, τὸ δὲ τραχὺ καὶ ὀστῶδες ὡς εἰπεῖν ὑπολείπεσθαι. (4) σηραγγώδεις τε οὖν οἱ ὄγκοι ἐξ ἀνάγκης γίγνονται, καὶ αὐχμῷ μὲν δοθέντες ἐς κόνιν διαλύονται, ὕδατι δὲ σὺν κονίᾳ φυραθέντες συνίστανται, καὶ ἐφ᾽ ὅσον γ᾽ ἂν ἐν τῷ ὑγρῷ ὦσι, πήγνυνταί τε καὶ πετροῦνται. αἴτιον δὲ ὅτι τὸ μὲν κραῦρον αὐτῶν ὑπὸ μὲν τοῦ πυρὸς ὁμοφυοῦς οἱ ὄντος ἐπιτείνεταί τε καὶ θραύεται, τῇ δὲ δὴ συμμίξει τῆς νοτίδος ἀναψύχεται, κἀκ τούτου εἴσω διὰ παντὸς συμπιληθὲν ἄλυτον γίγνεται. (Boissevain in Cary 1917: 1895–1901: 330).
>
> (3) Now, besides these products, the hill behind Baiae furnishes an earth (*gē*), the special nature of which I will describe. The subterranean heat cannot burn anything because the admixture of ground water quenches its scorching properties, but it can still separate and melt the substances with which it comes into contact. In consequence, the soft part of the earth is melted out by the heat, while the hard and as it were bony part is left behind. (4) Hence the masses of earth necessarily become porous and when exposed to the dry air crumble into dust (*kónis* = *pulvis*). When this dust is mixed with water and lime (*konía*) they become a compact mass, and as long as they remain in the water they continue to set and harden. The reason for this is that the brittle element in them is disintegrated and broken up by the fire, which possesses the same nature, but by the admixture of moisture it is chilled and so once again becomes completely dense and indissoluble.

Although the meaning of this passage is not entirely clear, it seems that Cassius Dio is describing, first, geothermal heating of ground water that is associated with the melting of rock to form magma, leaving behind the rocky edifice of the volcano. He then describes the weathering of porous deposits of earth (*gē*), possibly pumiceous ash, to form dust (*kónis*), possibly the *pulvis* of related Latin texts. Strabo's term (Passage 12) for *pozzolana* is *kónis*, which also signifies "dust." Finally, he describes the "compact," "dense, and indissoluble" mass that forms when lime, "dust," and water are mixed and allowed to remain in water. This is seems to be a testament to the enduring qualities of the lime-pumiceous pozzolan mortars in sea-water, perhaps derived from observations of maritime concrete structures built 250 years earlier, during the late Republic.

[27] *Roman History* 60.11.2–5. The location and construction of Portus.

> (2) ἐπεσάκτου γὰρ παντὸς ὡς εἰπεῖν τοῦ σίτου τοῖς Ῥωμαίοις ὄντος, ἡ χώρα ἡ πρὸς ταῖς τοῦ Τιβέριδος ἐκβολαῖς, οὔτε κατάρσεις ἀσφαλεῖς οὔτε λιμένας ἐπιτηδείους ἔχουσα, ἀνωφελές σφισι τὸ κράτος τῆς θαλάσσης ἐποίει· ἔξω τε γὰρ τῶν τῇ τε ὡραίᾳ ἐσκομισθέντων καὶ ἐς τὰς ἀποθήκας ἀναχθέντων οὐδὲν τὴν χειμερινὴν ἐσεφοίτα, ἀλλ᾽ εἴ τις παρεκινδύνευσε, κακῶς ἀπήλλασσε. (3) τοῦτ᾽ οὖν συνιδὼν λιμένα τε κατασκευάσαι ἐπεχείρησεν, οὐδ᾽ ἀπετράπη καίπερ τῶν ἀρχιτεκτόνων εἰπόντων αὐτῷ, πυθομένῳ πόσον τὸ ἀνάλωμα ἔσοιτο, "ὅτι οὐ θέλεις αὐτὸν ποιῆσαι"· οὕτως ὑπὸ τοῦ πλήθους τοῦ δαπανήματος ἀναχαιτισθῆναι αὐτόν, εἰ προπύθοιτο αὐτό, ἤλπισαν· ἀλλὰ καὶ ἐνεθυμήθη πρᾶγμα καὶ τοῦ φρονήματος καὶ τοῦ μεγέθους τοῦ τῆς Ῥώμης ἄξιον καὶ ἐπετέλεσε. (4) τοῦτο μὲν γὰρ ἐξορύξας τῆς ἠπείρου χωρίον οὐ σμικρόν, τὸ πέριξ πᾶν ἐκρηπίδωσε καὶ τὴν θάλασσανἐς αὐτὸ ἐσεδέξατο· τοῦτο δὲ ἐν αὐτῷ τῷ πελάγει χώματα ἑκατέρωθεν αὐτοῦ μεγάλα χώσας θάλασσαν ἐνταῦθα πολλὴν περιέβαλε, καὶ νῆσον ἐν αὐτῇ πύργον τε ἐπ᾽ ἐκείνῃ φρυκτωρίαν ἔχοντα κατεστήσατο. ὁ μὲν οὖν λιμὴν ὁ καὶ νῦν οὕτω κατά γε τὸ ἐπιχώριον ὀνομαζόμενος ὑπ᾽ ἐκείνου τότε ἐποιήθη. (Boissevain in Cary 1917: 1895–1901: 392–94).

> (2) Nearly all the grain the Romans consumed was imported, but the coastline near the mouth of the Tiber had neither safe landing places (*katárseis*) nor suitable harbour basins (*liménas*).... Apart from supplies brought in during the summer sailing season and stored in warehouses, there was nothing imported during the winter, and whoever ran the risk [of a winter voyage] suffered disaster. (3) With this in mind, Claudius undertook to construct a harbour basin. He would not be dissuaded, even though his architects replied to him, when he asked how great the cost would be, "You don't want to do it!" They hoped that if he knew of the enormous expense ahead of time, he would be put off by it. But he conceived a project worthy of the dignity and greatness of Rome and brought it to completion. (4) First, he excavated a considerable plot of land near the coast, built quay walls all around it, and let in the sea. Next, in the sea itself he laid down great moles (*chómata*) on either side of the basin entrance and thus enclosed a large body of water, and in it he fashioned an island carrying a lighthouse. He built the Port (*límen*), as it is still called by the locals, at this time.

It is interesting that in this passage Dio Cassius does not mention concrete or *pozzolana*, or the use of Caligula's obelisk ship as a floating form, as described by Pliny and Suetonius (see Passages 15, 17, 24). Perhaps the passage of time had obscured these details, or they simply had become standard procedure for harbour construction and as such not subject to comment. Suetonius (*Claud.* 20.1) and Plutarch (*Caes.* 58.10) both mention that Julius Caesar had frequently contemplated development of a harbour at Ostia, but he had given up the project as too difficult. Advances in harbour engineering may have given Claudius confidence for the undertaking, although his engineers did not share it. Their strategy to dissuade Claudius indicates that budgets had to be prepared even for enormous prestige projects proposed by the emperor.

## 2.15. M. Cetius Faventinus

Sometime around 300, Faventinus prepared an abridged version of Vitruvius's *De architectura*, apparently designed to provide instructions to private individuals who wished to serve as architects for their own domestic projects – an approach Vitruvius himself recommended (*De arch.* 6, *praef.* 6–7). For the most part he simply truncates Vitruvius' text, omitting material concerned with public buildings, along with speculation about the geological processes that produced various construction materials. In the passage below, however, he makes a few changes of his own. These passages reveal that Vitruvius' work was felt to have remained relevant to the practice of architecture even after the passage of 300 years, but that some details of formulae or procedures had changed. This is understandable if Vitruvius' handbook was in fact a useful practical guide rather than an ideal canon. Palladius, who wrote a handbook *De agricultura* about a century later, borrowed information from Faventinus rather than from Vitruvius (Plommer 1973: 2), and without change, so he will not be quoted here.

[28] *De diversis fabricis architectonicae* 4. How to mix mortar for a brick wall.

> In signinis autem operibus haec servare debebis. primo ut harena aspera paretur et caementum de silice vel lapide toficio calcis proxime extinctae duae partes ad quinque harenae mortario misceantur… sed licet auctores ad quinque partes harenae duas partes calcis mitti docuerint, isdem mensuris et redivivas expensas fieri monstraverunt, melius tamen inventum est ut ad duas harenae una calcis misceatur, quo pinguior inpensa fortius caementa ligaret. Similiter et in testaceis operibus facies. (Plommer 1973: 48–50).

> In structures made with baked bricks, you must hold to the following instructions. First, let sharp sand (*harena aspera*) be furnished, along with large aggregate (*caementum*) composed of a hard stone or tuff (*de silice vel lapide toficio*). Two measures of recently slaked lime should be mixed in the trough (*mortario*) with five measures of sand (*harenae*)… Although various authorities have instructed us that two measures of lime should be added to the five measures of sand, they have also shown that the same formula will lead to renewed expenses later on. A better formula has been found in which one measure of lime is mixed with two of sand. In this way a greater initial expense provides

> stronger bonding of the *caementa*. Act accordingly with all brick construction.

This and the following passage are lightly adapted from Vitruvius, *De architectura* 2.4.1 and 2.5.1–3 (Passages 5 and 6); they are repeated in Palladius, *De agricultura* 9.10. Although Faventinus does not use the term *harena fossicia* in this passage (as he does in the next), the *harena aspera* he cites should be this same material. He states that the sand should be "sharp", echoing the characteristic of *asperitas* Vitruvius attributes to proper *harena fossicia*. In *De architectura* 2.5.1 Vitruvius implies that the lime is added to the mix soon after slaking, but Faventinus insists upon immediate use. Pliny (*HN* 36.176; Passage 18), in contrast, recommends ageing the lime putty for at least three years. The proper ratio of lime to sand varies in our ancient sources from 1 to 2, to 1 to 4, depending upon the type of sand and the location of the structure on land or in the water. See the discussion above (pp. 22–23). The formula of 2 to 5 that Faventinus mentions as traditional but insufficient is significantly richer in lime (28.6 volume % dry quicklime to 71.4 volume % sand) than Pliny's formula of 1 to 4 (20 volume % to 80 volume %) (Passage 18), but he nevertheless recommends going all the way to a ratio of 1 to 2 (33.3 volume % to 66.6 volume %).

[29] *De diversis fabricis architectonicae* 8–9. How to evaluate the quality of sand and lime.

> Harenae fossiciae genera sunt tria, nigra, rubra, carbunculus. ex his quae manu comprehensa stridorem fecerit, optima et purgata erit. quae autem terrosa fuerit, non habebit asperitatem. etiamque in vestimentum candidum si miseris et effusa si nihil sordis reliquerit, idonea erit. si vero non fuerit unde harenae fodiantur, tunc de fluminibus aut de glareis excernenda erit aut de litore marino. sed marina harena in structuris hoc vitium habet, tarde siccat. unde onerari se continenter non patitur. nisi intermissionibus requieverit opus, pondere gravata structura rumpetur. cameris etiam salsum umorem remittendo tectorium opus saepe resolvit. fossiciae vero celeriter siccescunt et tectoria non laedunt et concamerationes utiliter obligant. sed fossiciae recentes statim in structuras mitti debent. fortius enim comprehendunt caementa. nam si sub sole diutius fuerint aut imbribus pruinisque solutae, et terrosae et evanidae fiunt. fossiciae itaque cum recentes sunt, tectorio operi propter pinguedinem non conveniunt. fluviaticae autem propter macritatem signino operi incongruentes sunt, sed iaculorum subactionibus in tectorio opere recipiunt soliditatem. in caementicias autem structuras pura harena mittatur.
>
> Calx itaque de albo saxo vel tiburtino aut columbino fluviatili coquatur aut rubro aut spongia. quae enim erit ex spisso et duro saxo, utiliter structuris conveniet. quae autem ex fistuloso aut exiliore lapide fuerit, conveniet operi tectorio. in commixtione ad duas partes harenae una calcis mittatur. in fluviatili autem harena si tertiam partem testae cretae addideris, miram soliditatem operis praestabit. (Plommer 1973: 54).
>
> There are three types of quarry sand (*harenae fossiciae*): black, red, and *carbunculus*. Of these three, that which makes a crackling noise when grasped with the hand will be the best quality, and clean. The sand that is earthy in quality, however, will not have that sharpness (*asperitatem*). Another test: throw the sand on a white garment, then shake it off; if no stain remains it will be suitable. If, however, there is no quarry from which quarry sand (*harenae*) can be dug, then it will have to be sifted out from rivers or gravel pits, or from the seashore. But sea sand (*marina harena*) has the following fault in concrete structures: it cures (*siccat*; literally "dries") slowly and for that reason cannot be put under a load immediately. Unless the project has been given a rest by occasional pauses in the work, the structure (*structura*) will collapse under its own weight. Moreover, in vaulted rooms (*cameris*) it often spoils the plasterwork by releasing briny moisture. Quarry sand (*fossiciae*), however, cures quickly, does not harm plasterwork, and is advantageous in binding vault work. But recently dug quarry sand (*fossiciae recentes*) ought to be put to work in concrete construction without delay, for then the sand grips the aggregate (*caementa*) with greater strength. For if the sand has spent some time in the sun or is loosened by rain and frost, it becomes both earthy and weak. On the other hand, recently dug quarry sand is not appropriate for plasterwork on account of its rich character. River sand (*fluviaticae*), however, on account of its lean character is inappropriate for *signinum* work, but if thoroughly pounded with a tamper it takes on the strength for plasterwork. But let pure sand (*pura harena*) be used for concrete structures (*in caementicias…structuras*).
>
> Lime should be burned from white stone, or travertine, or grey river stone, or from red stone or sponge-stone. Lime that comes from close-grained or hard stone will be of more use for construction. Lime from porous or lighter stone, however, will be of use for plasterwork. In the mortar mix (*commixtione*), put one part lime to two parts sand. If using river sand, however, the structure will gain remarkable solidity if you add a third part of pounded ceramic (*testae*).

Like the preceding passage, this too is adapted from Vitruvius *De architectura* 2.4–5 (Passages 5–6), and it is echoed in Palladius, *De agricultura* 1.10. Faventinus leaves out the "white" sand (*cana*) mentioned by Vitruvius, while including *carbunculus*, which likely was quarried in Etruria, north of Rome, possibly from poorly consolidated deposits of the *Tufo Grigio a Scorie Nere* (Jackson *et al.* 2007: 30–42). Inclusion of *carbunculus* suggests Faventinus knew what it was. He recounts both practical tests of these sands: rubbing in the palm and tossing in a white garment. *Harenae fossiciae* speed up curing of concrete, but they must be used immediately after quarrying. The ratio of one part lime to two parts sand, first seen in Passage 28, is repeated here – unless the context refers to the mixing of wall plaster.

## 2.16. Procopius of Caesarea

Procopius describes the construction of a harbour for Constantinople sometime between 527 and 553–555.

[30] *On Buildings* 1.11.18–20. Justinian's use of box forms for a harbour at Constantinople.

> (18) ἐνταῦθα δὲ καὶ λιμένων σκέπας ἀποτετόρνευται οὐ πρότερον ὄν. ἀκτὴν γὰρ εὑρὼν ἑκατέρωθι τοῖς τε ἀνέμοις καὶ ταραχῇ τοῦ ῥοθίου ἀποκειμένην, σωτήριον εἶναι τοῖς πλέουσι κατεστήσατο ὧδε. (19) τὰς κιβωτοὺς καλουμένας ἀναρίθμους τε καὶ παμμεγέθεις πεποιημένος, ἀμφοτέρωθέν τε αὐτὰς τῆς ἠϊόνος ἐπὶ πλεῖστον ἐγκαρσίας ἀπορριψάμενος, ἀεί τε τῶν προτέρων καθύπερθεν ἑτέρων ἐν τάξει ἐπιβολὴν ἐντιθέμενος, τοίχους πλαγίους ἀπ' ἐναντίας ἀλλήλων ἀνέστησε δύο ἐκ τῶν τῆς ἀβύσσου κρηπίδων μέχρι ἐς τὸ ὕδωρ, ᾧ δὴ αἱ νέες ἐναπερειδόμεναι πλέουσι. πέτρας τε τὸ λοιπὸν ἀποτόμους ταύτῃ ἐμβέβληται. (20) ὧν δὴ πρὸς τοῦ ῥοθίου ἀρασσομένων, ἀποκρουομένων τε τὴν τοῦ κλυδωνίου ἐπίθεσιν, καὶ ἀνέμου χειμῶνος ὥρᾳ καταβάντος σκληροῦ, διαμένει τὰ ἐντὸς ἡσυχῇ ἅπαντα τῶν τοίχων, μεταξὺ μιᾶς ἀπολελειμμένης ἐπὶ τὸν λιμένα τοῖς πλοίοις εἰσόδου. (Haury 1964: vol. 4, p. 44).
>
> (18) There (at Constantinople) he (Justinian) brought to completion with great skill a sheltered harbour (*liménon*) where there previously had been none. Finding a shore exposed from both directions to the winds and the force of the breaking waves, he established it in the following way as a refuge for voyagers. (19) He prepared great numbers of a very large, box-shaped formwork – the so-called "cribs" (*kibotoús*) – and dropped them in oblique lines on either side (of the basin) for a great distance out from the shore. By repeatedly setting a new course of forms in careful order on top of those laid previously, he constructed two walls (*toíchous*) angled out towards each other from opposite sides (of the harbour), rising from their foundations (*krepídon*) deep in the water up to the surface where ships float and manoeuvre. He threw untrimmed boulders on top of them, (20) and when the surf pounds these boulders they toss off the force of the waves. Even when a strong wind rises in the winter, the whole area within the breakwaters (*toíchon*) remains still, since one entrance (*eisódou*) into the harbour (*liména*) has been left between them for ships.

It is not clear what kind of formwork was used for this construction, but given the emphasis on the difficulty of the location and the piling of the resulting blocks on top of each other, floating barge forms seem most likely (Hohlfelder 1988, 1997). If the engineers did not have hydraulic concrete at their disposal, they might have filled the forms with stones, as a more temporary type of construction now referred to as "cribs." Iohannes Tzetzes (*Chiliades* 2.91–94) uses the related term *kibótion* ("box") for formwork placed in the Danube River for the foundations of the great bridge built for Trajan by Apollodorus of Damascus in AD 105. He is probably quoting from the book Apollodorus wrote about the project (*cf.* Procopius, *Aed.* 4.6.13).

> …τὸν Ἀπολλοδόρον τὸν Ἴστρον γεφυρῶσαι, κιβώτιον τεκτήναντα πρὸς προθεμελιώσεις, μῆκος ποδῶν μὲν ἑκατὸν καὶ εἴκοσι σὺν τούτοις, εἰς πλάτος δ' ὀγδοήκοντα. (ed. Kiessling 1826: 44)
>
> (It is said) that Apollodorus bridged the Ister (Danube) by building wooden formwork (*kibótion*) for the foundation, 120 feet long and 80 feet wide.

If the dimensions are correct, these were probably not floating barge forms, which in any case would not have provided a secure foundation in a flowing river. Apollodorus may have pounded planks into small portions of the riverbed in sequence, to provide a series of wet or dry working areas, according to the type of mortar employed, then laid the concrete or stone block foundation. The remains of the bridge show that it was about 1135 m long. By blocking only a part of the channel at a time, the need to divert the entire flow of the river was avoided. A passage in the tenth-century author Mukaddasi describing the construction of the harbour fortifications in Acre/Akko suggests that this technique of floating box forms survived for centuries after Procopius wrote (Hohlfelder 1988: 60), long after the formula for marine concrete had been forgotten.

## 2.17. Inscriptions

[31] *CIL* 10.1781. *Lex parieti faciundo Puteolana* 2.16–21, 105 BC. Specifications for the construction of a wall.

> Eosq(ue) parietes | (17) margines omnes, quae lita non erunt, calce | (18) harenato lita politaque et calce uda dealbata recte | (19) facito. Quod opus structile fiet, in te[r]ra calcis | (20) restinctai partem quartam indito: nive maiorem | (21) caementa<<m>> struito quam quae caementa arda | (22) pendat p(ondo) xv, nive angolariam altiorem (unciis quattuor semuncia) facito. (Arangio-Ruiz 1943: vol. 3, p. 474).
>
> And those walls and copings that have not been plastered over, coat them properly with (a mortar of) lime and sand (*calce harenato*), smoothed, and whitewashed with moist lime. As for the construction material, put 1 part slaked lime (*calcis restinctai*) in 3 parts *pozzolana* (*terra*). Coarse aggregate (*caementam*) weighing more than 15 pounds when dry should not be used, nor corner blocks more than four and one half inches high.

As in the early passage from Cato's *De re rustica* (Passage 3), the mortar is referred to as "sanded lime", *i.e.* lime with (possibly) volcanic sand added. The three to one proportions are the same as those specified by Vitruvius (*De arch.* 2.5.1; Passage 6) for the mixes with *harena fossicia* in terrestrial structures. The specified sizes for *caementa* and corner blocks seem to correspond with examples seen at Pompeii (Wiegand 1894: 711–13). Given the location of the construction at Puteoli, the use of local pumiceous volcanic ash (*pozzolana*) is likely.

[32] *CIL* 10.3414 (=*ILS* 2871), first or second century. Epitaph of L. Iulius Valens, *caementarius* with the fleet at Misenum.

> D(is) M(anibus) | L. Iuli Valentis dupl(icarii) | caementari(i) ex clas(se) pr(aetoria) | Misen(en)s(i), natione Syri. | Vixit an(nos) xl. Mil(itavit) an(nos) xxii. | Flavia Marina uxor | viro bene merenti.
>
> To the shades of Lucius Iulius Valens, *duplicarius*, concreting engineer (*caementarius*) with the Praetorian fleet at Misenum. Syrian by birth. He lived 40 years; he served 22 years in the military. Flavia Marina his wife (dedicated this) to her well-deserving husband.

There are numerous concrete harbour structures around the northern shores of the Gulf of Naples, many of them associated with the massive installations of the Praetorian Fleet at Misenum. This first or second-century tomb inscription was found in the harbour area. Lucius Iulius Valens was a *caementarius* – “concreting engineer” or “worker in concrete” – with the *Classis Praetoria Misenensium.* Since he was a *duplicarius*, a soldier receiving double salary because of a special skill, Lucius might have been some sort of engineer specializing in maritime concrete construction for the fleet’s home port. He was possibly a member of the *factio artificum* mentioned in another inscription at Misenum (*CIL* 10.3479 = *ILS* 2857). An inscription probably from this same locality (*CIL* 10.3392= *ILS* 2872) mentions a C. Vettius Gratus who was an *architectus* with the fleet, but this term is more general than *caementarius* and cannot necessarily be connected with concrete work. The profession of *caementarius* is also mentioned on a tombstone at Totia / ‘Ain Jannet in Tunisia, an inland settlement (*AE* 1997: 01591).

# Chapter 3

# History and Procedures of the ROMACONS Project

*C. J. Brandon and R. L. Hohlfelder*

## 3.1. History of the project (R. L. Hohlfelder)

An enigmatic archaeological find in Sebastos, the submerged harbour of King Herod's city of Caesarea Palaestinae, on the coast of Israel, was the genesis of the Roman Maritime Concrete Study (ROMACONS). During the survey and excavations conducted by the Caesarea Ancient Harbour Excavation Project (CAHEP) in the early 1980s, a large concrete block *ca.* 11.5 m × 15 m × 2 m was discovered *ca.* 300 m off the current coastline in an archaeological zone designated as Area G (Fig. 3.1; Raban 1989: 127–30). This massive block appears to have been placed at the terminus of the northern breakwater to serve as a pier head or stabilizing element for this structure at its vulnerable seaward end. The size and location of the block immediately raised questions about the method of transport of the formwork and materials, and the methods by which the block was created. Had it been transported from shore, or was it laid where it was found within a floating form? In his long descriptions of the harbour (pp. 29–31, Passages 20–21), Josephus mentioned large stones as part of the structure lowered into the sea, but not concrete blocks. There were, in fact, no archaeological antecedents for several of the types of blocks found at the site.

Oleson, one of the CAHEP co-directors, took a sample of the mortar from this concrete structure back to Canada for scientific analysis at the University of Victoria. An astonishing result was identification through trace element analysis of the possible source of the pumiceous volcanic ash used to make the mortar for the marine concrete: an undetermined but vast amount of this volcanic ash had been shipped *ca.* 2,000 km from deposits around the Bay of Naples to the eastern shore of the Mediterranean (Branton and Oleson 1992a–b). This discovery in turn raised many new questions about the technology of harbour construction in the early Roman empire, some of which could be answered by further underwater investigations at Sebastos, while others could only be addressed by exploring other harbours that had formed the maritime infrastructure of the Roman Empire. This revelation about a long-distance trade in pyroclastic rock for concrete, in combination with the previously unknown method of placing concrete blocks in floating forms, ultimately led to the list of ROMACONS research questions outlined above (pp. 6–8).

The research design for CAHEP's underwater explorations at Sebastos was redefined to include a systematic search for other examples of similar blocks or any other structural elements that were made of Roman maritime concrete. Was

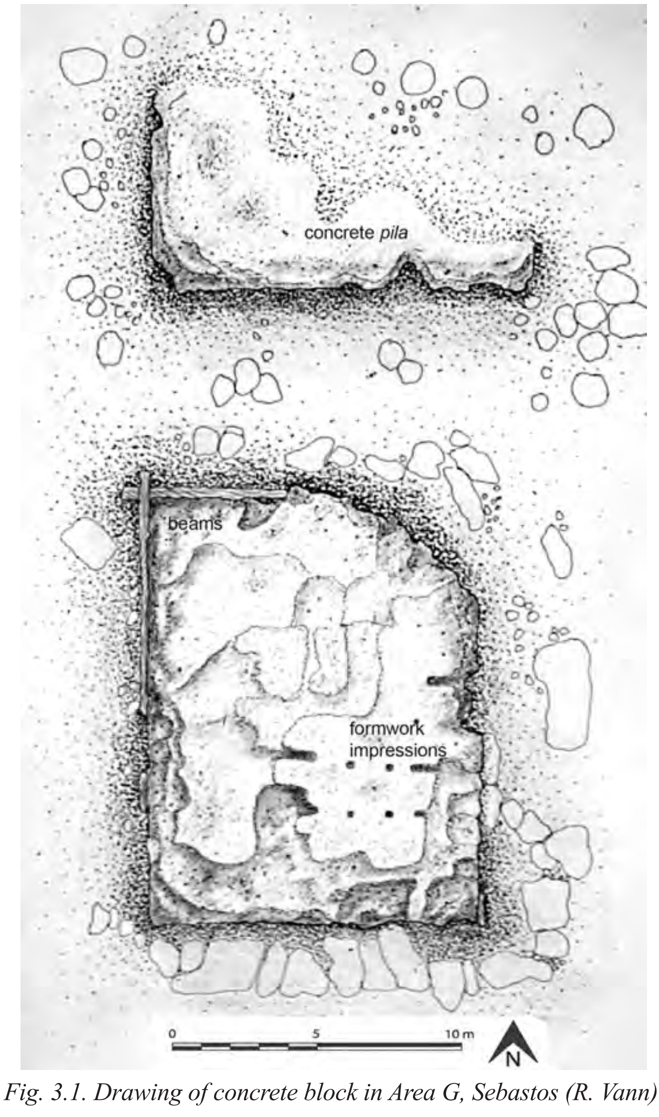


*Fig. 3.1. Drawing of concrete block in Area G, Sebastos (R. Vann).*

this block the only one in the harbour, or were there others, and if so, did they too contain pyroclastic rock imported from the Gulf of Naples? If so, how was this raw material brought in over such great distances. Furthermore, why did the builders of Herod's harbour not use closer sources of volcanic pozzolanic materials, such as the ash forming the island of Santorini, 1,000 km away (see pp. 154–55, 158). Was the presence of this Italian volcanic ash evidence as well for the involvement of Roman engineers or contractors in building the harbour installations of Sebastos, or had the new technology somehow already spread to Herod's own builders in the eastern Mediterranean? These, and other questions, broadened the focus of the underwater investigations in unexpected ways, as so often happens in archaeology. Answers to some of the broader questions that transcended the data from the Sebastos complex could only come from a pan-Mediterranean study of Roman imperial harbour installations and other maritime structures, such as fish-ponds and river constructions.

Oleson ended his affiliation with CAHEP's fieldwork in 1985 to concentrate on his excavations at Humayma in Jordan, while Hohlfelder continued to serve as a co-director of CAHEP for five more years. No significant progress occurred during the decade of the 1980s regarding the formation of a more expansive study of the use of Roman concrete in marine installations, but the idea for such a project stayed alive. In 1990 Chris Brandon joined forces with Avner Raban, the former director of CAHEP, to pursue investigations in the submerged ruins of Sebastos under the aegis of new international consortium called the Combined Caesarea Excavations. Brandon and Raban documented many concrete blocks scattered throughout the ruins of the southern breakwater and several more massive ones adjacent to its terminus that had characteristics different from the one found in the 1980s. Brandon's numerous publications of these finds have greatly enhanced our understanding of how Roman builders expanded the technology of maritime concrete construction beyond the techniques mentioned by Vitruvius in his *De architectura* (5.12; pp. 20–23; see esp. Brandon 1996, 1997a–b, 1999, 2001, 2011; Brandon *et al.* 1999). Moreover, Brandon's eagerness to undertake a comprehensive study of Roman harbour engineering in the Mediterranean became the catalyst for the formation of ROMACONS.

In the late 1990s Brandon, who had worked with Hohlfelder in the underwater surveys of the harbours of Paphos (Cyprus) and Aperlae (Turkey), broached the idea of initiating a project to explore as many Roman concrete harbour installations as possible to address specifically some of the questions raised by the earlier explorations at Sebastos and to expand more generally our understanding of the history and technology of Roman concrete engineering in the sea. Oleson was invited to participate in the project, and he joined forces to plan the Roman Maritime Concrete Study (ROMACONS). This project was designed as an extensive, multi-year effort involving pioneering techniques of sample collection and unparalleled laboratory testing of the samples recovered. The target structures were Roman concrete constructions that had originally been built in or adjacent to the sea. They might at present be located on land (because of coastal uplift), at the interface of land and sea, or completely underwater. The three co-directors agreed that the key to a successful project was the integrity and consistency of the samples. This goal required that the same equipment be used to collect large, undamaged core samples from Roman marine structures throughout the Mediterranean, that uniform testing protocols be followed to determine the chemical, physical, and mechanical properties of all the samples, and that if possible all scientific analyses be conducted in the same world-class laboratory and by the same personnel.

In 2001, Brandon, Hohlfelder, and Oleson met in Victoria B.C. and agreed to form ROMACONS and begin a systematic study of maritime concrete and its employment in Roman construction in the sea. Reaching agreement on the mission, the sites that ideally should be included in its purview, the shared and individual responsibilities of the three principal investigators, and other administrative matters was relatively easy, since all three had been thinking about such a research project for years. The most daunting task, however, lay ahead: acquisition of the considerable funds necessary to begin the initial fieldwork and to support the required laboratory facilities and scientific personnel. Ideally, we hoped to find a sponsoring agency to make what in many respects was an open-ended commitment for an indeterminate, but significant period of time. Oleson and Hohlfelder both had been successful in the past in obtaining financial support for their various projects, but neither had undertaken fund raising for such a complex and lengthy project. In the end, the fieldwork lasted seven years, and the culminating series of analyses and preparation of the final publications another four.

An extraordinary confluence of circumstances occurred the same year that enabled the dream of ROMACONS to become a reality. Hohlfelder was spending the spring at the American Academy in Rome as a visiting scholar. In conversations with the then director, Lester Little, the ROMACONS project came up in the context of Hohlfelder's future research plans and the Academy's long-standing interest in Roman maritime history and archaeology, dating back to F. E. Brown's excavations at the coastal city of Cosa in the 1950s and 1960s, research that had resulted in a conference and then a publication (D'Arms and Kopff 1980). Dr. Anna Marguerite McCann continued this tradition with a survey of the harbours at Populonia, Cosa, and Pyrgi in 1968–1973. While Little expressed great interest in ROMACONS, particularly in its interdisciplinary focus and its pan-Mediterranean scope, he indicated that it was not possible for the AAR to fund such an undertaking. He did, however, willingly agree to endorse the project and to help our efforts in any way, including supporting our applications for permits to begin our fieldwork at Portus. This site was the maritime gateway for imperial Rome, arguably the most important Mediterranean harbour during its long existence and the logical place for ROMACONS to begin its fieldwork. Furthermore, he indicated that his brother-in-law, Piero Gandini, worked for the CTG Italcementi Group, one of the largest cement companies in the world. It was possible that he might be personally interested in our project and, if so, might be able to encourage his company to provide financial and technical assistance. Little indicated that he would not be able to approach Mr. Gandini officially, but would find some opportunity at a family gathering to raise the topic informally. Hohlfelder thanked him profusely for any help that he might be able to provide and indicated that if Mr. Gandini and Italcementi were interested in ROMACONS, he would fly to Bergamo, where the research arm of this international company is located, to discuss ROMACONS in detail and to answer any questions anyone might have.

Shortly after Christmas in 2001, Hohlfelder received a call from Little indicating that Italcementi had expressed interest in the project. He immediately flew to meet Mr. Gandini as well as Dr. Luigi Cassar, director of the Italcementi research facility, and other members of the management team. From this very successful meeting, Italcementi agreed to sponsor ROMACONS and to provide funds for acquiring or making the unique drilling equipment that we would need for collecting our core samples. Even more important, Dr. Cassar agreed to have his research scientists work with us to develop a protocol of comprehensive analysis and study of our samples. The director of the Bergamo facility since 2005, Dr. Enrico Borgarello has enthusiastically continued and expanded Italcementi's support of ROMACONS, including a generous subvention for this publication. Throughout the 2000s, Drs. L. Bottalico, E. Gotti and R. Cucitore have supervised and conducted the testing of our material, with Dr. G. Vola assuming a leadership role in recent years. Dr. Marie Jackson joined our team in 2009 and worked primarily with Vola in Bergamo expanding the tests conducted on the ROMACONS cores before moving on to the University of California, Berkeley where her analysis of our samples continues.

With the guarantee of substantial funding from Italcementi, Oleson was able to obtain additional financial support from the Social Sciences and Humanities Research Council of Canada, the University of Victoria, and the Loeb Classical Library Foundation to support the collection and study of ancient cores from eight sites in Italy and from four elsewhere in the Mediterranean. These sources funded the personal travel expenses associated with our fieldwork, and some analytical testing, while Italcementi funded the preparation and shipment of heavy equipment to and from the coring sites. Our fieldwork was not as extensive as we had first envisioned, primarily because contemporary political realities made it impossible to conduct coring in Libya, Tunisia, and Algeria, but also because of the logistical and customs difficulties of shipping a ton of equipment into countries sensitive to contemporary security issues. Our inability to take cores at Carthage was particularly disappointing, given the importance of the harbour during the empire, and the similarity of the mortar and coarse aggregate (based on gross visual inspection) to that found in Central Italy. The Tunisian Department of Antiquities made no response to our proposals.

A ROMACONS survey showed that Greece had far fewer Roman concrete harbour installations than we had envisioned, since sites such as Anthedon and Mavra Litharia turned out to be composed of extensive deposits of beach rock rather than concrete (Figs. 6.63–65). Nevertheless, in 2007 we were able to take several cores at the small Roman harbour of Chersonesos (pp. 89–93, *cf.* Brandon *et al.* 2005). There are numerous Roman harbour sites in Turkey with structures in maritime concrete, but it is difficult to obtain permits for any kind of archaeological work. Thanks to the kind invitation of Dr. R. Yagçı, director of excavations at Soli/Pompeiopolis, we were able to take cores at the submerged Roman harbour there in 2009 (Brandon *et al.* 2010a–b). This work was very nearly subverted by superfluous customs investigations and shipping delays. Our negotiations to study the mortar/concrete structures uncovered during the salvage excavations of the massive Late Antique harbour of Yenikapı, Istanbul were unsuccessful. This failure was particularly unfortunate since the ancient formwork in that harbour seems to include the only known surviving example of the double-walled caisson described by Vitruvius, which provided a dry area below sea level for the placement of concrete mixed without the addition of pumiceous ash pozzolans. The ancient harbour of Massalia (Marseilles) did have Roman concrete structures, but modern construction has obscured these features for the foreseeable future (Hesnard 1999, 2004). Other obvious sites that might have yielded important results were also unavailable for a variety of reasons. In short, our selection of sites was in some cases governed by availability rather than by relative importance, although in the end we were able to take cores from three of the four major Roman emporia: Portus, Alexandria, and Sebastos. With the exception of a fish-raising pond (*piscina*) at Santa Liberata, we did not core secondary maritime structures, such as the numerous fish-ponds along the coast of Toscana, Lazio, and Campania. Along with riverine structures such as bridge supports, they proved too numerous and scattered to include in our limited time in the field.

Nevertheless, the ROMACONS fieldwork conducted from 2002–2009 in Italy, Greece, Turkey, Egypt, and Israel did result in the collection of 36 cores from 11 separate sites around the Mediterranean (Fig. 3.2), totalling 63.55 linear m of Roman maritime concrete (Hohlfelder *et al.* 2008, 2011; Oleson *et al.* 2011a). This book presents the results of the team's historical, archaeological, and scientific analysis of segments of this database, of issues associated with the cores, and with Roman marine concrete in general. The authors hope that it fulfils in some way the promise of its title and provides a incentive for future investigations relating to its general topic by those interested in the history and technology of Roman concrete engineering in the sea. There is more to be learned from the cores collected by ROMACONS and about the main

*Fig. 3.2. Map of the sites cored by ROMACONS, 2002–2009 (black dots), along with other sites mentioned in the text (white dots) (Will Foster Illustration).*

theme of this report, and we hope that scholars in the future will make use of our data and of our remaining samples to advance the study of Roman maritime concrete. There seems to be a permanent home for the remaining core samples at CTG Italcementi in Bergamo.

## 3.2. Coring equipment and procedures (C. J. Brandon)

Sampling Roman concrete, especially Roman maritime concrete, can be problematic. The remains of Roman maritime concrete infrastructure might now be landlocked, or lying on a shoreline where their outer surface has been affected by weathering, erosion, and environmental pollution. The structures can also be partially or fully submerged and consequently covered in marine biological encrustations, including algae, seaweed, sponges, and worm casts, all of which have altered the surface of the concrete. In order to sample unaffected concrete, it is necessary to get below this disturbed outer layer, which can be up to 15 cm thick. Collecting samples with a hammer and chisel is very destructive, since a relatively large area of the surface has to be hacked off in order to collect even the smallest fragment of mortar, and it is even then only possible to obtain material from areas that are closest to the outer layers. Furthermore, extraction of a sample by hammering significantly alters its mechanical characteristics. The interior of a block of Roman concrete remained inaccessible until relatively recently, when developments in coring technology presented the opportunity taken by ROMACONS.

An added problem is that Roman concrete is an exceptionally heterogeneous cementitious material. It includes particles of lime and pumiceous volcanic ash that vary considerably in size. In addition, the irregular chunks of coarse aggregate (*caementa*) vary in size and composition and can be unevenly distributed within the concrete mass. Consequently, it was necessary for the ROMACONS team to develop techniques for extracting several samples from deep within a particular concrete block in order to obtain reasonably representative results. The extraction of a 9 cm diameter core from the entire height of a concrete block is the equivalent of the excavation of a sounding through an intact cultural deposit, although the concrete belongs to a single historical moment. Finally, since these ancient structures are inevitably important and highly visible cultural heritage monuments and their conservation and protection are a concern, the sampling strategy is an important and sometimes controversial issue.

***3.2.1. Coring Equipment***. In 1999, with the assistance of the University of Haifa and University of Tel Aviv, Brandon took concrete samples from the remains of the ancient harbour structures at Caesarea in Israel. A Desoutter Model 183 pneumatic, handheld rotary drill was fitted with a 50 mm diameter, diamond tipped, 1 m long core drill bit. While this equipment recovered samples from just below the marine concretion on the surface of a concrete block, it was not possible to penetrate deeper into the interior. The main problem was that the drill lacked a water feed to lubricate the drill bit and core. Using the same pneumatic supply from a compressor mounted on a boat moored over the site, a Kawasaki pneumatic hammer drill fitted with a 50 mm diameter steel tube with a hardened end was able to penetrate up to 300 mm into the concrete through percussion drilling. While percussion drilling was in this instance more successful than spin drilling in penetrating the concrete, it was, however, difficult to extract intact samples from the barrel of the drill bit. Nevertheless, in October 2001, five samples of mortar were successfully collected from the Roman harbour of Chersonesos in Crete by means of percussion drilling. Five 30 cm long hardened stainless steel tubes, 3 cm in diameter were driven into the Roman concrete with a 2 kg lump hammer (Fig. 3.3). The mortar samples were removed from the tubes laboriously by cutting each tube along its length with a hacksaw.

Based on the experience gained at Caesarea and Chersonesos, ROMACONS chose for its coring project standard diamond core drilling equipment, as used by the construction and civil engineering industries. The cores taken by this procedure provide a completely new perspective of Roman maritime concrete structures. Previous methods of sampling involved either smashing fragments off the outside of a structure with a heavy hammer and chisel, salvaging interior samples from a structure being demolished to make way for a modern construction project, or percussion drilling with steel tubes. All these techniques failed to produce complete samples, and the mechanical characteristics of the concrete could be considerably altered in the process of collection. Surface-collected samples, in particular, cannot be representative of the whole block, and their collection requires the removal of a significant amount of the protective marine growth, involving the risk of long-term damage to the structure. Core sampling, on the other hand, despite the apparently more intrusive character of the process, preserves the appearance and structural integrity of the ancient remains. Once the core sample has been extracted, the only visible alteration is a 10 cm diameter hole, which is immediately filled with sea sand and sealed with a reinserted plug of the original surface material set in a lean lime and *pozzolana* mortar.

*Fig. 3.3. Brandon collecting hand cored mortar sample, Chersonesos.*

Coring concrete underwater involves the use of a pneumatic or hydraulically powered drill as opposed to the electrically driven machine that is typically used on terrestrial sites. The drill motor must be mounted on a rack and pinion rail that is secured to the concrete, and it has to be powerful enough to drill through the whole height of the concrete block being cored. Most importantly, the drill must have a water supply to keep the cutting edge of the drill bit clear of debris, even when drilling underwater. The need for a relatively powerful machine capable of drilling through the whole height of a block of Roman concrete means that a hydraulic drive system is required as opposed to a pneumatic one.

Xcalibre Equipment Ltd., a UK based engineering company involved in the design and manufacture of specialist diamond drilling equipment, provided Brandon with initial operator training in hydraulic diamond core drilling equipment, and advice on the specifications for the machinery that was required for the sampling envisaged. Subsequently, CTG Italcementi introduced Brandon to Cordiam S.r.l., a specialist supplier of drilling equipment that has been designing and producing diamond core bits and fittings in Guanzate, near Como, since 1972. Cordiam, through CTG Italcementi, supplied the entire suite of core drilling equipment used by ROMACONS in the fieldwork seasons from 2002 through 2009 and also provided training in the use of the machinery.

*Drill bit.* A wide array of core drill bits is used in civil engineering to cut through stone or concrete. The bits that Cordiam manufactures include:

- CORMET: a bit that has hard metal teeth braze-welded onto the steel rim of the core bit; suitable only for soft materials (Fig. 3.4).
- CORPAX: a drill bit that has PCD (polycrystalline diamond) teeth set onto the hardened rim; suitable for soft to medium-hard materials (Fig. 3.5).
- CORSIN: a drill bit with a PCD tooth (polycrystalline diamond) surface set; suitable for cutting medium-hard materials (Fig. 3.6).
- CORSET: a drill bit with natural diamonds set on the cutting surface; suitable for cutting soft and medium-hard materials, and hard materials that are not fractured (Fig. 3.7).
- CORDIM: a drill bit with synthetic diamond powder; suitable for cutting hard and fractured materials (Fig. 3.8).

Cordiam provided ROMACONS with CORSIN, CORSET and CORDIM drill bits, although only the CORSET and CORDIM heads actually proved effective in drilling into Roman concrete.

*Fig. 3.4. CORMET drill bits with hard metal teeth (Photo: Cordiam).*

The initial series of ROMACONS cores were drilled with a CORDIM bit. Following several instances where the core fractured in situations where there were significant differences in hardness between the mortar and the aggregate, a CORSET bit was used. Although slower in penetrating the concrete, the CORSET head became stuck less frequently. It cut a slighter wider shaft and narrower core, as the diamonds were set on the sides of the bit as well as on its lower edge.

*Core characteristics.* For the ROMACONS project we decided to produce as our standard sample a *ca.* 9 cm diameter core, as it has predictable characteristics and can be subjected to a recognized standard set of civil engineering tests. The outside diameter of the drill barrels supplied by Cordiam is 102 mm, and the resulting core diameters are around 88 mm, depending on which bit is selected (Fig. 3.9). This method is ideally suited for modern concrete, which has a uniform consistency and relatively small aggregate. Roman concrete, an exceptionally heterogeneous cementitious material, includes particles of lime and pumiceous volcanic ash that vary considerably in size. In addition, the coarse aggregate chunks vary in size and

Fig. 3.5

Fig. 3.6

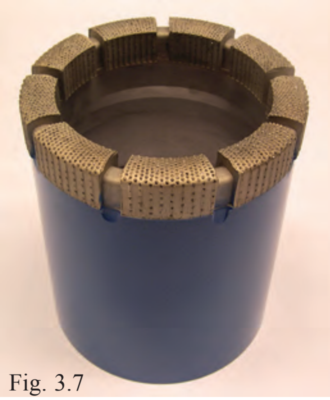


Fig. 3.7

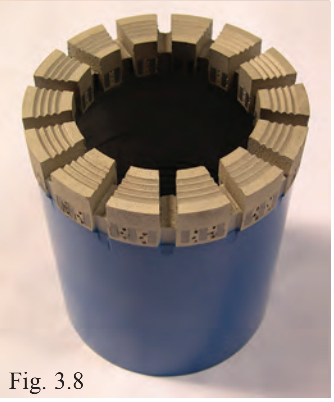


Fig. 3.8

*Fig. 3.5. CORPAX drill bit with PCD (polycrystalline diamond) teeth.*
*Fig 3.6. CORSIN drill bit with a PCD tooth (polycrystalline diamond) surface set.*
*Fig. 3.7. CORSET drill bit with natural diamonds set on the cutting surface.*
*Fig. 3.8. CORDIM drill bit with synthetic diamond powder (Photos: Cordiam.)*

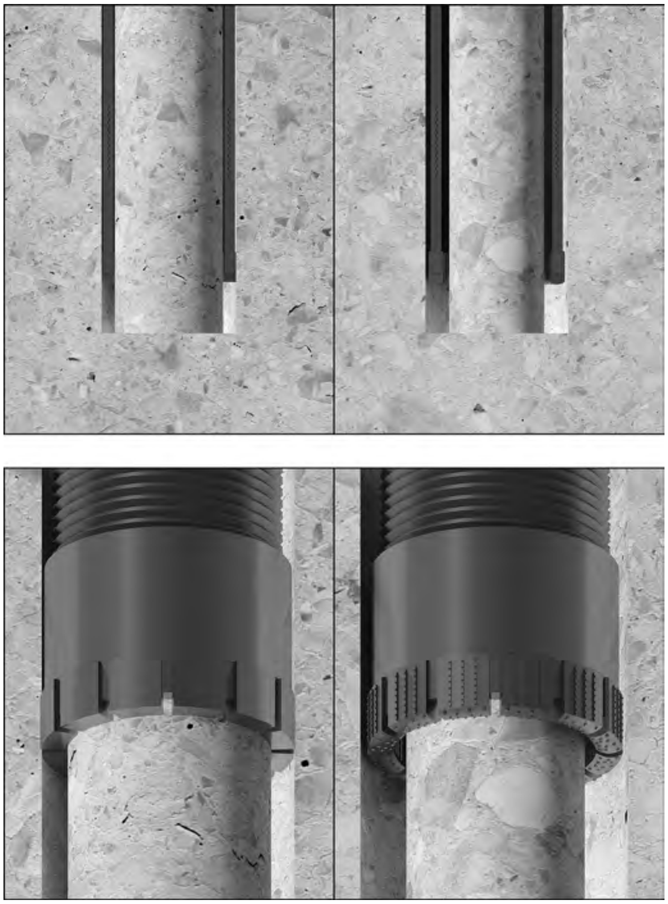


*Fig. 3.9. Corset and Cordim bits and resulting cores (Will Foster Illustration).*

*Fig. 3.10. Nine centimetre diameter core samples prepared for testing (Photo: Italcementi).*

composition and can be somewhat unevenly distributed within the concrete mass. Compressive testing cannot be carried out unless uniform sections of mortar are recovered that have an aspect ratio of diameter to height of 1:2. Samples need to be selected carefully to ensure that the large aggregate does not induce shear failure along interfacial zones with the pozzolanic mortar. As a result, longer cores have to be extracted than would be the case for modern concrete, which employs much smaller and more uniform aggregate (Fig. 3.10). For the same reason, it is also often more difficult to extract an intact core from Roman concrete structures.

*Continuous coring system.* At the outset of the project, a continuous coring system was selected in order to sample the complete stratigraphic section through a concrete block, providing the longest possible lengths of intact cores (Fig. 3.11). In this method, extension drill tubes are screwed one onto another up to a length sufficient to extract a complete core from top to bottom of the structure, which ideally was only extracted when the structure had been completely penetrated.

The drilling bit or head, approximately 15 cm long, was screwed on to the core catcher, a 20 cm long, 10 cm diameter steel tube with an internal split sprung sleeve with roughened ridges on the interior, designed to clasp the concrete core as the barrel is being withdrawn from the concrete mass. The bit and core catcher are screwed onto 1 m or 50 cm long threaded steel tubes that can be screw-fitted one to another incrementally as the drill penetrates the concrete. A final section, which connects the line of drill pipes to the drill drive, is only 10 cm long, in order to allow easier accommodation of the longer tubes at the beginning of the coring process. We used a set of 6 × 1 m long tubes and 1 × 50 cm long sections that theoretically allowed for a maximum concrete core 6.65 m long to be extracted, when taking into account the drill bit, core catcher and the height that the drill is mounted above the surface of the concrete. The longest core extracted was SLI.2004.01 from the outer *pila* at the fish-pond at Santa Liberata, 5.9 m long (Fig. 3.12). Although the Santa Liberata core was cut and extracted without difficulty, we found that as the number of drill pipes increased, so did vibrations and the apparent strain on the hydraulic motor.

In practice, the continuous coring procedure was not always adopted, and the cores were often extracted in 1 m long sections or whenever the drill jammed, to prevent loss of material. The core frequently fractured in situations where there were significant differences in hardness between the mortar and the aggregate, or when the rig was not rigidly fixed to the concrete and vibrations or the alignment of the drill line caused the drill to bind. The only way to loosen the bit was to slightly back up the drill. This action, however, inevitably broke the core free from the mass of concrete, because the core catcher was clamped to the core. If the loose core length was not then removed and the drilling re-started, friction between the barrel and the core often started it spinning, and the softer mortar was gradually ground to a paste and washed away by the flushing water.

In addition, long lengths of concrete core proved too heavy for the core catcher to hold, so that the core slipped out as the

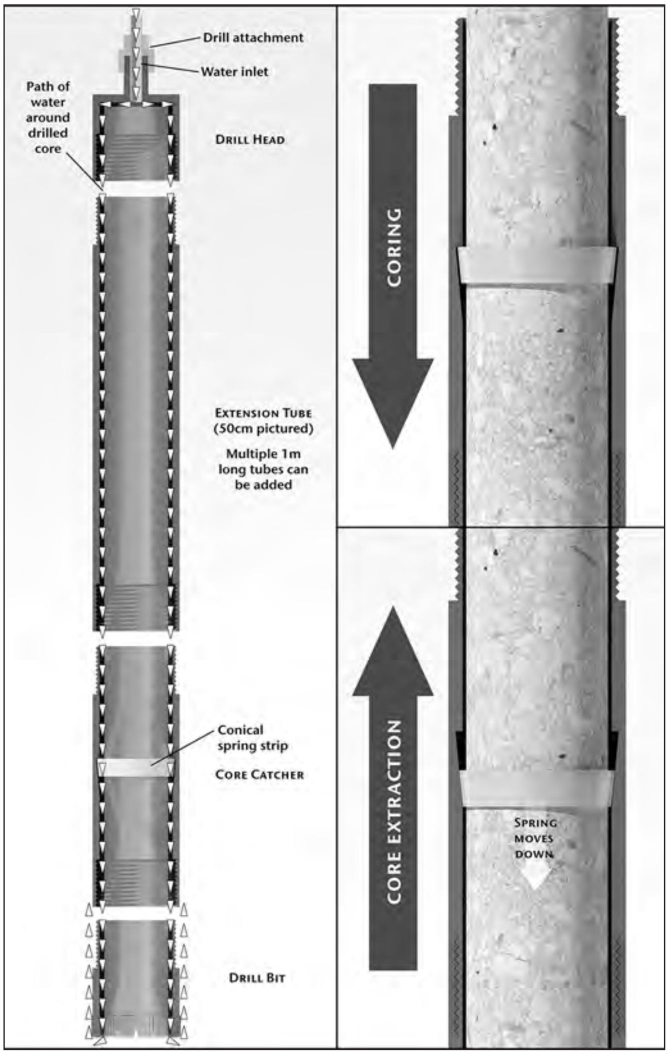


*Fig. 3.11. Continuous coring system (Will Foster Illustration).*

*Fig. 3.12. Santa Liberata core SLI.2004.01 with human scale.*

drill pipe was raised, particularly when a CORSET drill bit was used. Although extracting the cores in short lengths was slower and considerably more labour intensive, the technique did ensure that the cores were collected with very little loss or damage.

A key component of the coring procedure is a steel collar consisting of two semi-circular sections with terminations projecting beyond the circle. The two sections were placed around the drill tubes and bolted together, forming a clamp around the upper part of the tube or tubes still in the coring hole when the uppermost tube was unscrewed from the drive socket so that other sections could be removed or added. The collar and its projections prevented the tube sections in use from dropping out of reach down the drill shaft during this process. If a tube was to be added, the collar was fixed near the top end of the uppermost tube in the core hole, two large pipe wrenches were used to loosen the uppermost tube from the socket on the gearbox (Fig. 3.13), and the tube was lowered until the collar rested on the top of the core hole. The motor and gear box were then worked up to the top of the gear rack, another tube was screwed on to the topmost tube in the hole, and its upper end was screwed into the gear drive by running the motor slowly. The series of tubes was then lifted slightly, the collar removed, and coring resumed. The removal of tubes involved the same procedures in reverse.

*Stand-mounted drill.* A hydraulic powered Cordiam Hydro 25 drill motor provided sufficient power to drill through at least 6 m of Roman concrete at a rate of approximately 1 to 1.5 m per hour (Fig. 3.14). The motor unit was mounted on a type M60 drilling rack, with 1050 mm carriage travel, and was designed to be fitted to a scaffold frame or purpose-made stand (Fig. 3.15). The drill had a manual speed control that ranged from 10 to 1000 rpm and a swivel pipe connector for water feed. A constant flow of water of at least 150 litres / hour was required to cool the drill and to wash away the disaggregated concrete paste from the cutting face of the diamond bit, even when drilling underwater.

*Drilling Frame.* During the first field season in 2002, the drilling frame that held the rack to which the drill motor was fixed was a conventional tubular scaffold structure that had to be assembled from scratch at every site (Fig. 3.16). This inconvenient and time-consuming arrangement was subsequently replaced with a purpose-built stand made out of 48 mm diameter aluminium tubing welded together to form two triangular frames with horizontal cross rails that tied them

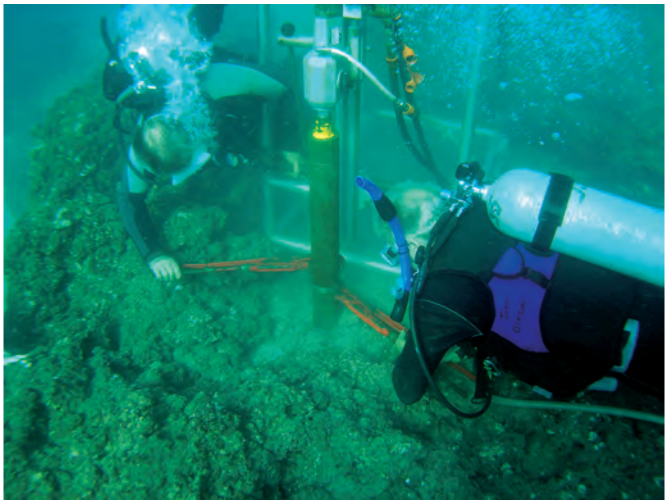


*Fig. 3.13. Use of wrenches to separate core tubes.*

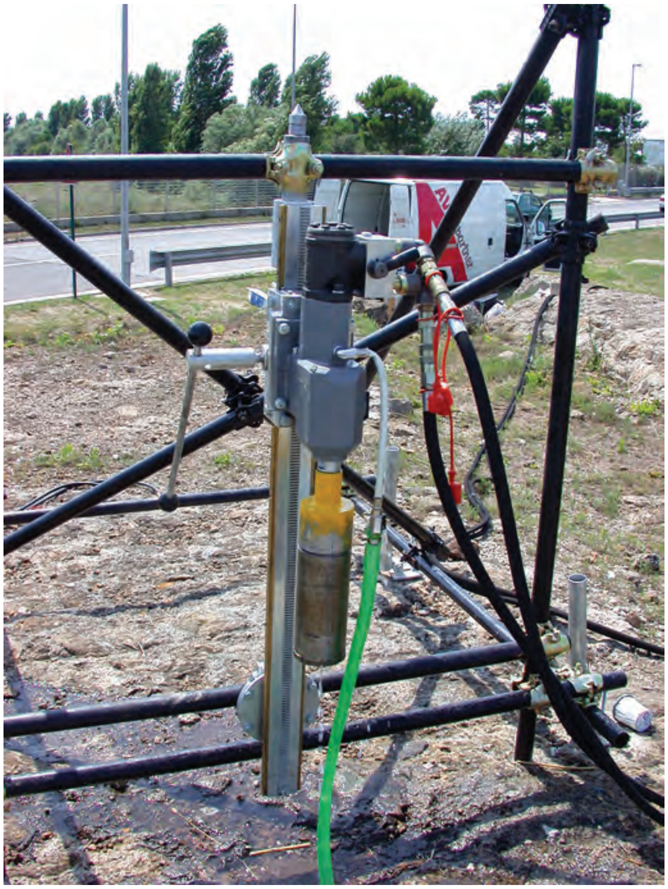


*Fig. 3.15. Drill motor unit mounted on Cordiam M60 rack clamped to scaffold frame.*

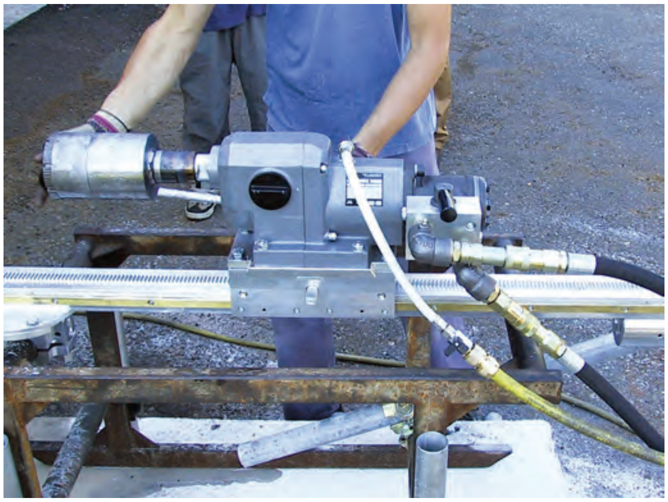


*Fig. 3.14. Cordiam Hydro 25 rotary drill motor unit.*

*Fig. 3.16. Frame constructed of iron scaffold tubes.*

together and provided better stiffness (Fig. 3.17). The bottom clamp of the M 60 drilling rack was set onto the upper of the two lower horizontal rails while the upper part was secured with a scaffold clamp to a horizontal tube fixed at the top of the frame. Underwater, the frame was nearly neutrally buoyant, and the pre-assembly saved significant time.

The custom-made feet comprised articulated base plates each with a slotted hole fixed with a hinged joint to an aluminium tube 48 mm diameter and 600 mm long that could be clamped securely to the triangular drilling frame with a conventional scaffold clamp (Fig. 3.18). At least four feet were required to fix the frame securely to the concrete, and where the surface of the block was exceptionally irregular sometimes five feet and on one occasion all six feet were deployed.

In order to be able to drill a core without jamming the bit, or at least to reduce the instances of jamming and thus to have a better chance of obtaining a core with minimal breaks or loss of material, it was essential to have the drill rack immobile and to eliminate vibration from the system. This requirement necessitated that the assembly be securely fixed to the concrete throughout the whole of the procedure for core drilling and extraction. Because of the friable and uneven surface of the concrete, it was necessary to get a fixing deep enough into the block to grip concrete unaffected by the sea and marine borers. A concrete anchorage assembly was specifically developed for the purpose, comprising a conventional 20 mm diameter expansion bolt with a 250 mm long 10 mm threaded rod (M10) and an 85 mm long × 20 mm diameter extension tube (Fig. 3.19). Washers ensured that as the nut was tightened the force was transmitted through the spacer tube and onto the shoulder of the expansion bolt. Further torque on the threaded rod caused the expansion head to expand deep within the concrete and become securely fixed into the pre-drilled hole. Loosening the bolt at the end of the coring operation and tapping the threaded rod enabled the expansion bolt to be withdrawn. Subsequently, the small holes were filled with a lime-sand mixture.

Fig. 3.17. Cordiam M60 rack clamped to purpose-made aluminium frame.

*Hydraulic power unit.* A mobile hydraulic oil pump powered by a petrol engine provided the power to drive both the stand mounted and hand-held drills (Fig. 3.20). The machine was rated at 11 Kw and delivered 30 litres per minute of hydraulic oil at 140 bar, or 21 litres per minute at 100 bar. Twin 25 m long reinforced hydraulic oil-filled flow and return hoses connected the pump to the drills with male/female quick release, self-sealing connectors (Fig. 3.21).

*Hand-held drill.* A hand held hydraulic core drill, model MAG15, was used with a 20 mm diameter diamond core bit to drill the holes for the expansion bolts that anchored the feet to the concrete (Fig. 3.22). As with the stand-mounted drill, the hand-held machine also had a water feed.

*Water pumps.* The importance of an adequate and continuous flow of water to diamond core drilling cannot be overstated. Without it, the drill bit becomes clogged and ineffective and does not cut into the concrete. In order to maintain the water flow either the drills need to be connected to a mains water supply through a hosepipe, or a dedicated water pump is required to provide the supply from the sea or another nearby source of relatively clear water. Two water pumps were available for the ROMACONS project, one was a submersible electric water pump served by a portable petrol motor powered

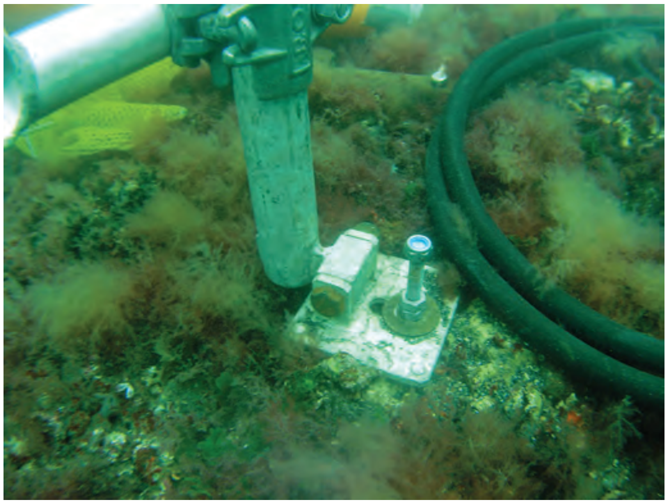


Fig. 3.18. Feet clamped to frame and fixed to concrete with an expansion bolt.

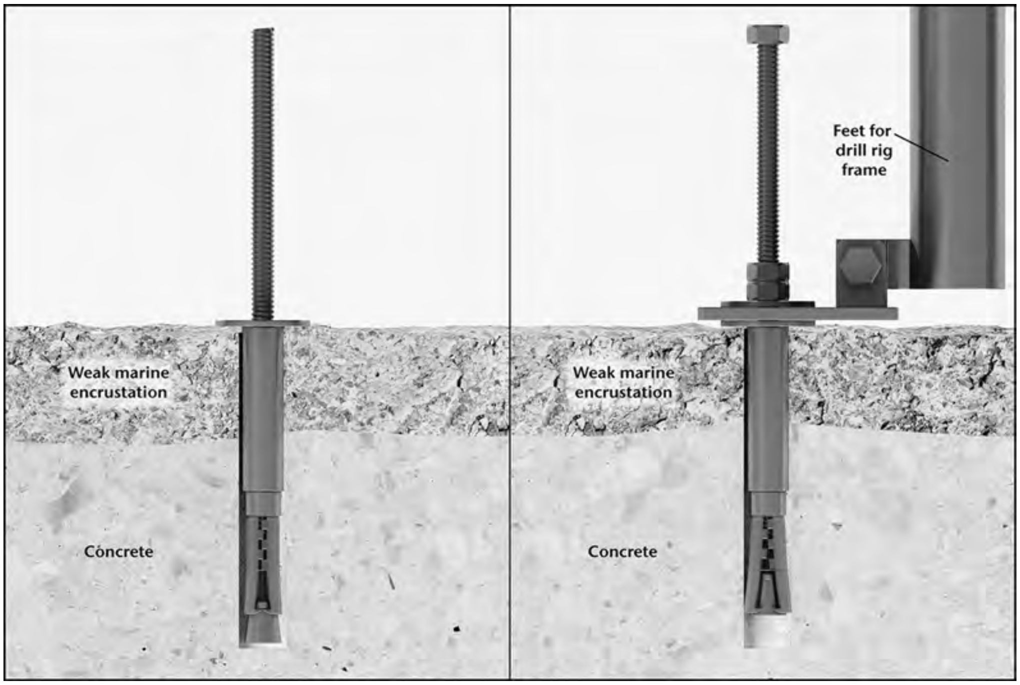


*Fig. 3.19. Diagram of expansion bolt assembly (Will Foster Illustration).*

*Fig. 3.20. Hydraulic fluid pump (foreground), electric generator (background).*

electrical generator (Fig. 3.23), and the other was a small, self-contained centrifugal Honda water pump system driven by a two-stroke petrol-driven motor. The submersible pump was particularly effective when coring had to be carried on in open water, using a small boat as a base for the machinery, the pump hanging over the gunwale. In this situation both the hydraulic pump and the electrical generator had to be mounted on a service boat. The divers usually worked from a separate boat.

*Fig. 3.21. Twin hydraulic hoses connected to the drill motor unit.*

*Fig. 3.22. MAG 15 hydraulic rotary hand drill.*

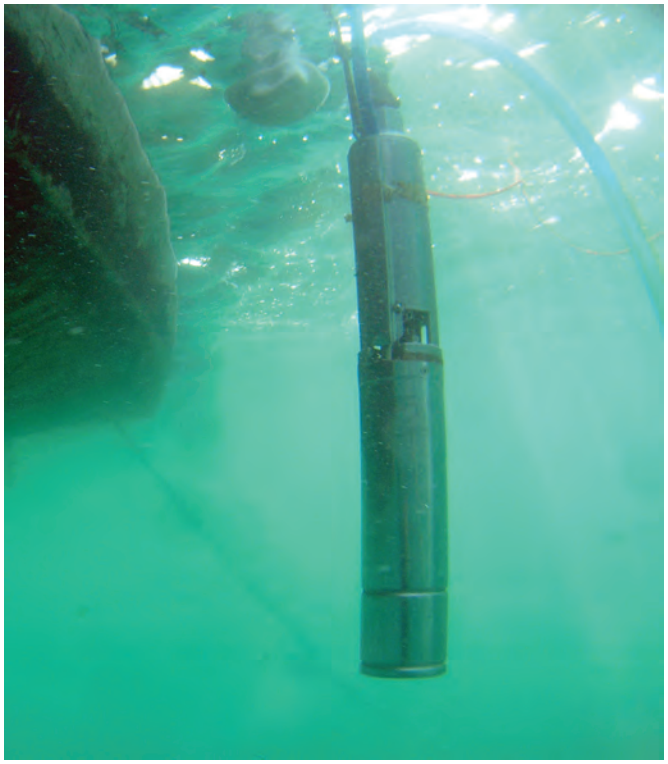


*Fig. 3.23. Submersible water pump hanging off tender boat.*

*Tools.* A set of tools comprising two 4-inch adjustable pipe wrenches, a 2-inch adjustable wrench, size 17, 19, and 22 ring spanners, screw drivers and hammers were kept together in a plastic mesh dive bag. These tools were essential for putting together the scaffolding tube frame and tightening the expansion bolts associated with the feet. We found that it was essential to carry the tools and small parts in plastic mesh diving bags, and to replace the tools in it immediately after use. Otherwise, even in conditions of good visibility our larger tools could disappear in the seaweed or sand adjacent to the coring site.

*Fig. 3.24. Drilling equipment being loaded into a rental van.*

*Fig. 3.25. Drilling equipment packed into a crate for air freight transportation.*

*Transportation.* The core drilling equipment was transported to and from each Italian coring site in the back of a van (Fig. 3.24). For the first few years of the project, the equipment was stored and maintained in CTG Italcementi's warehouse in Bergamo, then subsequently in their base near Brindisi. Air freight transportation was used for all field work outside Italy, with the exception of Greece, and the equipment was shipped in a purpose-built wooden crate, 1.5 m × 1.2 m × 1 m tall weighing 700 kg when fully loaded (Fig. 3.25). Boats were used for all the sites where the concrete blocks selected for coring were beyond the shoreline. These ranged from Guardia di Finanza patrol boats, to small fishing boats, rowing boats, and inflatable boats (Figs. 3.26–32, 34).

*Fig. 3.26. Guardia di Finanza patrol boat with support vessel at Santa Liberata.*

*Fig. 3.27. Small inflatable dinghy used to transport equipment at Santa Liberata.*

*Fig. 3.28. Fishing boat and zodiac used to transport equipment at Caesarea.*

*Fig. 3.29. Two small rental boats used for offshore coring at Baia.*

*Fig. 3.30. Small caique and rowing boat at site of CHR.2007.02, Chersonesos.*

*Fig. 3.31.* Princess Douda *in the Eastern Harbour of Alexandria.*

*Fig. 3.32. Dive boat at Alexandria.*

*Fig. 3.33. Coring on the* Molo Sinistro *at the Claudian harbour of Portus.*

*Fig. 3.34. Dive boat and equipment boat positioned over off shore coring site at Sebastos.*

***3.2.2. Coring Procedures***. At least twelve months before any fieldwork was undertaken, the sites were inspected to establish means of access, the methodology of the sampling and procedures for coring, requirements for any special equipment including boats and diving equipment, and an accessible source of flushing water. All the sites from which cores were taken are historical monuments of national heritage, and sampling the concrete required permits from the governing archaeological authority. Requests for such permits took time, and in most cases the process involved a local archaeological representative who actually secured or administered the permit. On the whole, we found that our proposals to core a concrete harbour structure in the sea aroused relatively little opposition. Proposals by another team to core terrestrial Roman structures, in contrast, were unsuccessful, apparently in part because of the greater visibility of the coring locations, along with a more highly developed sensitivity concerning architectural conservation on land (H. Goldsworthy, Oral Communication, 2005).

The concrete structures sampled varied from landlocked moles such as those at Portus (Fig. 3.33), where a van with all the drilling equipment could be driven right up to the sites being cored, to fully submerged off-shore concrete remains such as at Caesarea, where a boat was used for the working platform (Fig. 3.34), moored 300 m from shore. In each case consideration had to be given to a variety of issues.

- Mounting location of the hydraulic pump, as the hoses connecting it to the drills were only 25 m long.
- Method of transporting all the drilling machinery to the site, and if offshore, also the divers and diving equipment.
- If on shore and landlocked, how to obtain an adequate water supply for flushing the cores.
- Sea conditions and underwater visibility.
- Safety of both the operators and the general public.
- Arrangements for and availability of an inspector from the relevant regional antiquities authority.

Initially, the selected harbours or fish-pond were inspected to designate the locations likely to provide the most useful information about the concrete, while taking into account the practical feasibility of being able to take a core. Each block was carefully inspected to ascertain the most suitable coring point, checking for voids or fractures and identifying any relatively even platform where the frame could be placed and the feet set (Fig. 3.35).

In situations where the chosen site was landlocked or on a shoreline, it was sometimes necessary to manhandle the hydraulic pump to a location close enough to the drill to put it within reach of the hydraulic hoses. Very occasionally the van could be parked close enough to require only that the pump be off-loaded to the immediate vicinity for operation. Where the concrete was off shore, it was necessary to securely moor the boat containing the pump close to the block to be cored and in such a position that the hydraulic hoses were not put under any load when the boat swung at anchor.

Surprisingly, the actual physical work of setting up the core device underwater with SCUBA was easier than on land, because of the beneficial effect of buoyancy during the preliminary work of assembly, which above water required constant stooping and lifting. The transport and delivery of gear to a submarine coring site, however, was more complicated, and rough weather occasionally made it impossible to work. When working underwater, and especially in zero visibility as was the case in the eastern harbour of Alexandria, the tools were kept in a bag and were also secured with lanyards and kept close at hand on top of the concrete block.

The drilling frame was positioned and oriented to suit the core location and the profile of the concrete surface (Fig. 3.36). In situations where time was short or there was a likelihood that weather conditions would deteriorate, we selected coring locations that allowed us simply to rotate the frame 180 degrees after the first core and take a second core quickly, without the need to move all the equipment and reinstall the feet.

Prior to coring, any loose concrete and aggregate or marine growth was removed from around the foot positions and the actual site of the core with a hammer and chisel. Then the holes for the expansion bolts were drilled with the MAG 15 hand-held hydraulic drill fitted with the 20 mm diameter diamond drill bit, after connecting the water feed and hydraulic hoses (Fig. 3.37). A minimum of four articulated feet base plates were fixed to the concrete block with expansion bolts, equally spaced around the frame. In situations where the surface of the concrete was very uneven, or its consistency was questionable, additional feet were set, to a maximum of six (Fig. 3.38). After the bolts were set, the hinged leg of each foot was clamped to the base of the triangular frame with scaffold clamps and adjusted so that the uprights of the frame were vertical and the crossbars horizontal. After all the feet were loosely attached to the frame, a bubble level was used to level it, generally requiring adjustment to the height of the clamps on the legs (Fig. 3.39).

Once all the clamps had been tightened, the drilling rack was mounted onto the frame; the built-in lower clamp was fixed to the upper of the two lowest horizontal rails, while a scaffold clamp secured the top of the rack to a horizontal bar at the top of the frame (Fig. 3.40). The Cordiam Hydro 25 drill motor unit was slid into an inset track on the drilling rack carriage and locked in place with bolts (Fig. 3.41), and the flow and return hydraulic hoses were connected on either ends to the hydraulic pump and to the drill motor. This connection was most easily achieved with the pump's on/off levers set to an "on" or open position to ensure that the oil pressure was balanced. Once the hoses were connected at both ends, the switches were set to "off" before starting the pump motor.

Where the coring site was on land and the source of the water was from a spigot, a reinforced garden hose was laid


*Fig. 3.35. Selecting the core location at Santa Liberata.*

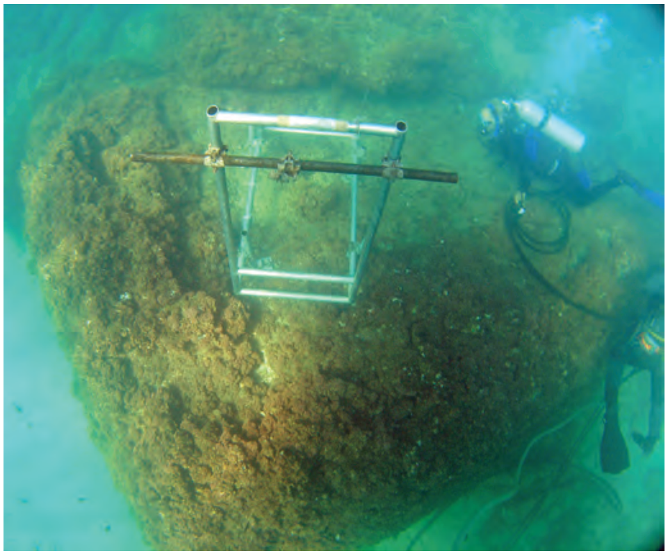


*Fig. 3.36. Drilling frame positioned on a* pila *at Caesarea.*

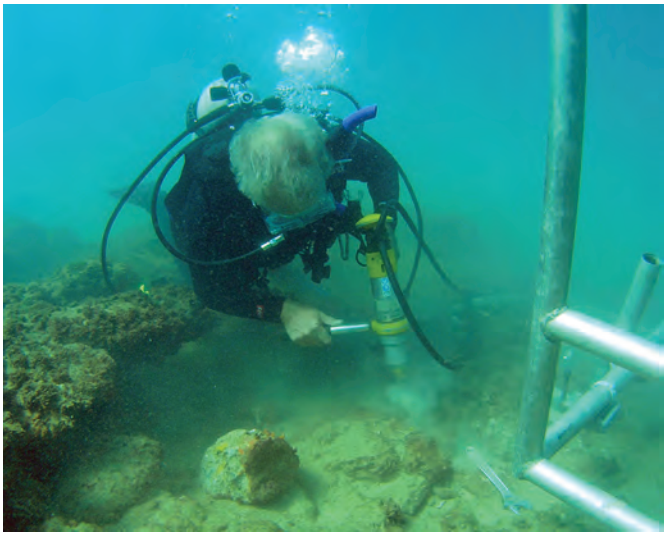


*Fig. 3.37. Drilling holes for the feet anchor bolts at Caesarea.*

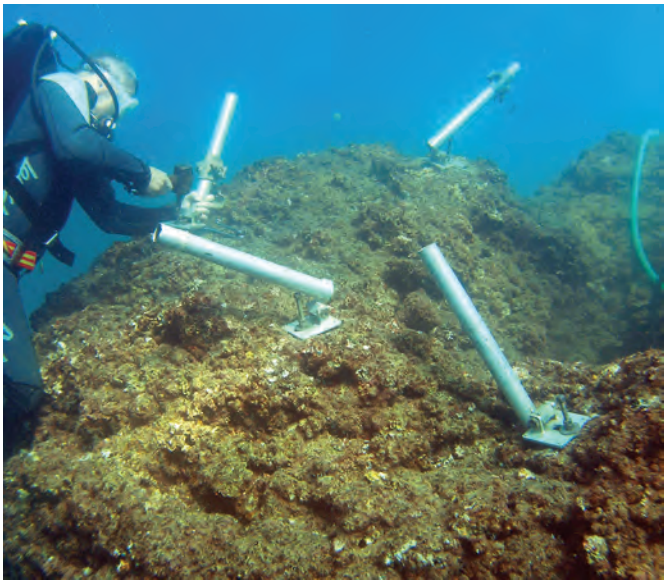


*Fig. 3.38. Frame feet being fixed to an uneven concrete surface at Caesarea.*

*Fig. 3.39. Clamping the feet to the frame at Caesarea.*

*Fig. 3.40. Cordiam M60 rack being clamped to the frame at Santa Liberata.*

*Fig. 3.41. Cordiam Hydro 25 rotary drill mounted on the M60 rack.*

out from the spigot to the drill, where it was connected with quick release fittings. When coring on the shoreline or in the sea, the electrically powered submersible pump was connected to the generator and submerged on a rope, with the outlet in the top connected by a hosepipe to the drill.

In starting to core, the CORDIM or CORSET diamond drill bit was connected with the core catcher assembly directly to the drill, the hydraulic pump re-started, the water turned on, and the flow checked. Initially a shallow hole was cut into the surface of the concrete with a short barrel to ensure that there was no deflection at the point where the bit first penetrated into the concrete. Once the first 10 cm had been cut, the drill was backed off and the initial surface plug of concrete and surface marine growth was carefully set aside for eventual re-insertion after removal of the core.

A 1 m long drill tube was then fitted to the drill motor, the core catcher and drill bit assembly were screwed onto the lower end, the hydraulic pump started, and the water turned on. The drill was cranked down the rack and pinion with a hand-operated windlass, maintaining a constant, even pressure. One operator turned the windlass while another monitored the water flow and adjusted the drill speed by means of a small handle on the drive assembly. As the bit cut into the concrete it was possible to sense the nature of the material being cored by the resistance to the lever and the colour of the flushing water, which carried away small particles of spoil (Fig. 3.42). The procedure that proved most reliable in collecting an intact core was to drill down into the concrete for the full length of the 1 m tube, then withdraw the tube, disconnect it from the drill and the drill bit and carefully remove the section of core secured by the core catcher (Fig. 3.43). The core sample was immediately put into a 100 mm diameter plastic tube and marked with the core number, sequence and orientation that were carefully and clearly noted on the outside of the tube.

The 1 m tube was re-connected to the drill bit and core catcher, and the assembly was inserted into the shaft with the collar clamp fitted to the top. Another 1 m tube, or in circumstances where the clearance was minimal, the 50 cm tube was screwed onto the tube in the shaft. The drill motor was connected to the tube, the collar clamp was removed, and the tubes were lowered to the bottom of the core hole. The motor was re-started and drilling continued down a further metre. The tubes were withdrawn section by section, using the collar clamp to prevent the remaining line of tubes and core from dropping down the shaft. The windlass-operated rack and pinion was used to raise and lower the drill tubes. It was important to watch the water flowing out of the core hole, even underwater, since the colour of the sediments and the rate of cutting provided information concerning the nature of the material being cored, whether an aggregate or mortar or lime. A decrease in resistance to movement of the lever and the appearance of fine sand in the flushing discharge indicated penetration through the base of the block.

After completion of coring, the location of the core was recorded, and if possible in situations where the drill had penetrated the base of the block, samples were taken of the sediments from the seabed beneath the concrete. The depth of the core was measured and recorded.

Once the core had been removed, the rig was dismantled and the core cavity filled with sand and rubble to within 0.5 m of the surface of the block. The retained top section of core was re-inserted and set with a weak mix of *pozzolana* and lime mortar (*ca.* 4:1) (Fig. 3.44). The expansion bolts were removed, the resulting holes were filled with mortar, and the site tidied up so that there was very little evidence that the structures had been disturbed. Within the region of Baia, at the request of the Soprintendente for Naples and Caserta, each core position was marked with a plastic label

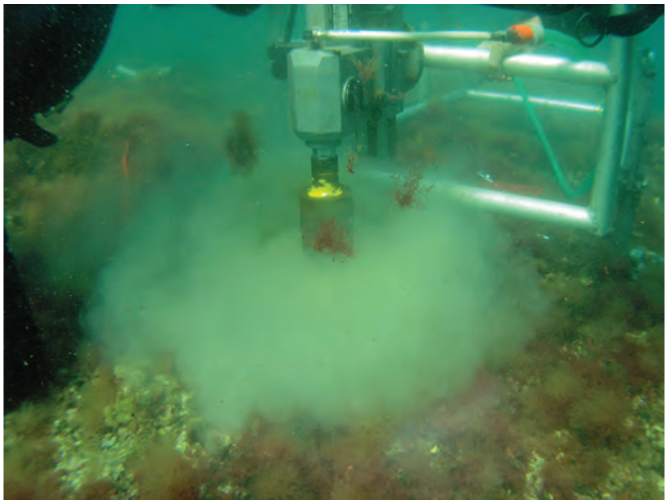


*Fig. 3.42. Drilling into concrete with a plume of flushed debris.*

*Fig. 3.43. Concrete core removed from the drill tube at Portus Iulius.*

*Fig. 3.44. Weak mortar mix being trowelled into core hole.*

*Fig. 3.45. Core location labelled at Secca Fumosa.*

*Fig. 3.46. Oleson recording a core at Caesarea before shipment to Italcementi.*

(Fig. 3.45) indicating the date and the responsible institution, the University of Victoria.

After each coring session, the cores were removed from the plastic pipes, studied, measured, and photographed, before being re-packed in the tubes with bubble-wrap and sent to Bergamo for analysis (Fig. 3.46). At the end of each coring season, all the drilling equipment was washed with fresh water, dried and oiled and greased before being transported or shipped back to CTG Italcementi for maintenance and storage. With each field season the ROMACONS team made improvements and modifications to equipment and procedures. By the end of the fieldwork programme, the team could deliver all equipment to a submerged coring location, mount the coring rack and take a core, then disassemble and remove the equipment within a period of about four hours, depending on local circumstances and the length of the core.

# Chapter 4

# Narrative of the ROMACONS Fieldwork

### *R. L. Hohlfelder and C. J. Brandon*

This chapter provides a description of the location and local circumstances of the cores taken by the ROMACONS team. It is intended to serve as an archaeological record of the context of the cores, both the larger context of the surrounding structures forming the port or fish-pond, and their history, along with the character and function of the block itself. The stratigraphy and composition of the concrete forming each block is described in Appendix 3. In this chapter the sites and cores are arranged chronologically by the sequence of coring, since the narrative includes an evaluation of the evolution of our approaches to coring and the incremental improvements to our techniques. For the location of the coring sites, see the maps in Figs. 3.2 and 6.1.

## 4.1. Portus, Fieldwork July–August 2002

***4.1.1. Background.*** The ROMACONS team decided to initiate its fieldwork at Portus. The emperor Claudius (AD 41–54) began to construct the enormous complex in AD 42 but did not complete it before his death, although it was functioning in some manner as early as AD 46 (Keay and Paroli 2011: 1; Keay 2012). This immense harbour complex, located *ca.* 4 km north of the mouth of the Tiber River, was commensurate in all ways with the Imperial capital of the Mediterranean world and was intended to be the architectural and engineering showpiece of his reign (Fig. 4.1), Functionally, Portus was meant to supplement the river port of Ostia located on the Tiber River and most likely to replace the great emporium of Puteoli in the Gulf of Naples, which had served as the harbour of Rome since the early second century BC (Rickman 1996: 10). During much of Republican era, ships that skipped the well-protected harbour of Puteoli while bringing cargo to Rome had been forced to off-load their products at sea near the mouth of Tiber for trans-shipment up river to the city on smaller craft (Dio Cassius 60.11.2–5; pp. 32–33, Passage 27). Shifting sand bars at the mouth of the river and along the channel upstream had rendered the Tiber impassable for large, ocean-going vessels. Ostia served as the hub for this commerce based on transhipment. The hazards and inefficiencies of this system became less and less tolerable as Rome grew into the capital city that ruled the Mediterranean world. Politically, the building of Portus had local significance as well, for it secured Claudius' position as patron of the numerous inhabitants of Rome and its immediate hinterland by providing employment for a multitude of citizens, regularizing grain imports, and possibly mitigating the periodic flooding of the Tiber River.

On the political side, following his unexpected accession to the Imperial office after Caligula's assassination, Claudius needed to confirm his legitimacy and enhance his public image, since his earlier life had been largely invisible to the average Roman. A high profile project that provided Rome with a monumental gateway to her Mediterranean empire, while addressing pressing social needs, served his purpose well. The dream of constructing an all-weather, international emporium for Rome dated back to Julius Caesar and perhaps even earlier (Suetonius, *Claud.* 20). The engineering problems associated with turning the concept into reality, however, had deterred both Julius Caesar and Augustus from fulfilling one of Rome's most pressing needs. Building Portus, a maritime project that had daunted even his two most illustrious ancestors, burnished Claudius's Imperial image and *dignitas*. Like his Imperial predecessors, he had learned that these architectural feats were images of power.

The Roman knowledge and experience of building in the sea had progressed rapidly in the decades before Claudius' accession. Concrete construction at Caesarea, Alexandria, Cosa, Egnatia, the Gulf of Naples, and many other harbours, as well as at coastal villas with their *piscinae*, had expanded the collective knowledge of Roman builders who undertook construction projects in or near the sea. This continually expanding engineering competence may have encouraged Claudius to undertake a project on the scale and of the complexity of Portus. While the need for a safe seaside harbour for Rome had long been recognized, it may well have been that only at that moment of time, with at least 75 years of accumulated practical experience of building in the sea, that Roman engineering technology was sufficiently advanced to address the challenges posed by the Portus project. The site of Portus was exceptionally difficult from the engineering standpoint: it was open to the force of the sea, subject to inundation by the Tiber, prey to the constant load of silt carried

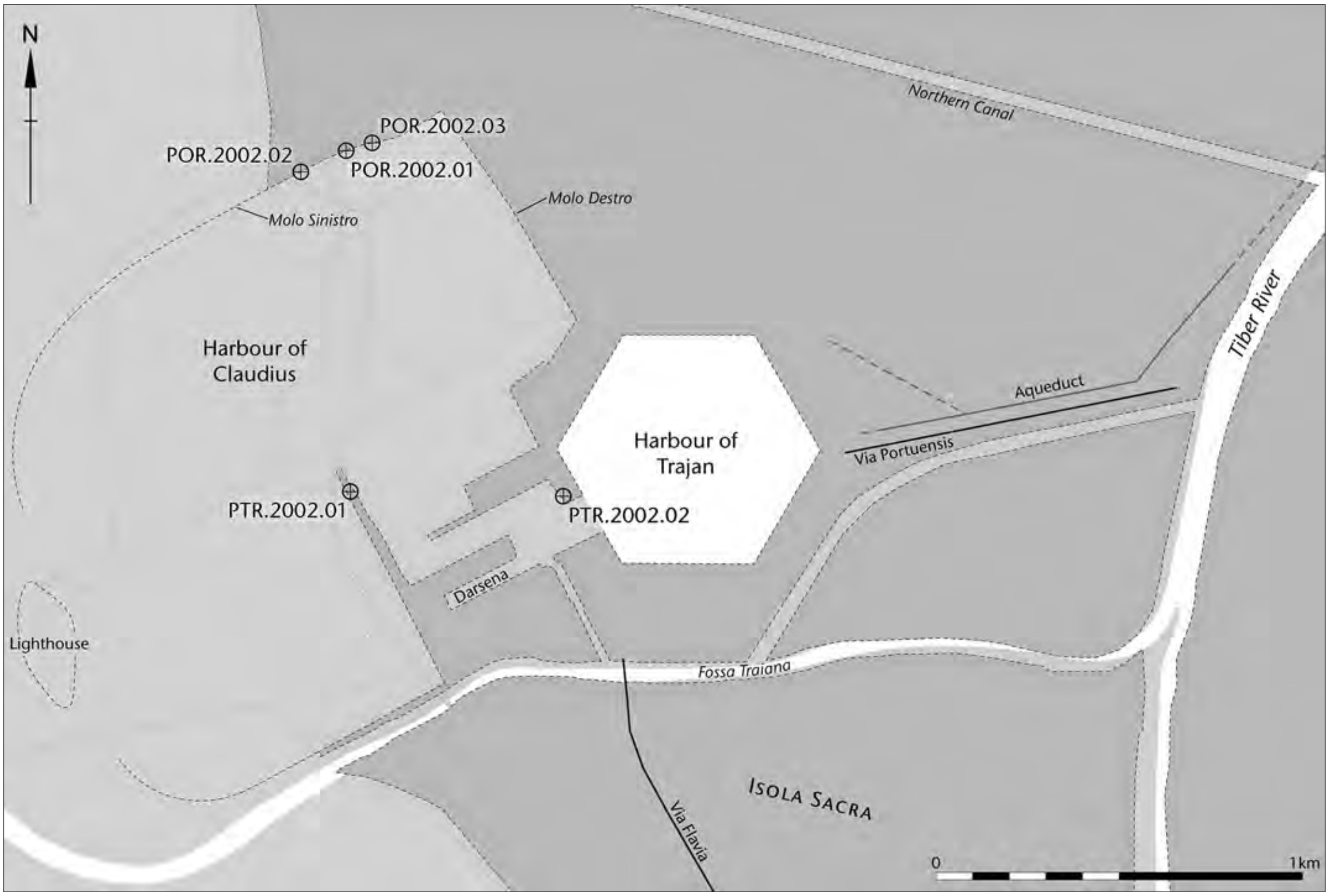


*Fig. 4.1. Plan of Portus with location of the coring sites (Will Foster Illustration).*

by the river, and situated on marshy ground. According to Cassius Dio, the consulting engineers called in by the emperor did not even want to provide the emperor with an estimate of the cost (p. 33, Passage 27).

Surprisingly, our knowledge of the Claudian harbour installations is still quite limited even after over 100 years of intermittent archaeological and salvage investigations at Portus. Only over the last 20 years has archaeological research been carried out in such a manner as to provide reliable data (Keay *et al.* 2005; Paroli 2005; Keay and Paroli 2011; Keay 2012). The size and shape of the sheltered basin and its original configuration are issues of ongoing scholarly inquiry. The nature and extent of the supporting terrestrial structures, as well as the length and design of the moles framing the harbour entrance, remain unknown and probably unrecoverable because of Trajanic and later renovations, modern interventions, and building activities that have rendered much of the ancient harbour a "congested urban zone" (Paroli 2005: 56). To add to the confusion, the traditional terms *Molo Sinistro* (or "*Bracchio Sinistro*") and *Molo Destro* (or "*Bracchio Destro*"), are deceptive (see below). In addition, there are at present restricted zones in which fieldwork is impossible. The entrance channel itself with its lighthouse was recently located by archaeological survey but has not yet been confirmed by archaeological investigations (Goiran *et al*. 2011: 42). While extensive recent fieldwork has occurred in other areas of Portus (Keay *et al.* 2005; Keay and Paroli 2011), the harbour itself still awaits an exhaustive, detailed study. This discussion accepts the plan of the Claudian harbour in which the entrance is on the west rather than the north and consists of two openings on either side of a lighthouse island (*e.g.* Keay *et al.* 2005: 274, fig. 8.2, 280, fig. 8.4; Keay 2012: 40, fig. 2.5). In this configuration, the remains termed *Molo Sinistro* are in fact the landward remains of the breakwater on the port side of a ship entering the harbour, while the character of the remains termed *Molo Destro* are undetermined (Fig. 4.1).

The many estimates of the size of the Claudian basin agree only on its extraordinary dimensions. The most recent and authoritative conjectures reconstruct a sheltered area of 200 ha (Keay and Paroli 2011: 2; Keay 2012: 44), making it nearly as large as the great Eastern Harbour of Alexandria (> 226 ha) and more than three times the size of the harbour of Puteoli in the Gulf of Naples (Schörle 2011: 96). The Claudian basin was created by carving out the coastline and also by creating two long curving concrete breakwaters that ran into the sea (Suetonius, *Claud.* 20.1; Cassius Dio 60.11.1–5). The main harbour entrance was divided into two channels of unknown width by an artificial island on which a lighthouse stood. The foundation of this structure was a huge freighter that in AD 37 had transported to Rome for Caligula the Egyptian obelisk that now adorns St. Peter's Square (see pp. 26–28, 32, Passages 15, 17, 24). The ship had been towed from Puteoli to Portus during Claudius' reign, filled there with concrete, and finally sunk in the channel as a kind of caisson. Recent sedimentological studies have also revealed the possible existence of a second, smaller entrance to the Claudian harbour in the break that now exists between the eastern terminus of the *Molo Sinistro* breakwater and the *Molo Destro*, although its function is not completely understood (Keay and Paroli 2011: 4; Keay 2012: 40–41).

This harbour was known as Portus Ostiensis or Portus Augusti after its completion and dedication by Nero in AD 64, when an issue of bronze coins commemorated the *Portus Augusti Ostiensis* ("The Port of the Emperor at Ostia"; Meiggs 1973: 56). As Meiggs remarks, *Portus Claudius* would have been a more fair designation, and that term will be used here since *Portus Augusti* might confuse some modern readers. How much of it was finished when Claudius died in AD 54 is unknown. Equally unclear is how Claudius intended to apportion Rome's maritime commerce between his new harbour, the river traffic through Ostia, and the installations at Puteoli in the Gulf of Naples. These questions, and many others surrounding Portus, linger unanswered and perhaps may remain unanswerable.

During the reign of Trajan a large hexagonal inner basin was added inland from Claudius' poorly protected basin, along with another canal connecting the port facilities to the Tiber. The overall project may have been planned by Claudius, but it was not finished until 112 or soon after, when coins were issued commemorating the *Portus Traiani*; inscriptions also mention the *Portus Traiani felicis* (Meiggs 1972: 162–64).

***4.1.2. ROMACONS fieldwork***. The objective of the ROMACONS team at Portus was to collect concrete cores from various maritime installations in the Claudian harbour. The hexagonal Trajanic basin, now owned by the Torlonia family, was not available for our investigations (Oleson *et al*. 2004a–b). Coring started with the breakwater on the north (*Molo Sinistro*), much of which was exposed in the 1950s during the building of the Leonardo da Vinci/Fiumicino Airport. These salvage excavations were carried out with considerable urgency and were published by Testaguzza (1970) without the detailed stratigraphic data or scientific observations that could have helped solve many of the puzzles that continue to surround Portus.

Thanks to this early fieldwork, however, the *Molo Sinistro* remains far more accessible for archaeological investigations than the still largely unknown and unrevealed *Molo Destro*. Testaguzza commented that the structure of the *Molo Sinistro* breakwater varied in places, and that a portion of its middle section had been formed by filling a ship's hull with concrete. He connected this feature with Pliny's discussion of the building of the lighthouse noted above. In the nineteenth century Luigi Canina identified this area as "Monte Arena" (Keay *et al*. 2005: 47, 53). This observation led Testaguzza (1970: 69–104) to posit that the entrance to the harbour was nearby and that it faced north rather than west, repeating an idea that had been put forth by other scholars as well. One core (POR.2002.02; Fig. 4.2) was taken at his putative location of the sunken ship, hoping that our sampling might provide scientific data to evaluate his hypothesis regarding the location of Caligula's ship and the northern orientation of the harbour entrance (Oleson *et al*. 2004a: 221–22). The prefix POR was used to designate cores collected from the north breakwater of the Claudian basin; PTR designates cores extracted from transitional structures between the Claudian and Trajanic basins.

We took two additional cores along the north breakwater at places where significant variations in construction techniques were observed (POR.2002.01 and POR.2002.03; Oleson *et al*. 2004a: 221–23). In addition, two more cores were collected from concrete structures at the transition between the Claudian and Trajanic basins. One was from the small breakwater built at some time during the harbour's development to protect the shipping channel that connected the Claudian and Trajanic basins (PTR.2002.01; Oleson *et al.* 2004a: 224). The other (PTR.2002.02) was from a section of waterfront buildings built during the Severan era (Oleson *et al.* 2004a: 224). Both PTR samples came from later chronological eras than the three extracted from the north breakwater. Our efforts to obtain permission to collect a core from somewhere in the hexagonal Trajanic basin were unsuccessful. All five structures analyzed appear to have had at least their lowest sections built in water. Mortar without coarse aggregate appears to have been placed directly on the sand, perhaps in an effort to seal any chinks in the wooden formwork and provide a relatively waterproof layer to prevent any seepage for the concrete placed above it. This bottom mortar layer easily crumbled when our drill reached and penetrated it.

Since Portus was the first ancient site where we attempted to implement our coring strategy and methodology, we were confronted with a series of problems as we learned how to install and operate our equipment, and as we attempted to perfect our collection technique. Our first sample, POR.2001.01, was limited in scope because of problems arranging a water supply sufficient to flush out the coring tube. The coring depth reached only 1.38 m below the surface of the concrete, and only a 0.11 m segment of core survived the process, collected from *ca.* 1.0 m below the exposed surface of the block (Fig. A3.19). The concrete above this depth seems to have been of a poor quality, since it disintegrated during coring. The mortar in the surviving 0.11 m segment was coherent, with a few relict lime

*Fig. 4.2. Portus, coring at site of POR 2002.02 (Testaguzza's "lighthouse").*

clasts. The aggregate was reddish brown, well-lithified volcanic tuff, Tufo Lionato from the nearby Alban Hills volcanic district (see pp. 253–58, Appendix 3.3). Like the other two cores, this concrete had been placed in wooden formwork consisting of horizontal beams against which vertical blanks were affixed, a method described by Vitruvius (*De Arch.* 5.12.3; p. 20, Passage 9) and classified by Brandon as Category 1 (pp. 191–205; *cf.* Brandon 2011: 126–30). At various points in the *Molo Sinistro*, holes that once contained horizontal cross beams are visible (Figs. 4.2–3), as are impressions of the vertical planks of the formwork, although today they largely obscured by fill (Figs. 8.15, 8.23).

POR.2002.02 was taken from a large concrete mass further to the west, apparently the mound that Testaguzza had identified as the lighthouse location and the site of Caligula's sunken ship (Fig. 4.2). The core recovered was quite long (2.80 m), reflecting both the good quality of the concrete and the improvement in our coring techniques (Figs. A3.20–22). Already with this second core a high proportion of mortar to aggregate (2 to 1; 66.6% mortar, 33.4% aggregate) could be seen in the maritime concrete. One section of the core at least 0.15 m long (at -1.83 to -1.98 m) consisted only of mortar. The concrete itself contained numerous fragments of charcoal, pieces of basketry, and fragments of rope, along with lumps of relict lime. The lowest levels of the concrete block (below -1.98 m) may have consisted of mortar alone, which crumbled and washed away during drilling. Our coring ended at -3.14 m, where we encountered fine grey brown sand either from the lagoon or the open beach on which the block had been installed. It was evident, however, that the upper levels of this block had been placed to cure in forms that stood above ancient sea level, and not been laid in submerged formwork. No wooden remains, either from formwork, ship or barge, were encountered in our coring. The absence of wood in our core

*Fig. 4.3. View of eastern end of* Molo Sinistro*, with sockets left by formwork. Site of POR.2002.01 in foreground, POR.2002.03 in background.*

does not conclusively prove Testaguzza wrong in his hypothesis that this mass was poured in Caligula's boat, but it makes the hypothesis much less likely.

POR 2002.03 came from the visible east end of the *Molo Sinistro*, immediately north of the Museo delle Navi and close to what may have been a small, secondary entrance to the Claudian basin (Fig. 4.4; Goiran *et al*. 2011: 41–3). At this point, the breakwater structure was quite thin, and it seems at some time to have been undermined by wave action. The core hole was only 1.56 m deep, and only two small sections of concrete totalling 0.36 m in length were recovered, both from the upper portion of the breakwater. The concrete was of poor quality, and much of the core disintegrated during our coring. This low wall had been built on sand, perhaps to serve as a retaining wall to hold back the lagoon sand that had been scooped out during the excavation of this portion of the inner basin. It is also possible that it was intended as a foundation for a more substantial seawall that has been washed away over the centuries or was never constructed. The commemorative bronze coin struck by Nero to honour the completion of the construction, shows a series of arches, shipsheds, or some other type of structure protruding from the north breakwater (Fig. 4.5). If such features ever existed, no remains can now be seen in the exposed sections of the *Molo Sinistro*. Was the iconography of the coin incorrect or simply suggestive of structures never built or finished; or were looters in the centuries following the abandonment of the harbour very thorough in removing even the traces of what would have been a monumental structure (whatever purpose it might have served in antiquity)? The pronounced under-trenching of the low wall of the eastern end of the *Molo Sinistro*, possibly caused by heavy sea penetrating deeply into the interior recess of the harbour, also poses another interesting puzzle (see below).

PTR.2002.01 was collected *ca.* 40 m south of the northern terminus of the breakwater constructed to protect an entrance channel between the Claudian basin and the Trajanic harbour (Figs. 4.1, 4.6). A 2.23 m long core was extracted from this structure, and the core tube penetrated an additional 0.20 m into sea sand below its base. The concrete of this core was consistently well prepared, with compact mortar and with uniformly sized and spaced pieces of Tufo Lionato tuff (p. 256, Figs. A3.24–25). The coarse aggregate also included pieces of brick and amphora fragments. The breakwater itself contained a levelling course of bricks, a feature observed by us only at Portus.

*Fig. 4.5. Reverse of Nero's Portus issue (Courtesy of the British Museum; CM BMC132, AN31942001).*

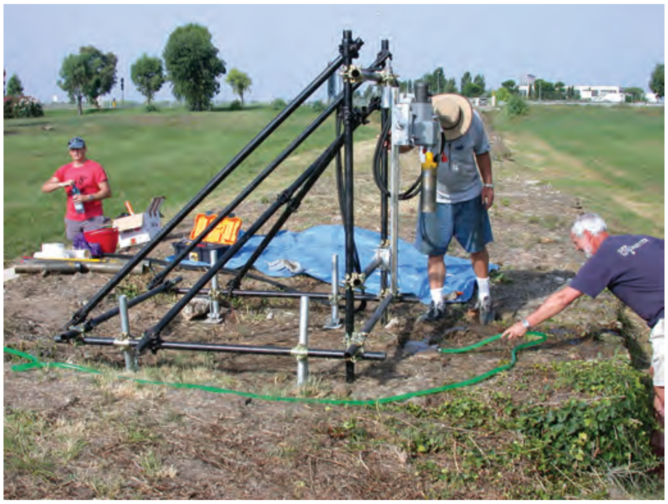


*Fig. 4.4. Taking core POR.2002.03.*


*Fig. 4.6. Taking core PTR.2002.01.*

PTR.2002.02 was taken from a quay wall in front of the "Severan Warehouse" defining the entrance channel to the Trajanic harbour (Fig. 4.7). The sloping location required construction of a coring frame significantly more complicated than usual, but the results were excellent. It was fortunate that we had chosen a harbour site above sea level for this first coring campaign, since the work on land allowed us more time to conduct the work, and easier communication as we solved technical problems. As with PTR.2002.01, the mortar and size and placement of the coarse aggregate are of a high quality. The lowest part of our 1.65 m long core was installed into an inundated form that rested on a dark grey sand (pp. 256–58, Figs. A3.26–27).

***4.1.3. Scientific analysis.*** While a preliminary analysis of the five cores collected at Portus in 2003 has been published (O*leson et al*. 2004a: 225–28), a more complete analysis appears in Appendix 3 (pp. 253–56) and Chapter 7.

***4.1.4. Observations and conjectures.*** Testaguzza (1970) was correct in his observation that the *Molo Sinistro* of the Claudian harbour exhibited structural variations, but he did not explain why these differences occurred. The concrete from the three cores taken on the Claudian breakwater was of relatively poor quality, consisting of mortar with many impurities that crumbled easily during the coring operations, and with large pieces of aggregate irregularly placed in the mix. In addition, the coarse aggregate to mortar ratio did not reflect the ratios found at other sites (usually around 35:65), but seemed lower, particularly in POR.2002.02 where large sections of mortar had no aggregate at all, while in other places the ratio was 20:80. Furthermore, the nature of the concrete showed considerable variations within the same core, something Testaguzza could not have observed. Such variations noted here and elsewhere in the ROMACONS survey suggest that the Roman builders were somewhat inconsistent in their day-to-day activities on this breakwater, often had to improvise to meet unexpected circumstances, and may have had to use workers who were inadequately trained or inexperienced.

*Fig. 4.7. Taking core PTR.2002.02.*

Regarding the last observation, we have suggested elsewhere that the workmen may have been seasonal, meaning that when cargos were being imported into Rome during the spring and summer sailing season, they worked at other tasks, such as *saccari* (grain handlers) or *saburrarii* (providers of ballast) (Oleson *et al*. 2004a: 206). With some new training, men who were used to carrying heavy loads as harbour porters could have been employed in a variety of tasks associated with the preparation and placement of concrete. The same could be said of slaves who were forced to work on the breakwaters. In either or both cases, the results could have been relatively sloppy work that might the have passed the scrutiny of crew bosses, since most of concrete would eventually have been covered in some way by cladding (Brandon 2011: 126–27) or essentially invisible beneath the sea.

Somewhat haphazard construction with some poorly mixed and placed concrete, along with inexperienced work crews, could be part of the explanation for why the Claudian basin required a supplementary docking area so quickly, necessitating the building of a second inner harbour by Trajan early in the second century. The destruction of 200 ships (probably river barges, fishing boats, river craft as well as the larger *naves onerariae)* within the protected basin by a storm in AD 62 (Tacitus, *Ann.* 15.18.3) may be an indication of poor design. Ultimately, Claudius's daring effort to provide Rome with the international gateway it had long needed may have become little more than a partially sheltered anchorage for ships waiting clearance into Trajan's new and completely safe harbour. Portus continued for centuries to serve Rome's maritime needs, but the Claudian harbour may have had an ever-diminishing role to play.

The quality of the concrete in cores PTR.2002.01 and PTR.2002.02 may reflect the fact that both structures were built considerably later than the *Molo Sinistro*. Additional decades of experience with building in a maritime environment may account for these qualitative improvements.

While these two cores provided no irrefutable evidence to date specifically either one of the structures from which they were extracted, a small bit of mortar taken from PTR.2002.01 was sent to the Oxford Research Laboratory for Archaeology and the History of Art to be tested by Dr. Fiona Brock in an ongoing experiment attempting to date mortar using Accelerator Mass Spectrometry. She and other scholars around the world are attempting to standardize a technique to date the carbon in the carbon dioxide fixed in the carbonate formed during the hardening of lime at the time of construction (Ringbom *et al*. 2011; Lindroos *et al.* 2011). The results are far from secure yet, although in some instances, where mortar has been removed from a structure with a known historical date, the results have sometimes been quite precise. Additional difficulties have occurred when mortars composed of pumiceous ash pozzolan have been analysed, but these dating anomalies occur primarily in mortar that set and cured in an underwater environment. The mortar sample from PTR.2002.01 was from a portion of the core that never was inundated, so it cured only in the air and not in the sea.

The radiocarbon AMS date for this sample provided a date range from AD 210 to 390 with a 93.0% of probability (1759 ± 30 BP) or a calendric age cal of AD 280 ± 40. The range is too great to specifically date the structure, but at the same time, it does suggest that this breakwater may not have been built as an integral component of either the Claudian or Trajanic constructions, but perhaps as a much later effort to address problems that had arisen in the third or fourth centuries. This test is mentioned here only because it may have more credibility in the years ahead as AMS dating has been refined, or this wide range of dating probabilities might even corroborate other chronological data that come to light in the future. Even so, the very high quality of the concrete correlates with those of the high performance concretes of the Markets of Trajan (Jackson *et al.* 2009), and it seems unlikely that such materials could have been produced during the late third century.

The thinnest section of the *Molo Sinistro*, nearest to the *Molo Destro,* seemed to be unfinished, as if a larger seawall or some other structure would have surmounted the existing section. Since it was constructed on beach sand, one can assume it was never intended to survive for long the erosive and destructive action of storm seas. Perhaps the wall was not as carefully constructed because its purpose was only to serve as a retaining wall to prevent the migration of coastal sand into the artificially hollowed-out basin that was a component of the Claudian harbour (Cassius Dio 60.11.1–5; p. 33, Passage 27). The severe under-trenching of the wall could not have occurred at the time it was functioning as intended. The wave action that washed away the sand on which the breakwater rested must have happened well beyond the *floruit* of the Claudian harbour, perhaps after it had fallen from use and the sea was able to penetrate the innermost reaches of the now derelict facility. Since this section of the breakwater had been constructed on sand alone, it clearly was never intended to withstand the ravages of the open sea.

Our physical investigations and visual reconnaissance of the excavated sections of the *Molo Sinistro* that were not in restricted zones indicated that the representation of the basin on the Neronian Portus issue of AD 64 was either incorrect or incomplete (Fig. 4.5). The type seems to show a series of arches on the *Molo Sinistro*, although that interpretation of these protrusions may be incorrect. Perhaps the coin depicts a line of wooden docks springing from the concrete breakwater. As discussed above, no signs of any permanent structures akin to this depiction now exist, but if the "arches" were actually wooden piers, evidence for their existence would not be obvious in a visual reconnaissance.

The apparent colonnade that distinguishes the other mole on the coin has not been discovered either, while the entrance channel on the coin features a large statue (perhaps of Nero?) rather than the lighthouse mentioned in the ancient sources. The coin also gives no hint of what repairs Nero had ordered to correct the original design errors that had occasioned the loss of 200 ships within the protective breakwaters in AD 62. One assumes that the entrance to the Claudian harbour may have been too wide, rendering the enclosed basin vulnerable to storms coming from the west. Even with the lighthouse dividing the entrance into two separate channels, it was possible for ships to enter Portus under full sail (Ammianus Marcellinus 19.10.4), a manoeuvre that could only have been accomplished safely if the channels were sufficiently wide.

The Nero coin, clearly incorrect in several respects in depicting the design features of the harbour, sheds less light on some of the puzzles surrounding the Claudian basin than one might hope. Its iconography is more symbolic than realistic, but it does convey in its busy details the importance of Rome's new maritime portal to the Mediterranean world. It is ironic that the massive harbour started by Claudius, the most challenging and complex building program of his reign, received its only numismatic recognition on a coin of his successor. While it is true that Nero claims the grand harbour as his own with this coin issue, history correctly assigns the construction project to Claudius.

## 4.2. Antium, Fieldwork August 2002

***4.2.1. Background.*** The site of Antium (modern Anzio), a rocky promontory located *ca.* 56 km south of Rome on the coastline of Latium (modern Lazio), was distinguished by a natural anchorage that afforded some protection to ancient mariners (Fig. 4.8). Although its history had been closely linked to Republican Rome from the fourth century BC on, Antium assumed a far more prominent role in the Late Republic and Imperial periods. It was a favourite location for the seaside villas of Rome's elite, while its modest roadstead became increasingly important as maritime commerce into Puteoli, Republican Rome's major emporium, increased. Antium became a port of refuge and secondary anchorage for coastal freighters transshipping their cargoes from the Gulf of Naples region to Ostia and Rome. Augustus had a large Imperial villa at Antium, one that was later used and embellished by subsequent emperors including Nero, who was born there and spent considerable time in the city of his birth. It was from Antium that Nero raced back to Rome in AD 64 upon hearing news of the famous fire that destroyed so much of the capital. His imperial munificence to Antium included the refounding of the city as a Roman colony and the conversion of its natural anchorage into a large harbour defined by the construction of two large breakwaters some 700 m and 850 m in length to enclose an area of *ca.* 25–35 ha, third in size after Portus and Puteoli (Suetonius, *Ner.* 9.1; Blake 1959: 84; Felici 1995, 56–63; Schörle 2011: 98).

***4.2.2. ROMACONS fieldwork.*** Our fieldwork at Antium was limited to a single day because of delays in obtaining an

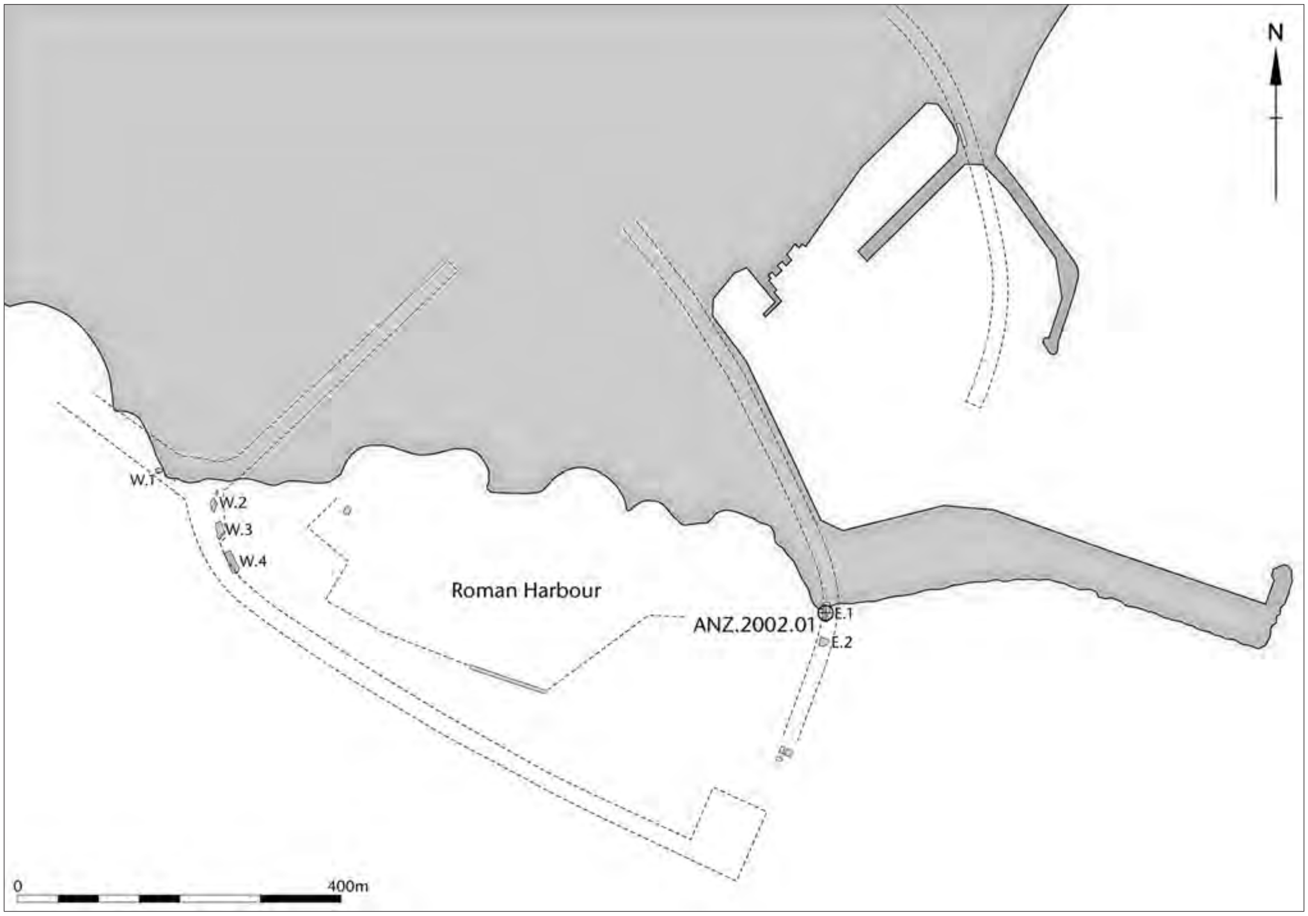


*Fig. 4.8. Plan of Antium harbour with location of core (Will Foster Illustration).*

excavation permit, along with safety concerns on the part of the Harbour Master regarding holiday crowds in early August (Oleson *et al.* 2004a: 223, 2004b: 189). Fortunately, we were able to locate a suitable spot for our sampling, on a large, easily accessible concrete *pila* at the base of the southeast Imperial breakwater (Felici 1993: 74–76). Numerous such *pilae* still exist in remarkably good condition in this part of the harbour in spite of daily pounding by the sea over 2000 years (Fig. 4.9). The original landward end of the mole is now covered by modern fill supporting a parking lot. In this area the mole consisted of a 4.75 m wide concrete wall with a level upper surface that now protrudes just above sea level. Westward of this 15 m long single block, the breakwater becomes a series of *pilae*, square in plan.

The core (ANZ.2002.01) was extracted at a point 10.99 m from the northwest corner of the block, and 12.90 from the northwest corner. It consisted of two distinct installations of compact mortar, each featuring a different pumiceous ash pozzolan (Fig. A3.28–30). The base of block was reached at -2.25 m. The last *ca.* 0.30 m of the core (to a depth of -2.25 m) consisted of loose mix of greenish grey pumiceous ash pozzolan and poorly mixed lime, but no coarse aggregate. Within this section of the core, -0.27 to -1.90, there were also two less compact lenses of mortar at *ca.* -0.90 m and -1.80 m. Our drill penetrated through the base of the block and then continued for another -0.60 m into very compact greenish grey sea sand.

*Fig. 4.9. Taking core ANZ.2002.01.*

***4.2.3. Scientific analysis.*** The Antium core is described in our previously published report (Oleson *et al*. 2004a: 223). For the more comprehensive scientific analyses, see pp. 258–60, and Chapter 7.

***4.2.4. Observations and conjectures.*** The recent underwater investigations of Nero's harbour at Antium by Felici (1993; 2002) have revealed a remarkably sophisticated complex that far surpassed the needs of the Imperial villa, including an artificial inner harbour within the great basin. The extent of the ruins suggests that the Imperial harbour of Antium was intended from the start to play some role in the maritime life of Rome beyond merely servicing Nero's villa. While the harbour is far too large to have been intended simply for his personal use, functionality and self-aggrandizement may both have been at play in its construction. Nero most probably envisioned the port of Antium as a reserve facility to serve the capital if some catastrophe, such as another storm as damaging as that of AD 62 (Tacitus, *Ann.* 15.18.3), or possibly an extraordinary flooding of the Tiber, should put Portus out of commission. In fact, the functional failure of Portus in AD 62 may have prompted the enlargement of the original harbour design at Antium. Upon its completion, Antium offered a safe haven for ships coasting up from Naples if bad weather precluded their running safely to either Portus or Ostia, about one day's sail beyond Antium. While no surviving ancient text speaks of a possible pragmatic purpose for this construction beyond hinting it was a further example of his decadent excess, the construction should be understood as an important and much needed addition to the growing maritime façade of Italy. The entire *ora maritima* between Portus and the Gulf of Naples was in essence part of the port of Rome (Rickman 2005: 235; Schörle 2011), and Nero made significant contributions to enhancing this maritime corridor. He was planning even more daring connections, such as the canal from the Gulf of Naples to the Tiber that he actually started toward the end of his reign (AD 65–68; Tacitus, *Ann.* 15.42.2, 4; Suetonius, *Ner.* 31.1; Statius, *Silv.* 4.3.7–8). No matter how addled some of Nero's actions might have been, one can see behind many of his acts a nascent maritime policy aimed at solving serious problems with Rome's food imports.

The construction of the harbour began sometime around AD 60 and was completed by AD 64. In other words, Nero's engineers had begun an extensive new building program in the sea while the finishing touches on Portus were still underway. After the great storm of AD 62 had revealed the need for renovations, his master builders would have been stretched by the magnitude of the simultaneous projects.

The one core that was collected during ROMACONS fieldwork at Anzio (ANZ.2002.01) appeared to have had at least three distinct phases of concrete placement, but there were no signs of settling or laitance in these layers to indicate the passage of any significant amount of time between the phases (see pp. 258–60). Laitance is a light wash of lime brought to the surface of mortar or concrete after placement, if sufficient moisture is present. The bottom layer lacked *caementa*, consisting of only a layer of mortar. This was also the case with PTR.2002.01 and 02, and with POR.2002.02. Because these concrete blocks had been placed in the sea in Category 1 Vitruvian formwork (Brandon 2011: 124; below pp. 191–205), this distinctive, lowest layer of mortar may have been placed first to fill in any gaps in the formwork to prevent seepage, and to provide a foundation course for the concrete that would level or stabilize the mass on a sandy seabed.

Variations in the types of mortar and aggregate within a single block are common in the concrete sampled by ROMACONS (*e.g.* Cosa, pp. 248–53). The reasons are not always immediately obvious, and the variations may only have been the result of on the spot decisions by the foremen of different work crews. Perhaps, during the pouring of the concrete into the Antium *pila*, an unexpected shortage of one type of pumiceous ash pozzolan had occurred as the next pour was being prepared, so a substitute was used to enable construction to continue unabated. Perhaps various separate crews had been assigned to work on the same *pila,* each coming from a different region and thus familiar with slightly different construction methods. Or it might be that less attention was paid to precise uniformity of building practices than is the case in modern concrete work, since variations in the mixing of the mortar, the mortar to aggregate ratios, the precise amount of water used to mix the lime and pumiceous ash pozzolan, *etc.* were less important to the production of strong and durable concrete than might be expected. Another reality was the practice of Roman builders to overbuild their structures (Hohlfelder *et al*. 2011: 111–12). The massive scale of the structure often could obviate minor errors or inconsistencies in the construction practice. All things considered, it turns out that Roman maritime concrete was a surprisingly forgiving building material.

## 4.3. Cosa, Fieldwork July–August, 2003

***4.3.1. Background.*** The Roman colonial foundation of Cosa was located on the coast of ancient Etruria about 140 km north of Rome, on the pinnacle of one of the few promontories on what is otherwise a predominately a sandy coastline (Figs. 3.2, 6.1). Portus Cosanus was on the eastern side of this headland, roughly at a point where it joined the shore (Fig. 4.10). To the west of the Cosa promontory, a much larger peninsula, known today as the Argentario, provided the port with some protection from winds and heavy seas coming from the north and west, as did the Cosa promontory itself. By virtue of this favourable geographical position, the Portus Cosanus was one of the best anchorages along the Tuscan coast. This natural advantage, coupled with the location of Cosa itself on the apex of a promontory in a region of rich soils, forests, and numerous fishing lagoons, explains the decision by Republican Rome to place a military colony at this location in 273 BC, as a key outpost in its efforts to complete its subjugation of Etruria (Brown 1980: 4–7).

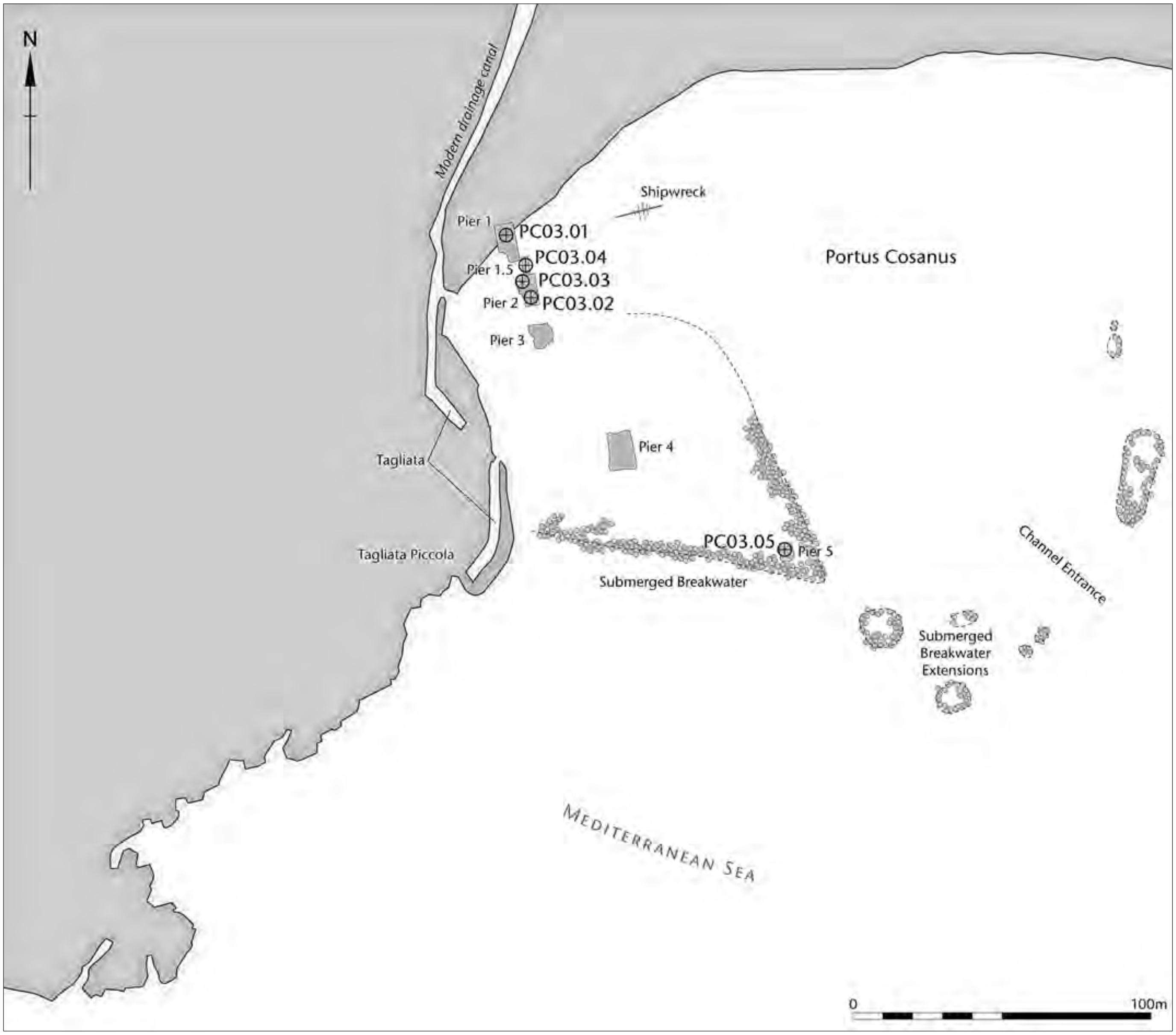


*Fig. 4.10. Plan of Portus Cosanus (Will Foster Illustration).*

Either at the moment of the foundation of Cosa or shortly thereafter, the colonists and/or the Republican government decided to augment the protection of this sheltered cove by building a rubble breakwater from the shore westward into the sea for a distance of *ca.* 110 m. The original width, height, and general configuration can no longer be ascertained, since natural forces at work over the centuries that followed Cosa's *floruit* have spread its building components over a large area (Fig. 4.10).

Extensive fieldwork was conducted in the harbour area in 1968 and 1969 by a team headed by A. M. McCann and J. D. Lewis (McCann *et al*. 1987). In 1970 and 1972 McCann directed a large, multi-disciplinary team that continued mapping of the harbour basin area while carrying out an extensive excavation of the large fish-raising installation in the lagoon landward of the beach (McCann *et al.* 1987; McCann 2002). The site's many architectural features and its role in the economy of the Roman Republic continue to attract scholarly interest (Ciampoltrini 1991; Felici and Balderi 1997a–b; Gazda 2008; McCann 2008; Gianfrotta 2011a).

In addition to efforts to understand better the original rubble breakwater that defined the harbour, McCann's underwater team (including Hohlfelder and Oleson) conducted an extensive study of the row of five *pilae* (Piers 1–5) made of Roman maritime concrete that extended from the sandy beach out into the sea on an approximate NW-SE axis for about 150 m (Figs. 4.11, 6.11). This investigation also included a small concrete platform between Piers 1 and 2, termed Pier 1.5 (Gazda in McCann *et al*. 1987: 76–8). Gazda followed up the fieldwork with a careful study of the maritime concrete used throughout the port, both in the sea and in the lagoon (Gazda 1987, 2001). The team also discovered a series of discontinuous smaller rubble mounds, identified as extensions of the breakwater, curving in a semicircle for about 100 m from the present end of the line of the main breakwater.

***4.3.2. ROMACONS fieldwork.*** The ROMACONS fieldwork in 2003 was limited in its scope to the collection of concrete cores from three of the five piers and from the small concrete platform between Piers 1 and 2. The collection of a sample from Pier 5 was of particular interest, since our previous fieldwork at Portus and Anzio in 2002 had not required executing our sampling procedures underwater.

The first three piers, Pier 1–3, and Pier 1.5 stand close together on or near the shore, but they may actually have been constructed on land rather than in the sea (Oleson *et al*. 2004a: 221; *contra* McCann *et al.* 1987: 65) (Fig. 4.11). Pier 4 is about 36 m to the south and east of Pier 3, its upper surface approximately at sea level, while Pier 5, believed by McCann to be the foundation of a lighthouse, is at present 2.2 m below sea level, about 55 m to the east of Pier 4 (Figs. 4.16, 6.11; McCann *et al*. 1987: 140). Both of the two outer piers appear to have been built on the rubble breakwater. No remains of other piers were found in the large gaps between Piers 3 and 4 or Piers 4 and 5. The unusual positioning of these concrete *pilae* – Piers 1, 1.5, 2, and most likely Pier 3 built on land in reasonable proximity to one another, and two, Piers 4 and 5, isolated from each other and the shoreward piers by considerable distances – may indicate a building program that was started and never finished.

A total of five cores were collected: from Pier 1 (PCO.2003.01), Pier 2, centre (PCO.2003.02); Pier 2, north end (PCO.2003.03); Pier 1.5 (PCO.2003.04); and Pier 5 (PCO.2003.05). A preliminary analysis of these cores has been published (Oleson *et al.* 2004a: 225–28), and additional analyses are presented in Appendix 3 (pp. 248–53) and Chapter 7. Pier 1 was selected for coring because it provided easy access, being entirely on land. It also provided compelling evidence of the wooden formwork into which the concrete had been placed. Excavations conducted by McCann in 1968 on the western corner of this block revealed distinct impressions of six vertical overlapping planks of the wooden formwork that contained the concrete while it set and cured (Fig. 4.12; McCann *et al.* 1987: 63, 76). The formwork that left these impressions belongs to Brandon's Category 1 form (pp. 191–205), similar to one of the forms described by Vitruvius (*De arch.* 5.12.2, pp. 20–23, Passage 9) and employed in variations throughout the Roman world.

Core PCO.2003.01 was extracted from the exposed top of Pier 1 at a location permitting the proper mounting of our drilling equipment. The depth of the core hole was 2.23 m, but only 1.65 m of core was recovered (Figs. A3.7–9). The *caementa* in the upper 0.50 m of the core consisted of the presumably local limestone, while the lower section of the core was distinguished by tuff *caementa*, at least some of which likely originated from Campi Flegrei (Figs. 7.10–11) and perhaps, also from Volsinii/Bolsena (as reported in McCann *et al.* 1987: 313–14). The decision to use limestone in the upper section of the pier may reflect economy on the part of the

*Fig. 4.11. Portus Cosanus, view of Piers 1–3.*

engineer, who recognized that the upper part of the pier would have little contact with sea water. This distinction in *caementa* does not seem to indicate two distinct phases of construction as was suggested by McCann, who posits an original construction of concrete with tuff *caementa* later surmounted by a repair or renovation using local limestone as the *caementa* (McCann *et al.* 1987: 326). Rather, our sample suggests one sequence of placement for Pier 1, as was also the case for Pier 2, with two distinct strata of concrete with different coarse aggregates employed during its construction (a sequence accepted by Gazda 2008: 277).

Since this was our first experience in coring concrete with *caementa* significantly harder and more dense than volcanic tuff, it was interesting to note that the diamond core bit cut through the limestone almost as quickly as it did through tuff, and the drill motor did not seem to be under significant strain. The mortar of PCO.2003.01 also produced a small fragment of carbonized wood that yielded a $^{14}$C date of 2020 ± 40 BP, providing a range of 57 BC to AD 33 (TO-11233; Oleson *et al.* 2004a: 225). The significance of this date is discussed below.

PCO.2003.02 and PCO.2003.03 came from different sections of Pier 2. PCO.2003.02, taken from the south end of the pier, breached a hole left after the decay of a wooden crossbeam of the original formwork. Although the coring continued *ca.* 3.5 m to the bottom of the pier and then 0.18 m beyond into the seabed (Oleson *et al*. 2004b: 187), only the uppermost 0.5 m was recovered intact (Figs. A3.10–12), necessitating another effort to recover a more complete sample. This second core (PCO.2003.03) was extracted in the northern end of the pier and successfully penetrated to the base (resting on beach sand), permitting the extraction of a well-preserved 2.25 m core (Figs. 4.13, A3.13–14).

No traces were discovered of vertical plank impressions from the wooden formwork that held the concrete, but a series of cross beam holes indicated the position of the interior wooden tie beams of the formwork (Fig. 4.14). In addition to holding the sides of the box-like formwork together, the beams served another purpose during the construction process. They provided platforms for workmen to distribute mortar and aggregate, and to tamp the concrete before it set (Oleson *et al*. 2004a: 217; below, p. 107). These may be the enigmatic *trastila* mentioned by Vitruvius (*De arch*. 5.12.3; pp. 20–23, Passage 9). Since such beams could not be removed once the block had been poured, they were left to decay in position, leaving the long, square holes typical of most Roman *pilae* (McCann *et al.* 1987: 77, figs. IV–11,12).

Another feature of these two cores was the presence of local beach sand in the mortar extracted from the top of the pier, with a scattering of ground ceramics, possibly as a supplement to the pumiceous ash pozzolan. In fact, the presence of beach sand in the mortar of all the piers, along with pumiceous ash pozzolan, was a surprise. One can only speculate on why this combination of beach sand and pumiceous ash pozzolan was used here. Whether or not the Cosa piers represent the first appearance of

*Fig. 4.12. Portus Cosanus, impressions of wooden formwork shuttering on Pier 1 (after McCann* et al. *1987: fig. III–13). (Courtesy of A. M. McCann)*

*Fig. 4.13. Portus Cosanus, coring of Pier 2.*

*Fig. 4.14. Portus Cosanus, seaward portion of Pier 2, showing upper and lower concrete mixtures and hole left by catena.*

Roman maritime concrete in maritime installations as McCann maintained, they most assuredly represent one of the earliest examples of the extensive employment of this building material in a marine setting. If so, it is possible that Roman builders were still experimenting with this material at Cosa and elsewhere, using various aggregates and pumiceous ash pozzolan/sand mixtures in varying proportions to discover the most effective mortar (*contra* McCann *et al*. 1987: 327). In fact, the overall results of the ROMACONS fieldwork suggest that some experimentation or at least regional variations were a constant wherever Roman maritime concrete was employed (Oleson *et al*. 2004a: 217). Another possibility could be that various crew chiefs charged with building different piers followed out their instructions with less diligence (or more personal initiative) than the architects in charge might have expected.

PCO.2003.04 and PCO.2003.05 were short cores recovered from the platform connecting Piers 1 and 2 (Figs. 4.15, A3.15–17) and from the southwest edge of the submerged Pier 5. Pier 5 was probably originally below sea level. The PCO.2003.04 core contains pumiceous ash and tuff, along with many relict lime clasts. The core PCO.2003.05, taken from Pier 5 represents the remnant of an aborted sampling (Figs. 4.16, A3.18). The irregular and friable surface of the block precluded a tight fastening of the drilling equipment. As a result, the coring was terminated at -0.48 m. The concrete consisted of primarily pozzolanic mortar and pumiceous volcanic tuff as coarse aggregate: the mortar also contained fragments of sand, pumice fragments, and small bits of ceramic amphora and lumps of lime.

***4.3.3. Scientific analysis.*** A preliminary analysis of the five cores collected at Cosa in 2003 has been published (Oleson *et al.* 2004a: 225–28), and additional analyses are presented in Chapter 7.

***4.3.4. Observations and conjectures.*** The ROMACONS objectives at Cosa concerned mainly the acquisition of samples of concrete from the piers, and not the outstanding issues about chronology and functionality of the maritime installations. Nevertheless, our work did produce some data relevant to these important issues.

The cores collected from Piers 1, 1.5, and 2 suggest that all three of these structures were constructed on the beach and not in the sea, an observation that fits with suggestions of a lower relative sea level in antiquity and underscores the importance of understanding such sea level change as it relates to functionality of the harbour.

At various points in her book, McCann indicates that sea level today may be 1 to 1.5 m higher than at the time the Portus Cosanus was in use (McCann *et al*. 1987: 19; *cf.* Bourgeois 1987: 57 for a change of +1.0 m), although more recent estimates suggest the relative sea level change (owing to local subsidence rather than eustasy) could be as much as + 1.65 m (Gazda 2008: 282, n. 42; Lambeck *et al.* 2004: 563, 572 for a change of +1.35 m). If any of these estimates is correct, the upper surfaces of Piers 1 and 2 and presumably of Pier 3, would have been far too high above ancient sea level to have served as efficacious loading or unloading surfaces (*contra* McCann *et al.* 1987: 138–39). The lifting and lowering of cargo from the top of the piers *ca.* 2 + m above the sea would have been

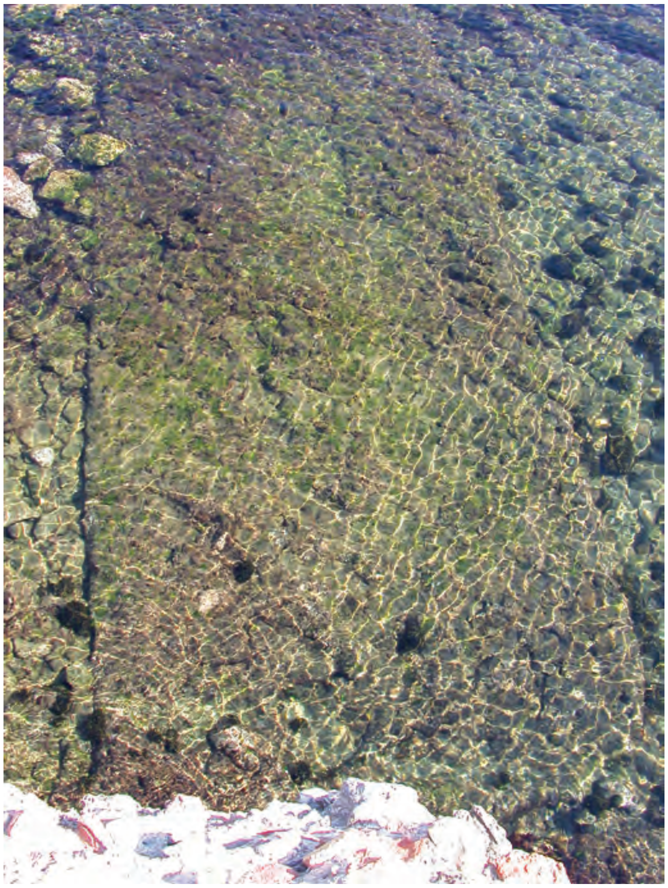


*Fig. 4.15. Portus Cosanus, view of Pier 1.5.*


*Fig. 4.16. Portus Cosanus, taking core PCO.2003.05 from Pier 5.*

unnecessarily onerous, given that better solutions existed along the shoreline for simple stevedore transfer to and from boats moored in shallow water adjacent to the coastline. Moreover, the likelihood that Piers 1, 1.5, and 2 were constructed on the ancient beach and not on submerged rubble of the main breakwater would have rendered them unusable for off- or on-loading boats at sea (Oleson *et al.* 2004a: 221; *contra* McCann 1987: 65).

We did not core Pier 3, which is now immured in a modern concrete construction dating from before World War II and marked with visible signs of modern repairs (Gazda 2008: 279), so we cannot say whether it was constructed on the original breakwater or on beach sand. But if it did stand in the sea when it was first constructed, the surrounding water would have been too shallow for anything other than a small boat to moor at its base. Pier 4 stands on its own, *ca.* 36 m distant from the first three piers, and it may have been far off shore. It is hard to see what role it might have had in the functioning of the harbour. The same applies to Pier 5, which McCann indentified as the base of a lighthouse, since it is even farther removed from the shore and the other piers (55 m east of Pier 4) (McCann *et al.* 1987: 140). In the late 1960s investigations by McCann's underwater team (which included Hohlfelder) of the openings between Piers 3 and 4 and between Piers 4 and 5 did not reveal any evidence of other piers. These gaps appear to have been empty of any significant structural remains.

Given their configuration, with two or possibly three piers constructed on beach sand and the other two separated by significant distances with only empty spaces between them, the five *pilae* make no obvious architectural or functional sense. McCann's explanation of how these piers with their odd placement might have been used in daily operations of the harbour is convoluted and unconvincing (McCann *et al.* 1987: 138–39), as is the attempt to see these concrete piers as "baffles" to protect a water channel leading to the inner lagoon (Gazda in McCann *et al.* 1987: 151–52, but now questioned by Gazda 2008: 262). Thus, the piers and their function remain enigmatic in spite of considerable study and sometime strained efforts to assign them a purpose.

Perhaps there is another explanation worth considering. To most people viewing these piers for the first time, they seem incomplete or unfinished. The distances between them are striking and inexplicable, while their visible surfaces show no signs of ancient cladding as one sees, for example, along the concrete breakwaters at Portus. It is as if one were viewing the partial skeletal remains of larger project that never was completed; could this be the solution for the apparently incoherent arrangement of the *pilae*?

Fieldwork by Brandon at Sebastos has shown that during an early phase of construction of the great southern breakwater of the main harbour, Roman builders erected a line of concrete *pilae* similar to those found at Cosa (Brandon 1996, 2011; Raban 2009: 88–89). Their purpose was to establish and stabilize the main axis of the breakwater, leaving intervals between the piers where rubble infill could be placed to form the mole. Perhaps these five Cosa *pilae* represent only the beginning of a larger construction effort to erect a seawall that truly would have maximized protection for the naturally sheltered cove of the Portus Cosanus. The new installation would have supplemented any protection afforded by the original rubble breakwater if sufficient portions of it were still above water, not yet having succumbed to liquefaction or prolonged lack of maintenance. For whatever reasons, such a project appears to have been started but never finished.

One might also see the isolated rubble mounds discovered in 1968 as components of an unfinished system of discontinuous breakwater elements flanking the harbour entrance. Such a maritime installation consisting of strategically placed piles of stones could easily have been another experimental element in Roman harbour technology intended to provide protection for the sheltered basin from south and southeast storms while also enabling the long-shore current to scour the enclosed basin to alleviate possible siltation. Once again, there is an analogous system of discontinuous rubble breakwaters as a feature of King Herod's harbour at Caesarea Palaestinae, although the intent of that system was to provide a first line of defence for the southern breakwater against winter storm seas (Raban 2009: 102–4).

The construction of the main components of the outer basin of Sebastos seems to have occurred between 23 and 15 BC. Did the building of the *pilae* at Cosa predate construction of Sebastos by a century or more, or was it possibly contemporaneous with the building of King Herod's harbour? Did the deposition of the rubble mounds as discontinuous breakwater elements occur when the original main rubble breakwater of Cosa was constructed sometime in the third century BC, or was the other unfinished project associated chronologically with the building of the five piers? If Ciampoltrini (1991) is correct about assigning the construction of the concrete piers to the Augustan Age (also Gazda 2008: 282–83; Gianfrotta 2011a: 188; Fentress 2009), could this project to revive or rebuild Cosa's harbour be understood not only in the local context of serving the city of Cosa but as one more example of efforts by Augustus to create, rebuild and renovate harbours throughout Italy and the Mediterranean as he strove to create a maritime infrastructure appropriate for the empire that he then governed (*cf.* below the discussions of Caesarea, Alexandria, Egnatia, and Chersonesos)?

This effort to try to discern either a broad or a local context for the rehabilitation of Cosa's harbour requires a clear understanding of when such work was first begun. Unfortunately, establishing an absolute date for the building of the Cosa piers remains an issue of controversy and uncertainty that has been the focus of considerable scholarly interest ever since McCann suggested that these piers represent the earliest known use of Roman concrete construction in the sea. She has variously assigned them to the first half of the second century BC (McCann *et al.* 1987: 326–27, 337), the late second century BC to early first century BC (McCann *et al.* 1987: 325, 327, 337; McCann 2002: 22), and then possibly to the first three decades of the first century BC (McCann *et al.* 1987: 331). In her most recent publication relating to this subject, however, she reaffirmed her commitment to the late second century to early first century BC (McCann 2008: 294). She also cautions that assigning an absolute date for the structures of the port and fishery of Cosa remains impossible. A date somewhat later than McCann's is offered by Gazda, from *ca.* 70 BC as a *terminus post quem* to sometime in the third decade of the first century BC or perhaps even later (Gazda 2008: 270; challenged by McCann 2008: 294). Ciampoltrini (1991), on the other hand, claims that the structures belong to the Augustan era.

These various claims have lacked scientific certainty since they are based largely on different interpretations and assessments of the significance of the pottery evidence discovered on land and in the sea at Cosa, and also on the acceptance of Will's typology and chronology of the Sestius amphorae that dominate the Cosa corpus (Will 1987: 171–220). Into this realm of subjective uncertainty, the ROMACONS fieldwork introduced one datum of more secure chronological certainty. A tiny piece of carbonized wood was discovered embedded in the mortar in the upper section of PCO.2003.01. The $^{14}$C dating of this sample at the University of Toronto yielded a possible chronological range of 57 BC to AD 33 (Oleson *et al.* 2004a: 225; pp. 66, 248). While this one $^{14}$C sample does not irrefutably establish the construction date for all of the concrete piers, it deserves serious consideration when other dating suggestions are based largely on a more subjective analysis of pottery fragments. The $^{14}$C date has been recently accepted by both Gazda and Gianfrotta (Gazda 2008: 281; Gianfrotta 2011a: 118) but challenged by McCann (McCann 2008: 293, n.1). The chronological range of this sample would allow for consideration of a possible Augustan era harbour construction project at Portus Cosanus at a time when there appears to have been efforts to revive the life of Cosa after its abandonment in *ca.* 60 BC (McCann *et al.* 1987: 27). Fentress (2009) has dated such a refoundation of Cosa to *ca.* 25 BC and suggests that the $^{14}$C date for Pier 1 is consistent with archaeological evidence she has uncovered in her terrestrial excavations.

If this date can be supported in the future by other evidence, it would still place Cosa in the forefront of "working laboratories" where Roman builders experimented with and explored ways of using maritime concrete to create structures in the sea, although its primacy of position as the earliest known example of the Roman use of such concrete now seems in doubt (McCann *et al.* 1987: 327). McCann's hope that the Portus Cosanus will be recognized as having a unique place in the still unwritten history of ancient maritime world remains secure (McCann *et al.* 1987: 342), even if the Cosa piers and perhaps other underwater maritime structures are from the age of Augustus. If they do date to his reign, why was such a renovation project started but not finished? Was the intent behind such an effort purely to advance the local interests of Cosa, or should the attempted revival of the harbour also be understood as a component of a much larger Imperial policy to create, sustain, and renovate the maritime infrastructure of the Mediterranean world to be commensurate with political, military and economic realities of the new world order that was emerging? As McCann implies in the conclusion of her magisterial book, there remains much to do and many questions still to be answered.

## 4.4. Santa Liberata, Fieldwork June 2003, September 2004, and June 2005

***4.4.1. Background*.** Sometime between 70 and 40 BC, the Domitii Ahenobarbi, a notable senatorial Roman family, established a villa and fish-pool at what came to be called the *Domitiana positio* on the *Itinerarium Maritimum* (Ciampoltrini 1998; Gambogi 2008: 255) for their economic gain. They, along with the Sestii at Portus Cosanus (see above), were undertaking to reorganize sections of the coastline from Albenga to Argentario to their advantage. This *positio*, known today as Santa Liberata, was located on a promontory on the northern shore of the Monte Argentario, jutting into the northeast part of the Gulf of Porto Santo Stefano (Figs. 3.2, 4.17–18, 6.1). The location afforded a partially protected natural anchorage and landing spot that the Domitii enhanced by building an elegant maritime villa, a *piscina* (traditionally referred to as *Bagni di Domiziano*), and functional docks and quays possibly intended for exporting *garum*, produced from the fish raised there, as well as other commodities produced on their neighbouring lands. In the early part of this century P. Gambogi, chief underwater archaeologist for the *Soprintendeza Archeologica per la Toscana*, worked with the Agnelli family, owners of the modern villa constructed on the ruins of the ancient one, to preserve and restore what survived the damage inflicted during what she calls "the architectural anarchy" that occurred in Italy following World War II (Gambogi 2008: 259).

Of particular interest to the ROMACONS team were two very large concrete *pilae* that appear to have served as wave breakers to protect the *piscina* and the main landing for the villa, and possibly as foundations for wooden piers that extended from the shoreline facilities out into the sea (Fig. 4.18; Gambogi 2008: 258, figs. 4–5). One core was taken from the *piscina pila* in June 2003 (SLI.2003.01), while the second core was extracted from the *pila* fronting the villa in September 2004 (SLI.2004.01). A small excavation was also carried out at the base of this *pila* in June 2005.

***4.4.2. ROMACONS fieldwork.*** In June 2003, the ROMACONS team extracted core SLI.2003.01 from the centre of the isolated *pila* located at the northeast corner of the *piscina* associated with the villa complex (Fig. 4.19; Oleson *et al.* 2004a: 225). The upper surface of the block (henceforth the "*piscina pila*") is now awash, covered by *ca.* 0.10 m of water, but it would have been above sea level at the time of its construction. We drilled from the surface of the concrete structure to a depth of -2.28 m, the last *ca*. 0.10 m of this core penetrating into

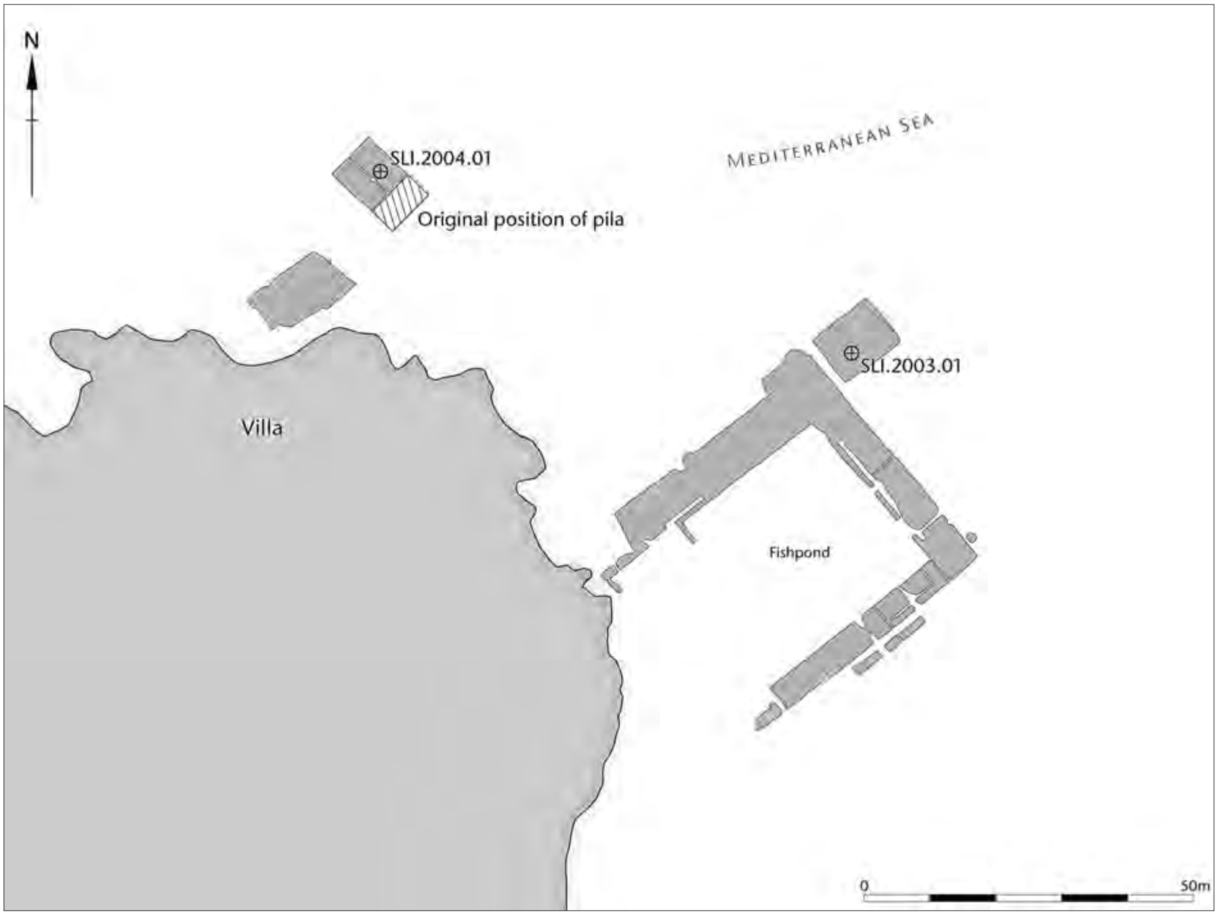


*Fig. 4.17. Plan of Santa Liberata (Will Foster Illustration).*

*Fig. 4.18. Santa Liberata, aerial photograph of villa,* piscina*, and* pilae *(Courtesy of P. Gambogi).*

the sandy floor of the bay. The concrete was compact and homogeneous, with the exception of a possible day joint visible at -0.78 m. The mortar was greenish grey to dark greenish grey in colour; the *caementa* were predominately irregular chunks of yellow brown tuff possibly from the Campi Flegrei (Figs. 7.10–11). The lowest portion of the core, from -1.5 to -2.28 m, disintegrated during the drilling.

The second core (SLI.2004.01) came from a massive *pila* that protected a landing platform of the villa (henceforth the "villa *pila*"; Gotti *et al.* 2008: 585–88). At present, the upper surface is covered by *ca.* 0.5 to 1.5 m of water, the depth disparity due to a slight tilt to the southeast (Fig. 4.20). A fracture line is visible running down the middle of the block.

The villa *pila* is one of three piers that front the ancient shoreline below the villa, but it is the only one that now sits in the sea. Its location, *ca.* 70 m west of the *piscina pila*, is too distant from the fish-pond to provide it with any protection, so its intended function must have been related only to the villa. It is the largest *pila* ROMACONS cored, with dimensions of *ca.* 8.8 m × 8.4 m × 8.5 m × 9.1 m along its sides and 6.3 m in height in its present orientation (lying on one side). At 420 m$^3$, however, this is by no means the largest *pila* known; the *pila* at Nisida north of Naples has a volume of 1,100 m$^3$ (Gianfrotta 1996: 71, fig. 4). The visible height in 2004 at the time we collected our core was only 5.9 m. Technical problems prevented us from coring to the current base of the block. To remedy this problem in June 2005, Brandon with the assistance of Gambogi and a team of underwater archaeologists from the *Soprintendenza Archeologica per la Toscana* excavated the sand around its visible base on the western face to reveal its complete height (6.3 m). The team also noted along the bottom edge the remains of what appeared to be a facing of thin tuff blocks, now eroded away except for the mortar joints (Fig. 4.21). The orientation of the pattern in the mortar suggests that this western face was originally the upper surface of the block, which had been undercut on the west causing it to collapse in that direction (Enrico Felici, oral communication). If tipped back up in a vertical position, the *pila* would line up nicely with the concrete block on the shoreline (Fig. 4.17), suggesting they were part of a coordinated construction plan. There was no visible evidence for any cross beams (*catenae*) or piles (*destinae*) that might suggest it was a Category 1 form as originally thought. Rather, the *pila* was most likely cast within a flooded, pre-fabricated Category 3 form (see pp.208–21).

The length of the core was 5.85 m, the largest recovered during our entire project (Oleson *et al.* 2006: 48), although, as it turned out, we cored this *pila* from side to side rather than from top to bottom. The concrete was composed of large pieces of brown tuff aggregate and well-compacted light grey mortar composed of dark pumiceous ash pozzolan particles, red fragments of crushed ceramics, and relict lime clasts.

***4.4.3. Scientific analysis***. Preliminary analyses of the two cores collected at Santa Liberata in 2003 and 2004 have been published (Oleson *et al.* 2004a: 225; Oleson *et al.* 2006: 48–49;

*Fig. 4.19. Santa Liberata, view of* piscina *and adjacent* pila *during coring of STL.2003.01.*

*Fig. 4.20. Santa Liberata, taking core SLI.2004.01 on the villa* pila.

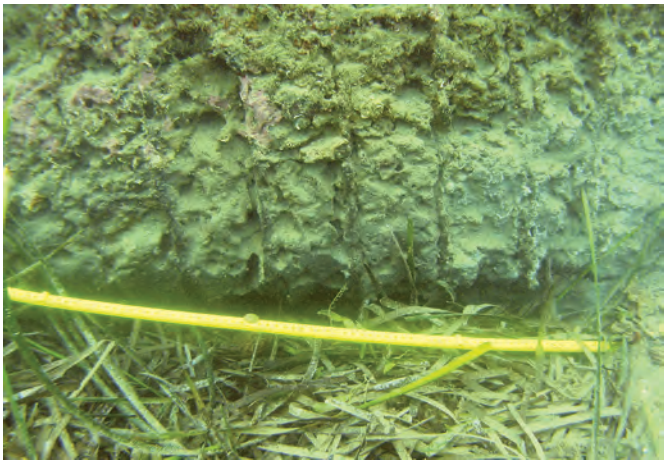


*Fig. 4.21. Santa Liberata, the side of the fallen villa* pila.

Gotti *et al.* 2008), additional analyses appear below in Appendix A3.1 (pp. 243–48), and in Chapter 7.

***4.4.4. Observations and conjectures.*** The purpose of the four *pilae* at Santa Liberata is not known. The one located adjacent to the northeast corner of the *piscina* seems to have been a wave baffle intended to diminish incoming storm waves and keep them from flooding or damaging the fish-pond. It could also have had a secondary purpose as a platform for a statue, or even a navigational beacon. A modern channel into the Lagoon of Orbetello, probably built in the same location as an ancient entrance, is only a few hundred metres east of the *piscina*. A beacon would have assisted sailors in plotting the proper approach. The other three *pilae* adjacent to the villa itself may have served a similar function as wave breakers but they too could have supported a wooden (?) loading platform intended to serve the needs of the villa.

It seems likely that the surfaces of the two *pilae* cored, both of which are now submerged 0.1 to 0.5 m below sea level, stood above ancient sea level when they were constructed. This section of the Tuscan coastline has been quite tectonically stable over the recent millennia (Marriner and Morhange 2007: 152), so the inundation of both *pilae* must be due to a rise in regional sea level since Roman times, estimated to be 0.50 m by Marriner and Morhange (2007: 183), and 0.60 to 1.0 m by Gambogi (2008: 257, n. 6). Either estimate would put the surface of the *piscina pila* above water in Roman times. Since the surface of the tilted villa *pila* must also have stood above sea level when upright in order to fulfil its intended function, the collapse of the block may explain the visible fracture line.

The two cores from Santa Liberata provided the only two samples collected from private rather than public maritime structures (*i.e.* municipal or Imperial harbours). The status of the *pilae* at Cosa remains somewhat ambiguous. Time did not permit collection of samples from the many other *villae maritimae* and their associated *piscinae* along the Italian coast, although that would have been a valuable addition to our project (Higginbotham 1997; Lafon 2001; see pp. 227–29). With no appropriate *comparanda*, one can only say that the overall quality of the concrete cores collected here seems generally to equal or even to exceed that of some of the cores collected from contemporaneous public Italian installations – the structures examined at Cosa (if the *pilae* are part of an aborted Augustan restoration), the Gulf of Naples, Portus, and Egnatia. Perhaps the resources, social standing, and expectations of the Domitii Ahenobarbi for quality construction, as well as a closer supervision of work in progress by the contractor, determined a better result.

Neither Santa Liberata core contained any organic material that could help provide construction dates. Gambogi's date for the possible construction of the villa, mid-first century BC (2008: 257) may well apply to the building of both *pilae* as well, although they could also have been later additions constructed to address problems that arose involving the *piscina* or the villa. Although the exact date when this villa and its associated maritime structures fell out of use is not known, it is likely that its beautiful and protected location guaranteed a long life, marked no doubt by normal and predictable repairs and renovations necessitated by proximity to the sea. It is not clear whether these *pilae* provide testimony to this process of regular rehabilitation or maintenance, or whether they were part of the original design of the maritime structures.

What is certain, however, is that no matter when the villa *pila* was built, its actual construction must have tested the limits of the Roman ability to build a concrete block in the sea in an inundated wooden form, whether built *in situ* or prefabricated. The ROMACONS project of constructing a reproduction of a Roman concrete block in Brindisi (Hohlfelder *et al*. 2005; Oleson *et al*. 2006; below, Chapter 5), demonstrated vividly the onerous character of the menial tasks of constructing the formwork in the sea: driving poles and planks into the sea floor; bracing the formwork with crossbeams; securing the vertical planks to the external skeleton of the formwork; mixing the mortar; placing it in wicker baskets in the frame, adding and tamping aggregate, etc. This was true even in the shallow, calm water (1.7 m at high tide) where Brandon, Hohlfelder, and Oleson could stand to work (Hohlfelder *et al*. 2005: 124). Based on the difficulties we experienced at Brindisi, it is almost unimaginable to envision achieving similar results in water that was at least *ca.* 5 m deep in a location exposed to the open sea; yet somehow the Roman builders were successful.

At the villa *pila* the mortar and coarse aggregate were placed alternately and then tamped together in a purpose-built inundated wooden formwork over 8.5 m in height, whether built *in situ* or – more likely – prefabricated (Category 1, Brandon 2011: 124, 130). The process of construction sounds simple, but the Roman builders encountered complexities and challenges that required extraordinary resourcefulness. With the completion of each project involving building concrete structures in the sea, the body of practical experience and knowledge of the engineers, architects, and crew supervisors involved grew accordingly. But how did this pragmatic knowledge spread throughout Italy and the entire Mediterranean basin? Given the scale of these engineering undertakings, and the involvement of state planners and engineers, there may have been some written practical manuals covering engineering in the sea. The master-apprentice system so important to the Greco-Roman crafts and trades might not by itself have been sufficient (DeLaine 2000, 2002; Oleson and Jackson 2010: 291–92; Harris 2011: 18). Each building project in the sea undertaken in the first century BC, and in future centuries as well, provided a laboratory for experimentation and the refinement of existing technology. New advances were somehow passed on to the builders of the next harbour in the ever-growing maritime infrastructure of the Roman Empire.

Another important issue surrounding the building of concrete structures in the sea involves labour costs, defined here as man-hours necessary to construct a massive structure like the villa *pila* in a marine environment. Based on our experience in building the reproduction *pila* in Brindisi, we can make some estimates of the labour involved. We calculated that it took *ca.* 30 man-hours of work for each cubic metre of concrete that we prepared and placed in our inundated formwork (Oleson *et al.* 2005: 44). If the ancient builders of the villa *pila* had worked at a similar pace, the labour required to construct this massive block (420 m$^3$) would have been *ca.*12,600 man-hours. Our earlier estimates of the labour costs for building the villa *pila* at Santa Liberata were based on a different scale of measuring labour productivity. We estimated that it took two man-days to prepare and place one cubic metre of concrete without specifying how many hours of labour would constitute a man-day (Oleson *et al.* 2004a: 219). If one attempts to apply our "productivity" at making and installing reproduction of Roman concrete to the construction of the villa *pila* at Santa Liberata, a man-day would have had to consist of 15 hours of work, an excessively long work day for any worker, even a slave.

It is also true that our estimates provided in 2004 had not been tempered by our practical experience at Brindisi. Even so, the Brindisi man-hours per cubic metre should only be seen as a very outside limit of labour that might have been expended per hour in antiquity. Economy of scale and efficiency at Santa Liberata would have reduced the man-hours of labour expended in numerous ways. Skilled, experienced crews, assigned to specific tasks such as mixing the mortar, delivering it to the formwork, tamping the coarse aggregate into the mortar, etc. would have performed far more efficiently than a novice team of three archaeologists masquerading as ancient construction workers. Thus, our earlier estimate of labour expended remains a far better one than trying to extrapolate a new one based on our Brindisi experience. One thing remains certain: however we try to estimate the labour costs expended on building this one concrete block, they would have been enormous.

We can only guess at the composition of the work crews that built this *pila* or other concrete structures in the sea. Was it predominately an unskilled slave work force? Or did slaves work side by side with freedmen and Roman citizens? Who were the skilled workmen who served as supervisors? Were they members of a distinct *collegium* unknown in surviving written sources whose members were perhaps individually called *caementarii*, or were they military engineers (see *CIL* 10.3414; p. 36, Passage 32)? Who designed and executed the maritime installations of the Domitii Ahenobarbi villa? Unfortunately, the surviving architectural features themselves at Santa Liberata and elsewhere provide no answers for these questions. DeLaine (1997, 2000, 2002) has documented the sophistication and careful organization of the Roman Imperial construction industry on land. Did similar refined administration and building protocols apply to building in the sea as well?

## 4.5. Caesarea Palaestinae, Fieldwork October 2005

***4.5.1. Background.*** The entry of Caesarea Palaestinae into the international world of the Mediterranean in 9/10 BCE was surprising and dramatic (Fig. 3.2). In less than two decades and on an essentially empty site midway between present day Haifa and Tel Aviv, King Herod of Judaea created a large, well-equipped Greco-Roman port city. The most striking feature of this new city was the construction of an artificial, all-weather harbour complex on a sandy coastline devoid of any natural anchorages (Figs. 4.22–24). Equally stunning was the short space of time required to accomplish this task. In about eight years of work (*ca.* 23/2 to 15/14 BC), the harbour installations were completed. This new international emporium was initially called "Sebastos" (= "Augustus" in Greek) and later *Portus Augusti*, after the re-founding of the city as a Roman colony by Vespasian in AD 71 (Patrice 2011: 90). Both these names specifically honoured the emperor and Herod's patron, Augustus. As Josephus reminds us, Herod also dedicated Sebastos to "the men who sailed in these waters" (*BJ* 1.414). The harbour was the *raison d'être* for the port city of Caesarea (Flemming 1996: 37).

This gateway to the political and economic centres beyond the eastern littoral of the Mediterranean Sea was intended to serve the king's interests in many ways. The names Herod bestowed on his city and its vast harbour complex were tangible symbols of the Jewish king's professed loyalty and commitment to the new world order that Augustus was forging. Caesarea's maritime facilities immediately took on an important role in the eastern Mediterranean. In what could be called a historical instant, a technologically advanced, safe, and commodious harbour had suddenly sprung into being along the main maritime corridor between the two major emporia of Alexandria and Antioch, and it was poised to become an integral component of the Imperial maritime infrastructure. In addition, it was Herod's personal entry point to the Mediterranean world for the many products produced in his own territories and for those that arrived on land routes from farther east.

There have been various suggestions for resolving the ambiguity of Caesarea's proper epithet. According to Suetonius (*Aug.* 60), all of Rome's client kings created (on their own initiative?) a city named Caesarea in the emperor's honour. For contemporaries, how would all the cities named Caesarea be distinguished? Herod's city may have been called Caesarea Stratonis at the outset (after its predecessor settlement Straton's Tower) but became Caesarea Palaestina or Caesarea Palaestinae sometime in the Roman era. Caesarea Maritima, the most commonly used modern appellation, appeared in antiquity only in Greek, as Καισάρεια ἡ παράλιος (*e.g.* Josephus, *JA* 13.313, *JW* 1.80) or ἡ ἐπὶ τῇ θαλάττῃ Καισάρεια (Josephus, *JW* 7.20.30). For the sake of historical accuracy, we have decided to use Caesarea Palaestinae.

A story of amazing maritime engineering experimentation and accomplishment lies behind the sudden appearance of

Sebastos: daring building innovations, technology transfer from the western to the eastern Mediterranean, and impressive solutions to the natural and logistical obstacles that were encountered. When completed, Sebastos was an ancient engineering *tour de force* that confirmed that harbours could be constructed throughout the Roman Empire wherever they were needed, and not only where nature afforded advantageous circumstances (Fig. 4.24; Oleson and Hohlfelder 2011: 821). The changing fortunes of King Herod's harbour over the next centuries remain controversial, but most certainly Caesarea always had a functioning harbour of some kind (Flemming 1996: 37). The city was a Roman colony after AD 71, the metropolis and administrative capital of Palaestina, and the recipient of numerous Imperial *beneficia* associated with various Imperial visits in the second and third centuries, and "…the best harbour of Judaea/Palaestina during its long Roman and Byzantine history" (Patrice 2011: 120). Along with Antioch, Caesarea was one of the two major maritime gateways between the Roman Mediterranean world and the Near East.


*Fig. 4.22. Sebastos, aerial view of submerged harbour installations (R. L. Hohlfelder).*

The archaeological remains of Caesarea's harbours are uncommon in many ways. Most other ancient maritime installations of the great harbours of antiquity have been disturbed or even obliterated by subsequent occupation (*e.g.* Massilia, modern Marseilles, and Portus). The state of survival and accessibility of King Herod's submerged harbour ruins are unique. Not surprisingly, Sebastos has been the object of more underwater archaeological survey and excavation than any other ancient harbour site in the Mediterranean. From the

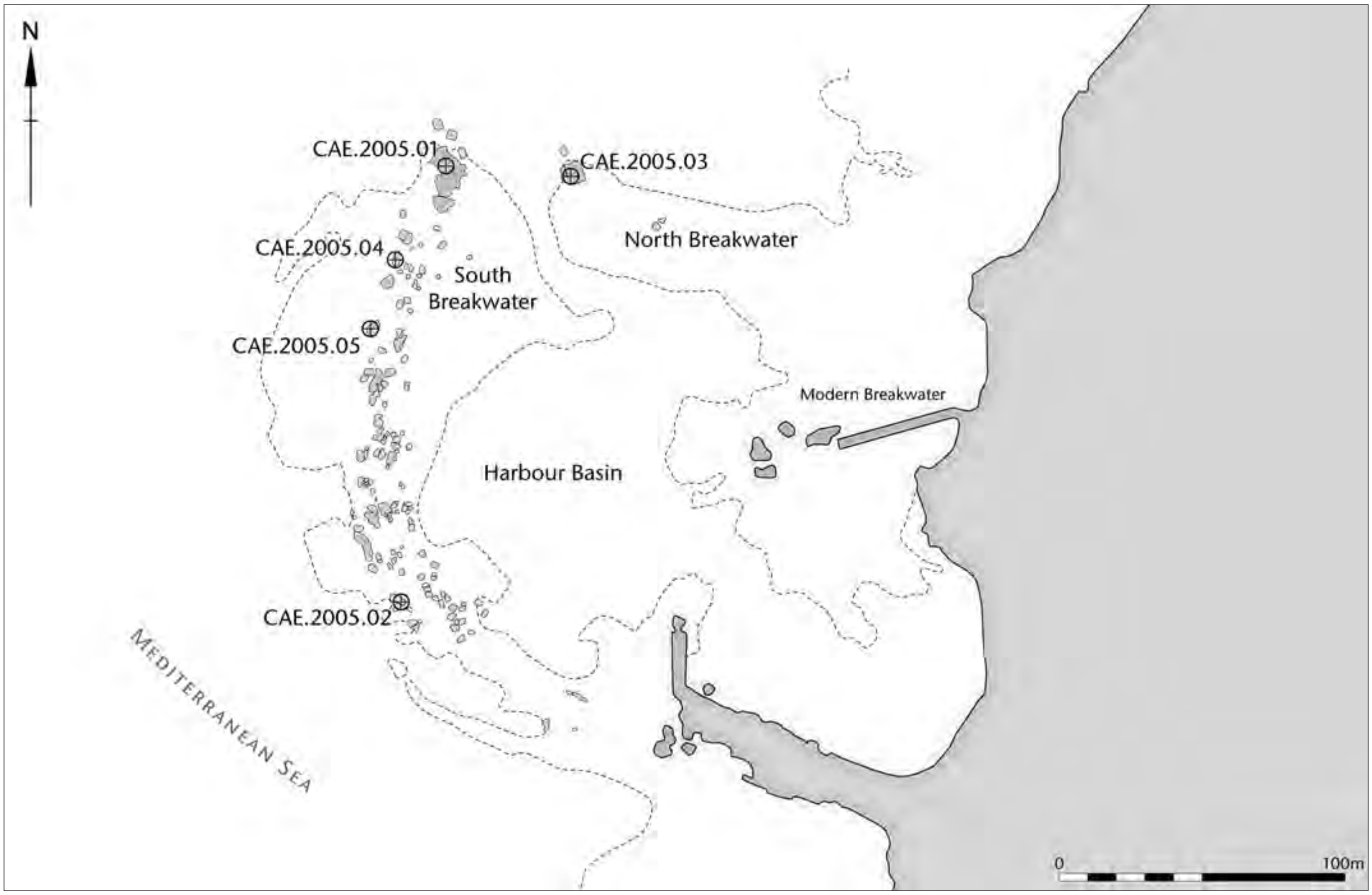


*Fig. 4.23. Sebastos, plan of harbour remains, with indication of coring locations (Will Foster Illustrations).*

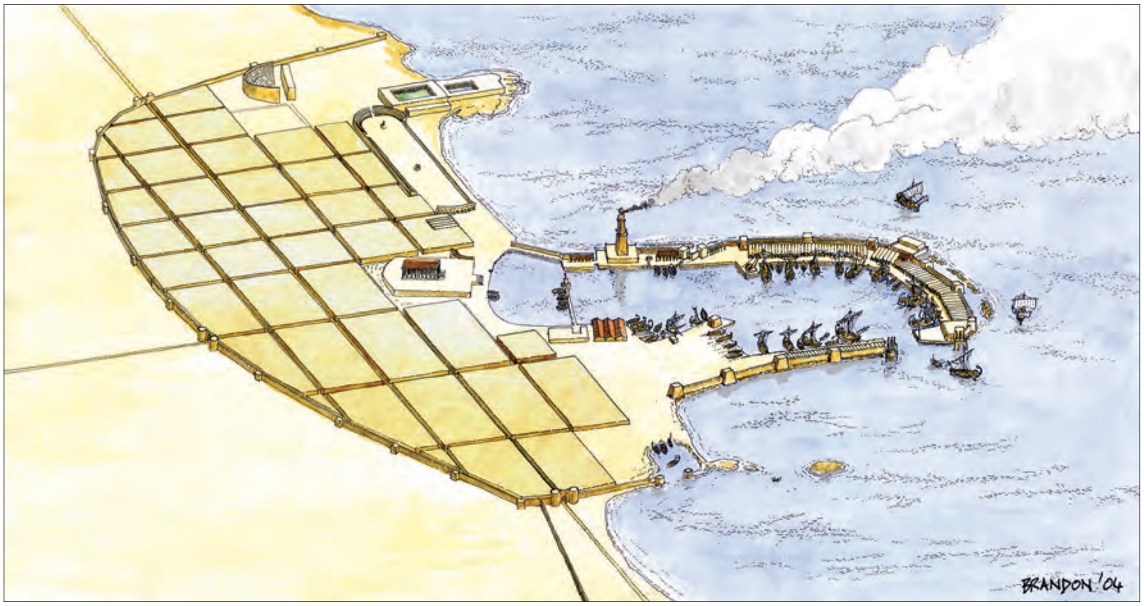


*Fig. 4.24. Sebastos, reconstruction of harbour remains (C. J. Brandon).*

1960s to the present, teams of Israeli and international scholars, including Raban (1975–2004), Brandon (1990–2004), Oleson (1978, 1981–85), and Hohlfelder (1978 –1992), have worked intermittently in the sea uncovering the history of this once magnificent harbour. The results of these many explorations are to be found in a vast number of published reports, while others are still in preparation (for bibliographies see Raban 2008, Holum *et al.* 2008).

During fieldwork conducted by the Caesarea Ancient Harbour Excavation Project (1981–1990), numerous concrete blocks were discovered among the rubble that now survives from the southern and northern breakwaters of the Herodian harbour. One of the most important individual finds was a large concrete block (*ca*. 11.5 m × *ca*.15.0 m × *ca*. 2.0 m) located in CAHEP's Area G (Oleson 1989a: 127–30; Raban 2008: 134–35) that formed the head of the northeast corner of the northern breakwater (Figs. 3.1, 4.25). Analysis of the concrete samples taken by Oleson from this structure revealed that the tuff and pumiceous ash pozzolan that composed the concrete were likely imported from the Gulf of Naples, 2,000 km to the west (Oleson and Branton 1992: 56–66). This startling discovery clearly linked the construction of this harbour with technological advances in Roman harbour engineering, and possibly with contemporary projects in the Gulf of Naples region. Continued survey uncovered other blocks of concrete, and ultimately the entire underwater ruin field was studied and recorded (Brandon 1996, 1999).

Brandon estimated that approximately 35,000 cubic metres of concrete were used in the construction of the enclosing moles of the Herodian harbour of Sebastos (Hohlfelder *et al.* 2007: 414). This is considerably less than the 78,000 cubic metres proposed by Boyce and Reinhardt (Boyce *et al.* 2004:

*Fig. 4.25. Sebastos, photo of concrete block and formwork in Area G.*

135). Brandon's estimate was based on measurements from the archaeological record whereas Boyce and Reinhardt calculated their value from a marine magnetic survey. One of the most significant differences regards the proportion of pozzolanic volcanic ash used in each cubic metre of concrete. Votruba (2007:327) estimated that percentages were 80 volume % *caementa* (coarse aggregate) and 20 volume % mortar. In contrast, measurements of the mortar to *caementa* ratio on the surfaces of four Caesarea core samples drilled by ROMACONS (Table 7.1) suggest that these figures should be reversed: values range from 83 to 59 volume % mortar and the average is about 70: 30 volume % mortar to *caementa*. The Vitruvian formula suggests that one cubic metre of mortar contains, on average, about 780 kg volcanic ash with unit weight 1,100 kg/m$^3$ (Table 7.2; pp. 161–63). Since one cubic metre of the Caesarea concrete has been shown to contain about 70 volume % mortar, or 546 kg ash pozzolan, the 35,000 m$^3$ Caesarea structure required about 20,000 metric tons of pumiceous ash pozzolan. This corresponds to about 17,370 cubic metres of volcanic ash. Ambiguities remain because of uncertainty about the degree of compaction of the ash resulting from mixing with water, but the general range should be correct. It was the discovery in Area G and the subsequent findings of Brandon that inspired the creation of ROMACONS and informed its research design.

***4.5.2. ROMACONS fieldwork.*** In October 2005, through the intervention of Professor Michal Artzy, then head of the Recanati Institute of Maritime Studies of the University of Haifa, we secured permission from the Israel Antiquities Authority to collect five cores from five different concrete blocks on the submerged breakwaters (four from the southern breakwater and one from the northern; Fig. 4.23) (Hohlfelder *et al.* 2007). CAE.2005.01 was a small core (L 1.10 m) from one of several large blocks from Area K. These blocks formed the north-south leg of an L-shaped extension at the terminus of the southern breakwater. All five blocks were arranged more or less in a north-south line, the inner or eastern edge seemingly aligned with the inner quay of the southern breakwater (Fig. 4.26; Raban 2009: 74–86; Hohlfelder 1996: 89, fig. 5; Brandon 1996: 39, fig. 8; 1999: 171, figs. 1, 3). Each of the blocks had been formed from concrete placed in single-mission wooden barges that had been purpose-built on shore, towed into position, then filled with concrete until they sank (see pp. 210–20). This

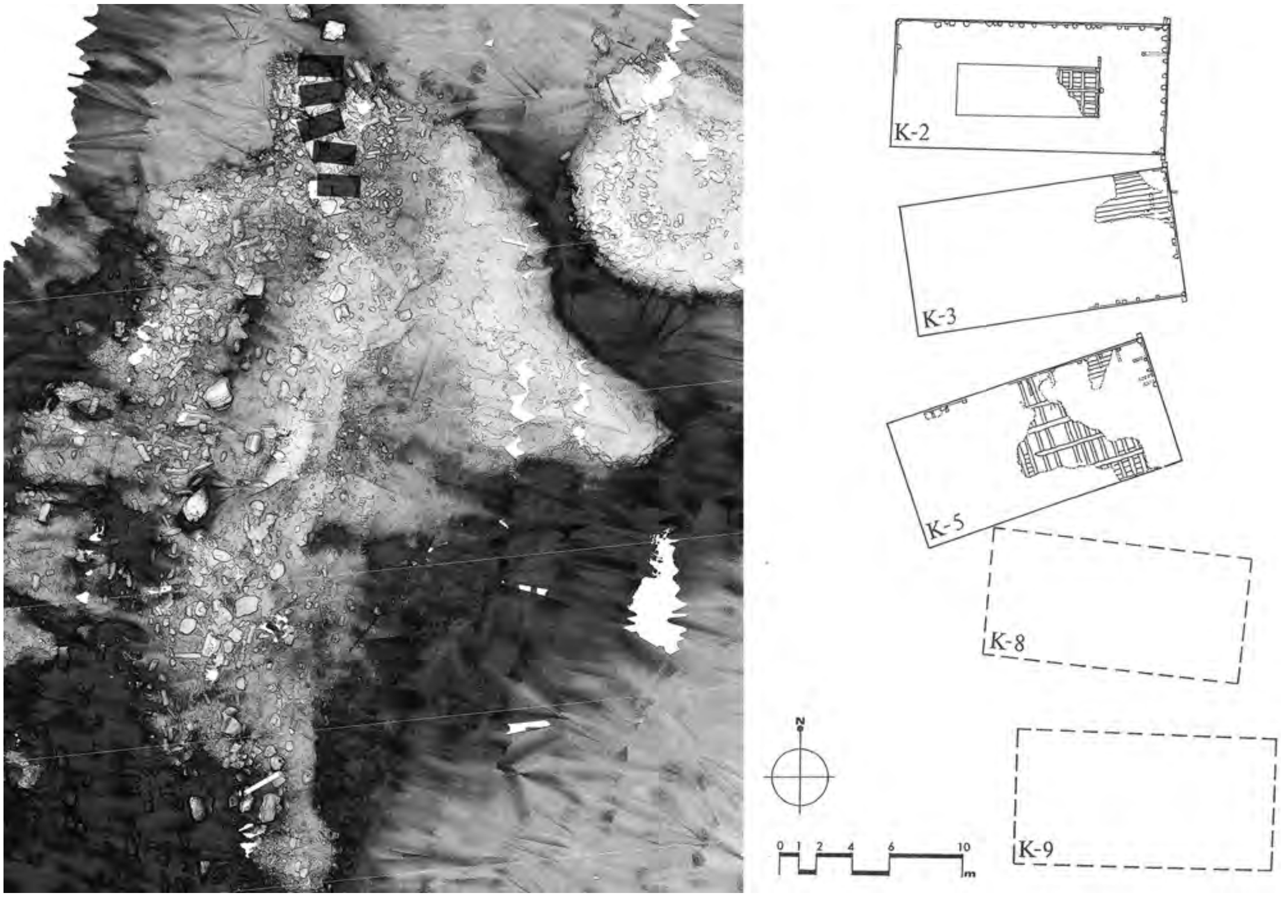


*Fig. 4.26. Sebastos, sonar image and plan of blocks in Area K (C. J. Brandon).*

method of placing concrete in the open water, and yet another variation used to construct the block in Area G that yielded CAE.2005.03, were not mentioned by Vitruvius. They may represent an innovation created on site by the Roman builders who came to provide technical assistance. The engineering challenges posed by such an exposed site where concrete structures had to be built far from shore in a high wave-energy environment required new techniques, and the experimentation with innovative types of wooden formwork seems an obvious and reasonable way to address some of the issues encountered.

The extraction of CAE.2005.01 terminated when the drill entered a cavity caused by deterioration of one of wooden crossbeams of the original formwork. We were unable to continue the drilling of this core. The bottom 0.1 m of the recovered core was moist from the water that filled the hollow (Figs. A3.58–59).

CAE.2005.04 and 05 were taken from *pilae* that appear to have been a "spinal" or skeletal element of the southern breakwater (Raban 2009: 88–89) (Figs. 4.23, 4.27). CAE.2005.02 was taken from one of a group of three blocks, formed following the Vitruvian instructions with predictable minor variations (Brandon Category 1, below pp. 191–205; Brandon 2011: 124–25). All three have tie-beam impressions on their upper surfaces (Fig. 4.28–30).

All four of these cores are similar in many respects (pp. 274–79). The quality of the mortar of each was reasonably good, and in all cases contained pumiceous ash pozzolan possibly shipped from the Gulf of Naples area (Figs. 7.10–13). Pumice *lapilli* up to 3 to 4 cm in diameter, also appeared in the volcanic ash supplied for the *pila* reconstruction at Brindisi; apparently no care was taken to sift them out. Alternatively, coarse sifters were used, and the *lapilli* (D 0.01–0.02 m) simply passed through. The mortar in these cores seemed to have more relict lime clasts and more large voids in the mix due to poorer compaction than we encountered in the samples from Italy. The coarse aggregate used in the Caesarea concrete was primarily the abundant calcarenite grainstone known locally by the Arabic word *kurkar*. It was an economical solution to use this local stone as aggregate rather than importing volcanic tuff from Italy, but it appeared to us during our preliminary on site analysis that the mortar did not adhere as well to the *kurkar* (see pp. 175–80).

Core CAE.2005.03 was extracted from Area G, the pier head at the end of the northern breakwater. While the core was


*Fig. 4.27. Sebastos, coring of* pila *at CAE.2005.04.*


*Fig. 4.28. Sebastos, view of block from which core CAE.2005.02 was taken.*

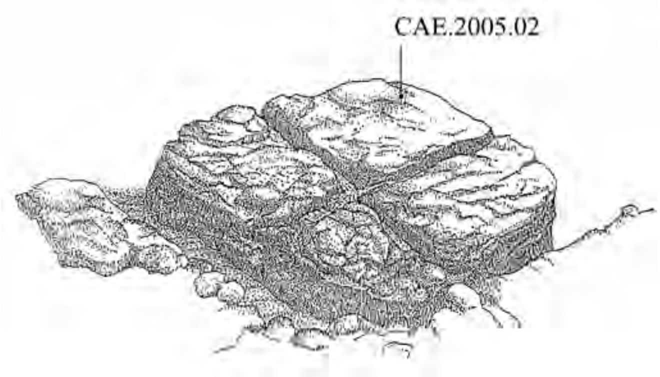


*Fig. 4.29. Sebastos, drawing of block from which core CAE.2005.02 was taken (C. J. Brandon after P. Dessauer and L. Reynafarje).*

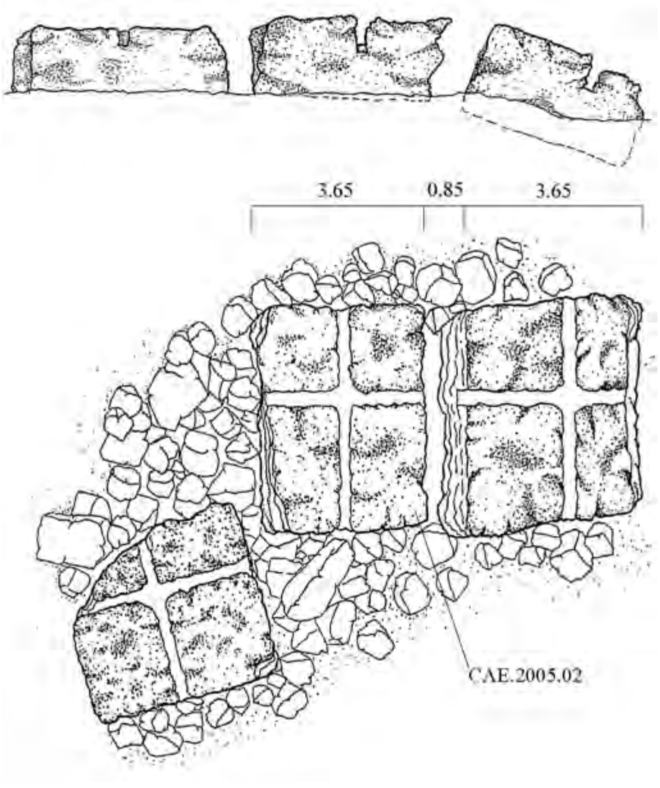


*Fig. 4.30. Sebastos, drawing of group of blocks from which core CAE.2005.02 was taken (C. J. Brandon after P. Dessauer and L. Reynafarje).*

made of the same materials as the other cores, it seemed less cohesive, and relict lime clasts seemed even more common in this sample (Fig. A3.63). Whatever shortcomings the concrete exhibited may be due to its placement in the open sea, where wave action might have washed away mortar before it had completely cured.

***4.5.3. Scientific Analysis.*** A preliminary evaluation of the five samples taken at Caesarea has been published (Hohlfelder *et al*. 2007; Vola *et al.* 2011). Further scientific analyses appear in Chapter 7.

***4.5.4. Observations and conjectures.*** Analysis of the five Caesarea cores revealed that the concrete shows greater variations in material and physical characteristics than cores from the concrete structures along the central Italian coast (pp. 168–79), excepting Cosa. This result is somewhat surprising, since Josephus clearly states that Herod had spared no expense in building Caesarea or Sebastos (*BJ* 1.408–11, *AJ* 15.332–35, pp. 29–31, Passages 20–21), and, considering the importance of this construction to Herod's plans and of the honorific nature of both constructions, more consistent material properties might have resulted.

Several factors may account for this. While concrete had been used extensively and nearly contemporaneously at Portus Iulius, the setting in the Bay of Pozzuoli was naturally more protected than the site of Sebastos. Portus Iulius was relatively sheltered from storms, and the fetch allowing heavy seas to build was much less. The engineers at Sebastos had to deal with winter storm waves that could reach 10 m; in December 2010 a storm of this magnitude even destroyed an "ancient pier" at Caesarea (*Haaretz,* 13 December 2010). Not only would work in the sea frequently have been impossible during the winter, but also any construction that was in progress or had recently been completed was at risk of being severely damaged or entirely swept away.

The Roman builders of Portus Iulius also had easy access to both local pumiceous ash pozzolan and local tuff *caementa*. Work did not have to be suspended due to a lack of available volcanic ash through delay in its importation. Such was not the case at Caesarea. Shortages of this critical ingredient, and perhaps even of lime and wood, could have led to stoppages, and the use of local substitutes, mainly small particles of carbonate rock. While the sea and contrary winds could have disrupted the importation of critical materials from Italy, Cyprus, and Anatolia, King Herod had his own schedule and reasons for completing Sebastos as soon as possible (Hohlfelder 2000a: 242–43; Oleson *et al*. 2011: 115–17). His master builders would have been challenged to find ways to expedite construction even when their initial plans had been thwarted by nature.

Other factors could also have played a role in producing the somewhat uneven craftsmanship in evidence in the Caesarea concrete. There may have been too few experienced master builders, trained senior workmen, or crew chiefs who had worked on extensive building projects in the sea. The supervising engineers most probably had seen experience at Portus Iulius and elsewhere along the Phlegraean coast (Hohlfelder 2000a: 252; Gianfrotta 2011a: 191). Raban (2009: 159), however, thinks the master builders came from Alexandria. Without adequate supervision over this new technology, the foremen may have been unaware of the unintended consequences of failing to mix the mortar properly. The Roman builders in King Herod's employ may also have experimented with labour, material, or cost-saving measures, some of which failed. For example, Brandon discovered that the concrete fill in the single-mission barge in Area K2 had both inferior non-pozzolanic as well as pozzolanic mortar (Brandon 1999: 169–78). At some point after its construction, once the wooden barge form had rotted away and the concrete within was exposed to the open sea, the stratum containing non-pozzolanic mortar deteriorated more rapidly than concrete containing the pumiceous ash pozzolan mix. Ultimately, the whole block failed. There also could have been a systemic indifference to the quality of workmanship on concrete blocks that would never be closely scrutinized by Herod or any major officials of his court. The upper surfaces of the blocks, all that would have been visible to officials and the public, were paved, while most of each block was submerged and essentially invisible.

The concrete block at the end of the northern breakwater at Area G (Figs. 3.1, 8.58–60) would have also stood *ca.* 1–2 m above ancient sea level, with a paving covering the upper surface. The concrete was placed within a hollow, purpose-built wooden caisson intended to hold the material until it cured. The wooden planking of the formwork appears to have been left in place, perhaps to ensure the integrity of the block during curing, or because it was too difficult to remove. Over time, the sections exposed to the sea naturally deteriorated. Wood was an expendable commodity, and it was probably not worth the effort required to recover planking that had been in the sea for several months and thus too waterlogged or worm-eaten for any useful recycling (Oleson *et al*. 2006: 50).

One unique aspect of the engineering of Caesarea's harbour complex that most authors have stressed was the placement of a bedding of rubble on the poorly consolidated sea floor before the two breakwaters were constructed (Raban 1989: 186–87). Raban does not discuss the nature of this bedding, its thickness, or the methods of its placement in his final, summary publication (Raban 2009). Throughout his book, however, its existence is assumed. If the master builders had decided that the installation of a rubble foundation at least as wide as the width of either breakwater were necessary, they would have made an important engineering advance neither suggested by Vitruvius nor employed at Portus Iulius.

Evidence for this element of the design, however, was found only inconsistently during the many years of underwater excavation. Although Raban does not discuss the rubble bedding, a recent study by Votruba (2007: 332) provides a clear description of bedding found under Area CO, the location of core CAE.2005.05. He notes that a 0.40 m stratum of imported river cobbles had been laid above a layer of unconsolidated sand, and that the concrete of this *pila* had been installed directly on the cobbles. While this distinct layer, which seems unique to this location, may have been only a small section of a larger layer of imported cobbles that formed a bedding for the entire southern breakwater, it seems more likely that these cobbles had been dumped in the wooden formwork to provide a foundation specifically for the construction of the large *pila*. His interpretation that this is "evidence of discrimination in the use of materials by the builders" to accommodate the construction of one of Caesarea's largest *pilae* seems right. It may also have been an experiment intended to advance the growing body of empirical knowledge for building in the sea. We do not know whether this use of imported river cobbles as a foundation course for a *pila* occurs only here, or if it was common practice at Sebastos when the *pilae* of the spinal wall were constructed. So far, it is a very localised phenomenon that has not been identified anywhere else in the harbour. The most likely explanation is that the cobbles were ballast dumped on the seabed and then recovered and transported to the form to serve as a foundation course. It is clear that no similar foundation course of imported cobbles was found beneath the block in Area G (Raban 2009: 96), or beneath the blocks in Area K (Brandon 1999: 176–77, fig. 9).

The blocks in Area K and, to an extent, the block in Area G, are tilted and askew, having slumped from their original position (Raban 2008:130–32, figs. 4–5). For several decades, the source of this slippage, along with the subsidence of most of Caesarea's harbour, was thought to be neotectonic faulting with a vertical displacement of 5 to 8 m (Mart and Perecman 1996: 11–17). Two offshore north/south fault lines were posited that ran parallel to the present coastline. One supposedly crossed the northern breakwater, while the second was either adjacent to the western side of southern breakwater or ran along its axis (Reinhardt and Raban 1999a: 881, fig. 1). In later publications Reinhardt and Raban (2008: 173, fig. 15) show the fault lines as putative; Raban (2008: 130, 134) shows both where they occurred or were suspected to have occurred; Raban (2009: 198, fig 7.14) does not show them as putative. Other scholars, however, claim that the Israeli coastline has been tectonically stable for at least 2,500 years and that no faulting at Caesarea or elsewhere has taken place during that time period (Marriner and Morhange 2007: 162; Gill 1999: 24; Sneh 2000: 27; *contra* Raban 2009: 205).

Raban pioneered the idea of a sudden tectonic submergence of the harbour and during his career suggested various dates for its occurrence. He never satisfactorily explained why there was no archaeological evidence for collateral damage to the terrestrial structures during the early Imperial era, or why there were no visible signs of structural damage to the Northern Breakwater allegedly transected by one of the two fault lines he proposed. In later publications Raban and Reinhardt dated the upheaval specifically to the period between AD 75 and 96 (Raban 1999a: 188; Reinhardt and Raban 1999a). Such a date seems most unlikely. Although Josephus had first described the grand functioning harbour built by King Herod in his *Jewish Wars* published *ca.* AD 75–79, he virtually repeated this description in his *Jewish Antiquities,* generally believed to have been published *ca.* AD 93–95. It seems incredible that he would not have indicated in his later work that these engineering wonders were now in ruins because of some recent tectonic upheaval, one with which many of his readers would have been familiar.

A specific date of 13 December 115 has recently been suggested by Reinhardt for the possible destruction of the harbour (Reinhardt *et al.* 2006). He argues that a tsunami of considerable force, recorded in Talmudic sources, overwhelmed the harbour installations that day and probably caused lasting damage. The sudden recession of the water may have scoured sand from beneath both breakwaters and was followed by a broadside impact on the southern breakwater of the tsunami wave of uncertain height that washed into the Inner Harbour. The subsequent backwash did further damage and continued the scouring of sand from beneath both breakwaters. There is no doubt that a sudden disaster such as this could easily have shifted and tilted the blocks in Area K and Area G. The scouring of sand from beneath these structures and the dispersing of the riprap berms that had stabilized the blocks during their construction would have increased their vulnerability to further destructive actions of the sea. The most damage to the breakwaters probably occurred where structures had been built on unconsolidated sediments with insufficient or no underlying foundations, such as in Area K and Area G. At the time of the tsunami, ships in the harbour or outside waiting for clearance to enter would have been swept up on the breakwaters as the wave swept in or receded. A ship carrying the six lead ingots cast during the reign of Domitian (81–96), probably as part of a repair kit, foundered in Area K at this time. But evidence for this one shipwreck does not mean that the southern breakwater fell completely out of use (Raban 1999b: 179, 188).

Neotectonic activity did not sink Herod's harbour in an instant. The tsunami of 115, if in fact it occurred, did not end its life either, although it may have begun its transformation. Some areas of the breakwater may have been breached; others remained intact, even if buildings that once adorned it had been destroyed; and other parts may have disappeared beneath the sea or remained awash. Hadrian visited Caesarea in AD 130, shortly after this disaster. Since he was known for providing funds for ports (Cassius Dio 69.5.3 and *infra*, Pompeiopolis) and did in fact bestow many Imperial *beneficia* on this city, it seems likely that he would have addressed the harbour's needs if it had slipped into a dysfunctional state (Holum 1992*:* 52). For his philanthropic activities the local coins of Caesarea hailed him as a "founder" of the city. Five of his successors, Antoninus Pius, Marcus Aurelius, Septimius Severus, Caracalla, and Macrinus, were also honoured as "founders" of the city, most probably for similar acts of Imperial beneficence (Hohlfelder 1992: 78). If Hadrian had somehow failed to respond to the dereliction of Caesarea's harbour, it is likely that one of his successors would have done so (Raban 2009: 194). The city and its role in Syria/Palaestina and the international maritime world of Rome were too important to ignore. One can safely say that Sebastos, or Portus Augusti as the harbour was called in Caesarea's Roman colonial epoch, would have been dealt a debilitating but not fatal blow by the AD 115 tsunami. Its former regal grandeur had ended and would never be restored. Its more mundane and utilitarian life as the maritime gateway for the province of Judaea/Palaestina and the harbour of its capital had begun.

Yule and Barham suggest (1999: 278) that this gradual transformation and reconfiguration of the Outer Basin may have occurred in the following way. The ruins of the arching southern breakwater, could have served as rim-reef protecting a "well-fluxed sandy lagoon environment in the Outer Harbour." Where necessary, harbour maintenance teams could dredge a channel from the Herodian harbour entrance into the eastern reaches of the Outer Harbour (Raban's so-called Intermediate Harbour) and then to the Inner Harbour. This expedient solution would have been the least expensive way of maintaining a functioning harbour to meet Caesarea's needs. Rubble could also have been dumped on the sunken or broken remains of the Herodian breakwater to fill in the gaps (Fig. 4.31). This may have been the type of renovation undertaken during the reign of Anastasius (Hohlfelder 1988: 58–59, 2000b; Raban 1996: 656–57; Procopius of Gaza, *Panegyricus in Imperatorem Anastasium* 19). Such procedures also explain the increased use of the Inner Harbour during the Roman period up to the fourth century.

Whatever other vicissitudes befell the Outer and Inner Basins following the tsunami, the harbour survived and functioned in some fashion. Its loss of elegance and grandeur and its metamorphosis into a utilitarian Roman harbour coincided with a general diminution of maritime trade throughout the Mediterranean beginning in the later second century and accelerating in the third (Parker 1996: 108), a trend discernable in the underwater finds at Caesarea as well (Oleson 1996: 371). Some scholars have argued that this decline in international trade was due to a non-functioning harbour, but general economic forces may have been responsible rather than local conditions. It may or may not have been "the best harbour of Judaea/Palaestina" throughout the Roman and Byzantine periods (Patrich 2011: 120), but somehow and in some way the harbour was sufficient to meet the needs of Caesarea, Syria/Palaestina, and Rome (Ringel 1988; Hohlfelder *et al.* 1992: 78; Flemming 1996: 37; Raban 2009: 188).

One of the few constants of life is change. The same can be said of harbours. They are man-made installations that are created to meet specific economic, military, and/or political purposes. As long as these imperatives persist and available resources permit, communities will continue to maintain them as long as they serve their needs (Hohlfelder 1996: 78). The character and fortunes of Sebastos surely changed over time, but through its long history it continued to meet the requirements of the port city of which it was an integral component. Without this portal to the seafaring corridors of the Roman and Early Byzantine world, Caesarea would have quickly withered. But that did not happen. The abundant

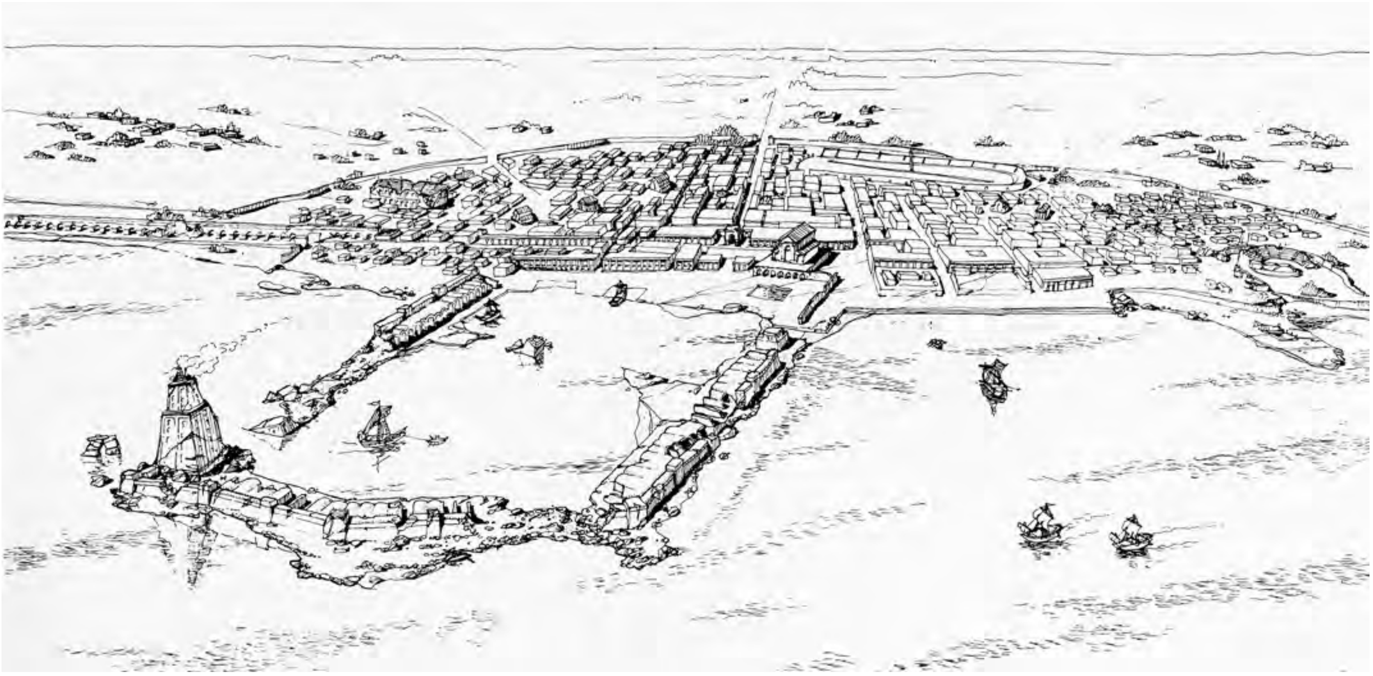


*Fig. 4.31. Sebastos, reconstruction drawing of the harbour in Late Antiquity, following renovation with dumped rubble (S. Giannetti, in Holum* et al. *1988: 159, fig. 110).*

evidence for its prosperity and importance recovered during years of terrestrial and underwater excavations suggests that its maritime window did not close until sometime in its Arab history.

## 4.6. Baianus Lacus, Baianus Sinus, and Portus Iulius (Bay of Pozzuoli), Fieldwork September 2006

***4.6.1. Background.*** The coring sites at Baianus Lacus, Baianus Sinus and Portus Iulius were all located in ancient Campania in the Bay of Pozzuoli (Brandon *et al*. 2008; Hohlfelder *et al*. 2011: 116–17) (Figs. 6.1, 4.32). This bay, located to the west of Naples and *ca.* 200 km south of Rome, is part of an ancient caldera in the Campi Flegrei (Phelegraean Fields) volcanic district. It was bounded by the Roman colony of Puteoli to the east, Republican Rome's major maritime emporium, and Misenum, the home of Rome's Western Mediterranean fleet, to the west (D'Arms 1970: 4, fig. 1). The coastline of the Campi Flegrei is a geologically active area: bradyseism, frequent earthquakes, fumaroles and bubbling mud pots, and the occasional smell of sulphur are constant reminders of the defining presence of Campi Flegrei and Mt. Vesuvius.

***4.6.2. ROMACONS fieldwork.*** The reason for taking concrete core samples from structures in the Campi Flegrei region is obvious. This is the source of the *Puteolanus pulvis* (*pozzolana*), mentioned by Vitruvius, Seneca, and Pliny. It is likely to have been the region where Roman maritime concrete first developed, since pumiceous ash from the entire Gulf of Naples area mentioned by Vitruvius is the critical pozzolanic ingredient in *opus caementicium.* Pozzolan from the wider region was found in all of the ROMACONS samples taken throughout the Mediterranean (Brandon *et al*. 2008: 375).

ROMACONS received permission from the archaeological authorities to take five core samples from three different locations in the Bay of Pozzuoli. Unfortunately, the long mole of ancient Puteoli built during the Augustan age (Figs. 2.2–3; Gianfrotta 1996: 67) was not available for sampling, since all but possibly the first pier on shore disappeared beneath modern construction in the 1920s. The first site that we did investigate was the entrance channel to Baianus Lacus, distinguished by two long moles or breakwaters (Fig. 4.33). The southern (or port side for inbound ships) structure is 232 m long, while the northern one is 209 m in length. Each mole is *ca.* 9.5 m wide, while the channel between them is *ca.* 32 m wide. A core was taken from the port side mole (BAI.2006.01) that today stands *ca.* 5.1 m below sea level (Brandon *et al.* 2008: 376, fig. 2). Its overall length was 2.15 m, while the total depth of the core-hole was 2.3 m (Figs. A3.31–33). Equipment problems on the last day of operations thwarted an attempt to core the other mole.

A similar location selected for coring was the entrance channel to the now submerged harbour of Portus Iulius (Fig. 4.34; Miniero 2010). This installation was the first one built in the Italian peninsula specifically to serve as a base for a naval fleet. It was constructed clandestinely in the early 30s BC by Marcus Agrippa, Octavian's trusted colleague and Rome's

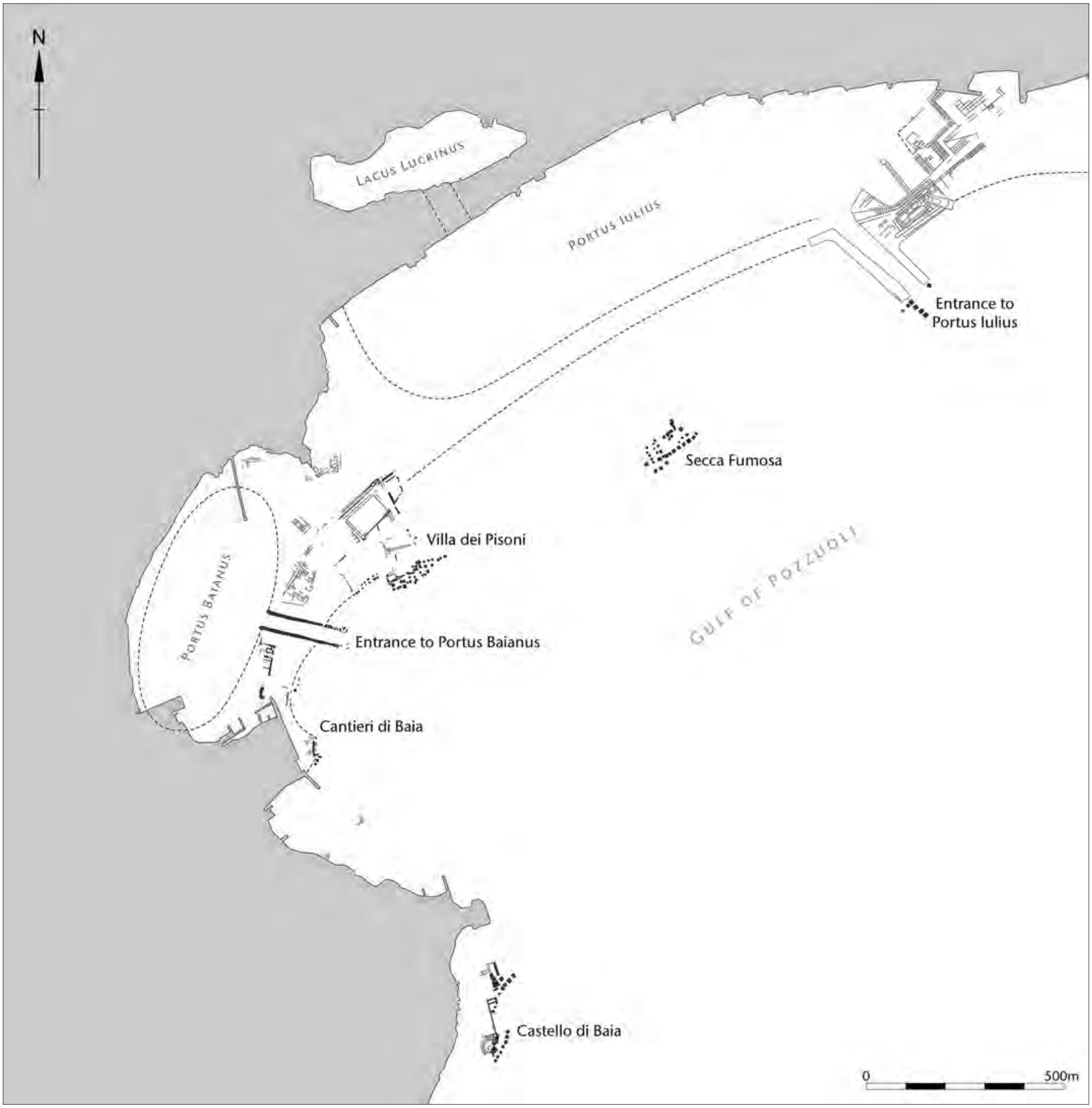


*Fig. 4.32. Map of Baiae area, with indication of structures mentioned and coring locations (Will Foster Illustration).*

most illustrious admiral. His plan was to construct and train a fleet in secret that ultimately would crush the naval threat posed by Sextus Pompey, Octavian's rival for control of Italy. His brilliant plan was carried out successfully, and in 36 BC, Agrippa won a decisive naval engagement off Naulochus in Sicily. The maritime installations of Portus Iulius then became strategically important in the forthcoming struggle with Mark Antony for control of the Roman world, a conflict that ended with the resounding naval victory of Octavian and Agrippa at the Battle of Actium in 31 BC.

A core was extracted from each of the two long moles or breakwaters that mark the entrance to Portus Iulius, and a third core from one of the *pilae* protecting the channel approach (Fig. 4.34). The moles, similar in design to the Baianus Lacus

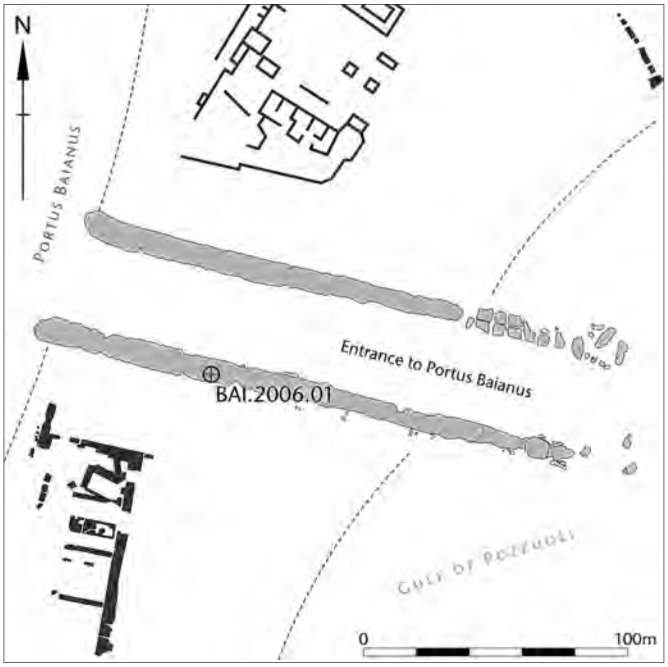


*Fig. 4.33. Plan of structures at entrance to Baianus Lacus, with indication of coring location (Will Foster Illustration).*

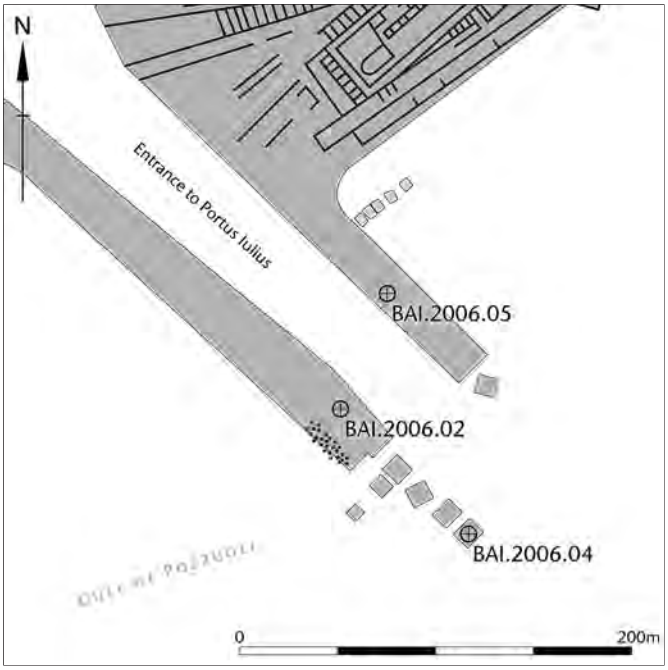


*Fig. 4.34. Plan of structures at entrance to Portus Iulius, with indication of coring locations (Will Foster Illustration).*

moles, were about 220 m in length but were much wider, *ca.* 20 to 30 m, and defined a much wider entrance passage of *ca.* 40 m (Brandon *et al*. 2008: 337, fig. 5). BAI.2006.05 was taken from the mole on the northern or starboard side for inbound ships, while BAI.2006.02 was extracted from the mole on the southern side or port side for entering ships. BAI.2006.04 was taken from one of the *pilae* on the port side of the entrance opening. Six *pilae* survive on the port side of the entrance, which faces open water, while there is only one on the starboard side. These *pilae*, like those outside the entrance to Sebastos, were probably intended to protect ships entering or leaving the harbour channel from deflection by waves adjacent to the entrance.

The concrete from all three cores was of rather poor quality (Figs. A3.37–40). It had eroded badly over time, and the structures themselves were broken up and in an obvious state of deterioration. BAI.2006.02 yielded a core of 1.2 m; BAI.2006.04 produced a core of 1.63 m, although a long section slipped out of the core-catcher and could not be recovered from the block. BAI.2006.05 yielded the shortest core, 1.1m in length. The surfaces of the blocks cored were 3.9 m, 3.8 m, and 4.0 m below sea level respectively (Brandon *et al.* 2008: 376–78; Gianfrotta 2011a: 191, fig. 1).

The third coring location was one of a series of *pilae* of uncertain date located between Baianus Lacus and Portus Iulius (Figs. 4.35, 6.46; Brandon *et al*. 2008: 377, fig. 3; Miniero 2010). This area, known locally as *Secca Fumosa* ("Smoking Shoals"), we now identify as Baianus Sinus, although little is known of its configuration, history or function in antiquity (see pp. 261–62).The modern name stems from the many fumaroles on the sea floor that discharge hot water and gas. Like the entrance breakwaters of both ports, this cluster of piers was intended to stand *ca*. 1.0 m above sea level at the time of their construction, but now they are at least 1.5 to 4 m below present

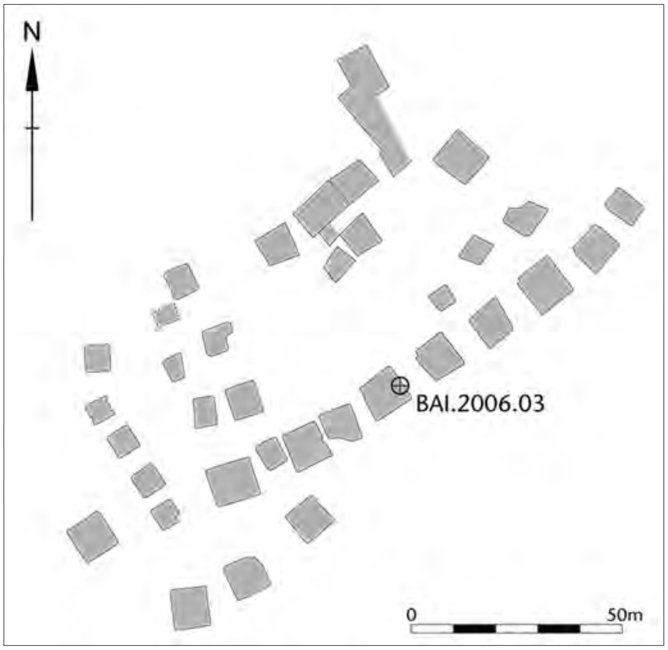


*Fig. 4.35. Plan of* pilae *at Secca Fumosa, with indication of coring location (Will Foster Illustration).*

sea level, testimony to regional "shoreline mobility attributed to volcanism and faulting" (Marriner and Morhange 2007: 150, fig. 13). Gianfrotta (2010) has argued convincingly that the *pilae* were at least partially submerged in sea-water at the time of construction, and that at least some of them supported a wooden platform just above ancient sea level that held baths "constructed in the sea" by M. Licinius Crassus Frugi in the first century (Pliny, *HN* 31.5; Pausanias 8.7.3).

BAI.2006.03 was a core of 2.9 m in length consisting of a much higher quality of concrete (Figs. A3.34–36), suggesting that either it was constructed after the initial building of Portus Iulius or was built by a better trained or more experienced work crew, or one working with less haste (Delgado 2008: 328). The surfaces of most of the *pilae* preserve or show traces of *opus reticulatum* facing, composed of small, tapering blocks of volcanic tuff that form a regular net-like pattern.

***4.6.3. Scientific analysis.*** Some very general descriptions appear in the preliminary report of the fieldwork (Brandon *et al*., 2008: 378); see Appendix 3 (pp. 260–65) and Chapter 7 for further descriptions.

***4.6.4. Observations and conjectures***. As noted above (pp. 2–4) there is some agreement among scholars that Roman pozzolanic mortar probably first appeared in the Gulf of Naples area sometime in the second century BC. Although the exact location and moment of discovery remain obscure, most probably this type of mortar came into being because local builders tried to duplicate a common, local natural phenomenon: the lithification of volcanic ash in the presence of ground and surface waters along the Flegrean coastline, to form the rock called tuff (see Seneca, p. 26, Passage 14). The practical advantages of being able to recreate this phenomenon were obvious. Alternatively, the origination of maritime mortar might have been serendipitous, the fortunate result of local builders simply using materials at hand that happened to replicate what nature had formed (Hohlfelder *et al*. 2011: 109).

What is surprising, however, is that no public structures dating from the second or early first centuries BC, as opposed to private *piscinae* (fish-raising tanks), have yet been found built into the sea along the Italian coastline in the general area of the Gulf of Naples. There must have been pioneering or experimental trials of this maritime concrete along the coastline during the construction boom that marked the late Republican and Augustan age, but none of these earliest, pioneering structures have survived or yet been recognized (Brandon *et al*. 2008: 374; Gianfrotta 2011a: 188). The only construction project now known with historical certainty that falls into this time frame of extensive development of maritime structures is the building of the Portus Iulius starting in 37 BC (Suetonius, *Aug.* 16). Prior to the ROMACONS investigations at Cosa, it seemed as if the five *pilae* there, dated by McCann variously but most recently to the late second to early first century BC (McCann 2008: 294; see pp. 63–69), represented the earliest use of maritime concrete in maritime constructions. This conclusion seemed anomalous, because this site in Tuscany was a relatively minor harbour and far removed from the presumed birthplace of *opus caementicium.*

The $^{14}$C date of 2020 ±40 BP, giving a range of 57 BC to AD 33, for a wooden fragment from PCO.2003.01 (p. 69) that dated the construction the Cosa *pilae* to the Augustan age has quickly gained acceptance (Gianfrotta 2011a: 188; Fentress 2009; Gazda 2008: 281) and has refocused attention to the Gulf of Naples area for the first extensive use of *opus caementicium* in the sea. Many private *villae maritimae* were constructed in the Gulf of Naples during the end of the Republic and maritime concrete was used to construct their *piscinae* and quays in the sea, but of the few surviving examples none can be dated convincingly to this early period (D'Arms 1970: 40–3; Lafon 2001: 395–29; Gianfrotta 2011a: 188). The passages from Horace, Virgil, and Seneca discussed above (pp. 23–24, 26) may provide literary evidence for such structures.

The moles forming the entrance channel to Baianus Lacus, however, may provide the earliest surviving example of construction in the sea with maritime concrete. Since Baiae was such a popular resort for the Roman elite, a well-defined entrance channel to Baianus Lacus may have been constructed at any time in the first century BC, even before Agrippa's building of Portus Iulius in 37 BC. Unfortunately, neither BAI.2006.01 nor the structure from which it was extracted can be dated closely. On the other hand, since the Baiae entrance channel bears a striking similarity to that at Portus Iulius, it may also have been part of the enhancement of the maritime installations in the Bay of Puteoli during the early Augustan age. The quality of the concrete in BAI.2006.01 and BAI.2006.03 (from Secca Fumosa) seems much better than that used in the Portus Iulius cores, suggesting a possible later date of construction for these two structures. This would be sometime after Roman builders had developed better protocols for the mixing and placement of concrete in the Category 1 form in the case of BAI.2006.01, and in the concrete placed in some modification of Category 2 or 3 form in the case of BAI.2006.03 (Brandon 2011: 129–38; below, Chapter 8).

Given the re-dating of the Cosa *pila*, the absence of available evidence regarding the maritime installations of the luxury villas of Baiae, and the uncertainty of the construction date for the breakwaters defining the entrance to Baianus Lacus, Agrippa's building of Portus Iulius in the Bay of Pozzuoli is a good candidate for the earliest dateable site where Roman builders used concrete extensively in a massive maritime project. Thus three cores from the moles and *pilae* that define the entrance to Agrippa's port, BAI.2006.02, 04, and 05, may be the oldest examples of Roman maritime concrete discovered to date.

Although literary sources are clear about the date of the construction of Portus Iulius, a piece of wood taken from the remains of the formwork of the *pila* from which BAI.2006.04 was extracted yielded a $^{14}$C date of 2060 ± 40 (Calendric Age of BC 87 ± 58), a date congruent with the historical evidence of 37 BC for the beginning of the construction of the port facilities (Suetonius, *Aug.* 16). These three cores can be considered as the benchmarks against which the evolution of Roman maritime engineering could be tracked, barring future discoveries of dateable maritime concrete structures in the Gulf of Naples region or elsewhere in Italy. It also seems likely that this construction project may have served as a training ground for builders, possibly military engineers called *caementarii* (*cf.* p. 36, Passage 32), and their apprentices who would later work on other, similar projects throughout the empire (Hohlfelder *et al*. 2011: 116, n. 17).

In addition, there is some proxy corroboration. The relatively unrefined quality of the mortar in the Portus Iulius cores provides support for this claim. It appears that too much water may have been used in the mixing of the mortar, and perhaps too little lime. There are also surprising irregularities of size and positioning of the *pilae* in the sites investigated in the Bay of Pozzuoli. These technological deficiencies could be due to the haste with which these facilities were constructed, considering the military imperatives behind the building of Portus Iulius, which had importance far beyond Baianus Lacus. Another explanation, would be the inexperience of the Roman builders employing concrete to construct major installations in the sea. If these structures do represent the first significant effort of building on a large scale in the sea, both the quality of the concrete and the irregularities in the building program can easily be explained. A third factor behind the porous and less cohesive fabrics exhibited by these *pilae* could be the qualitative difference ROMACONS discovered between the engineering of public marine installations like these and a private construction project such as the *pilae* at Santa Liberata (pp. 69–73). A wealthy individual could ensure better supervision of a construction project involving a *piscina* or quay for his own maritime villa and could insist on and pay for a high quality of workmanship and materials. The patron of such a project was the one who could dictate an acceptable time frame for its completion. In contrast, such tight controls were less likely for a public project such as the construction of Portus Iulius. We cannot know the size or training of the labour force involved or the nature of the pressure Marcus Agrippa exerted on the project supervisors. The building of a fleet and the facilities to support it at Portus Iulius was certainly a priority, but it was not his only one. At that moment, his future and that of Octavian (later Augustus after 27 BC), the man he served, hung in the balance as civil war with Marc Antony loomed. During the hectic decade of the 30s, Agrippa was severely tasked by Octavian in many directions. Neither the quality of the concrete used in structures that would be largely underwater at Portus Iulius, nor the precise configuration of *pilae* and their accurate placement on the seabed would have been among his major concerns. Expediency and speed of construction could have trumped quality control.

One of the more puzzling issues concerning some of the *pilae* at Baianus Sinus, Nisida, and Egnatia examined by Gianfrotta, ROMACONS, and others is the presence of an external facing of *opus reticulatum* (small square blocks in a net-like pattern) and *opus testaceum* (brickwork) on structures that seem likely to have been built underwater (Gianfrotta 1996: 71; Scognamiglio 2002: 52–55; Brandon *et al.* 2008: 375–76; Brandon 2011: 127, figs. 7–8). It is unclear how this could have been accomplished, since the external facing of stones or bricks had to be laid first, layer-by-layer within wooden formwork, before the corresponding mix of mortar and coarse aggregate were placed. It seems unlikely that Roman workers could have carried out this process in inundated formwork, and yet some of the blocks – such as the enormous one at Nisida (Gianfrotta 1996: 68–71) – seem far too large for the use of double-walled caissons that could be drained. One possible explanation is that the blocks with facing were built above water on temporary shoreline platforms, then allowed to fall into the sea, in the process described by Vitruvius and possibly by Horace and Virgil (pp. 24–26, Passages 9–11).

## 4.7. Alexandria, Fieldwork May 2007

***4.7.1. Background.*** Alexander the Great founded the city of Alexandria in 331 BC on a strip of land that lay between the sea and Lake Mariout, the site of an earlier Egyptian settlement thought to be Rhakotis (Fig. 3.2). It had the potential for a natural maritime harbour located in the lee of a string of islets, reefs and the larger island of Pharos, which were the extension of the limestone ridge that formed the promontory of Cape Lochias (Finneran 2005: 45–46).

The Eastern Harbour, or Great Harbour (*Portus Magnus*), in the Hellenistic and Roman eras would have been very different in appearance to what is seen now (Fig. 4.36). Instead of a large expanse of water bounded by the cornice to the south, Fort Qait Bey to the northwest and Cape Silsileh to the northeast, it would have been much smaller with a series of inner basins formed by extensions and jetties projecting from islands and reefs, now submerged, within the natural bay that was the harbour of Alexandria. The ancient shoreline is now also underwater and Cape Lochias concealed below the modern expansion of the headland that is now called Cape Silsileh.

Until the modern era, the approach into the inner harbour was treacherous, with ships having to pass between the outlying reefs. Strabo, who lived in Alexandria between 30 and 27 BC, describes how difficult it was to enter the harbour, although once inside there was relatively deep water that allowed even the largest ships to moor up against quaysides within the inner basins. He also describes how the Great Harbour (Eastern Harbour) was divided up into several harbours or basins (Strabo 17.1.6–17). Josephus wrote that the entrance channel was protected on the port side of ships entering, the side of Cape Lochias, with an artificial mole and on the right by the Island of Pharos (Josephus, *JW* 4.612–15). The artificial mole mentioned by Josephus is now buried under the modern harbour enclosure that protects the eastern harbour from the large swells caused by northerly winds (Goddio *et al*. 1998: 14). The actual location of the Pharos lighthouse is, however, in question, being either on the site of Fort Qait Bey or farther east on the now submerged eastern end of the island (Goddio *et al*. 1998: 16).

In the lee of Cape Lochias lay the Royal Harbour that served the palace sited on the Cape. Strabo (17.1.9) writes that it was a man-made harbour and hidden from public view, the private property of the kings. He goes on to mention that there was also a royal palace and small harbour on the island called Antirhodos (or Antirrhodos) close by, and a projecting peninsula "with an elbow" on which Anthony added a jetty that projected into the middle of the harbour. At the end of it he built a royal lodge that he called Timonium (Strabo 17.1.9). This structure has been identified by Goddio on the end of a jetty that projects towards the west and in the direction of the island of Antirhodos from the end of a large pier or peninsula, forming the third harbour basin (Fig. 4.36) (Goddio *et al*.1998: 51). On the eastern side of the peninsula is a small jetty that projects towards the northeast, designated "J2" by Goddio. It remains in a good state of preservation, made of concrete and 50 m long and 7 m wide with a 12 m right angle return at the end (Goddio *et al*.1998: 22). Core ALE.2007.04 was taken from this structure. Like any great harbour that was in constant use for hundreds of years, additions and modifications were inevitably made to it on an almost continuous basis. It is difficult to establish whether Jetty J2 was part of Anthony's works or a later addition. After his victory at the Battle of Actium Octavian (Augustus) made Egypt a Roman Province. Alexandria became a major export harbour, being the Imperial granary for all the Egyptian grain being shipped to Rome, and it is likely that the harbour infrastructure was adapted to cater for the increase in the volume of shipping.

The underwater exploration in the Eastern or Great Harbour (Portus Magnus) of Alexandria, begun in 1992 by Franck Goddio of the Institut Européen d'Archéologie Sous-Marine (IEASM), has produced impressive new data about the design of the maritime installations, and new information about the maritime life of one of the two most important harbours in the ancient Mediterranean world (Fabre and Goddio 2010, and the works there cited; Goddio 2011). These investigations have revealed that the Hellenistic harbour underwent significant changes in the Roman era, beginning in the Augustan age. Goddio very generously agreed to support ROMACONS fieldwork in Alexandria and he submitted the coring targets, that had been selected during the April 2006 reconnaissance

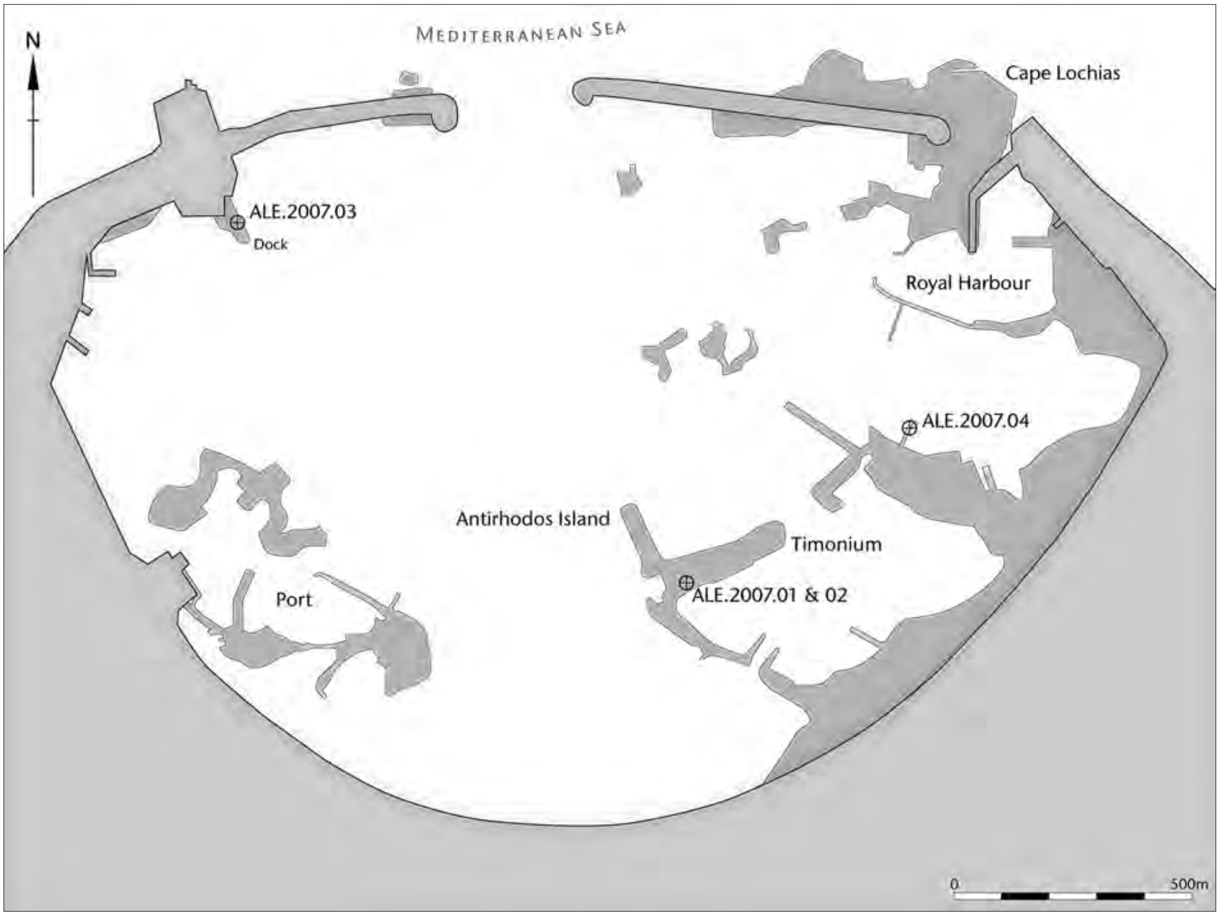


*Fig. 4.36. Eastern Harbour of Alexandria, with indication of coring locations (Will Foster Illustration).*

of the eastern harbour, as part of his permit to survey and excavate during the 2007 mission.

Goddio's work in the Great Harbour has uncovered numerous examples of blocks that he describes as being made with non-pozzolanic mortar, still encased within the remains of wooden forms. Since mortar without pumiceous ash pozzolan could likely not have cured underwater or survived for two millennia, if the material composing these blocks is correctly identified, they must have cured in the air in the timber frames before they were towed into position and then sunk (McKenzie 2003: 39). An ingenious but unlikely suggestion regarding the installation of these mortar blocks was offered by de Graauw (2000: 6). He suggests that wooden forms (probably Vitruvian Category 3 forms; Brandon 2011: 124–25) were placed on the seabed by filling them with sand until they sank, leaving the upper portion of the forms projecting slightly above sea level. A second set of slightly smaller forms was then placed on the sand and filled with non-pozzolanic mortar. Once this mortar had cured, the top wooden caisson was dismantled, leaving the mortar block standing on the sand contained by the lower forms. Large gates built into the lower wooden form were then opened to allow all the sand to be drawn out by the action of the sea. The mortar block then sank into the now empty wooden box. The exterior planking of the submerged wooden container was left in place either to provide at least temporary protection for the mortar block or because removing the waterlogged wooden planks would have been difficult and would not have yielded blanks that could be readily reusable. Although there is no archaeological confirmation for this hypothesis, and there are numerous practical objections, such a method would represent a variation on the method Vitruvius proposes for the preparation of blocks of non-pozzolanic mortar on contained sand foundations on the seashore (*De arch.* 5.12.3–4; pp. 20–23, Passage 9).

Goddio's divers also found blocks made of pozzolanic mortar (although Goddio describes them as non-pozzolanic) within wooden frames that in photographs appeared very similar to the barge forms found in Area K at Sebastos (above pp. 76–77). More significantly, a piece of timber from one of planks from a frame that contained a mortar block was dated by $^{14}$C to *ca.* 250 ± 45 BC (McKenzie 2003: 39). If this date is correct, the innovative technological advance of building blocks of maritime concrete in wooden barges was made not by Roman builders, but rather by Hellenistic engineers working decades or even centuries earlier for the Ptolemaic dynasty. The single-mission barges of Area K at Caesarea would not have been a Roman invention but rather simply an application of a method of harbour construction more than 200 years old. In addition, other maritime concrete blocks in similar wooden forms were found in various places throughout the Great Harbour (McKenzie 2003: 39).

The implications of this discovery as reported were staggering. If correct, the $^{14}$C date would mean that Hellenistic engineers had discovered not only the methods of placing mortar on the seabed, but also had invented pozzolanic mortar. With this breakthrough, they also would have discovered maritime concrete, well before the Romans did. One could go further and say that these blocks in the sea would have been the first documented example of any type of concrete. Could it really be that marine concrete, the building material that allowed Rome to create a maritime infrastructure appropriate for its Mediterranean empire and one of Rome's signature technological discoveries, actually had its origin in Hellenistic Alexandria around the middle of the third century BC?

Goddio realized the significance of these questions regarding the construction of subsidiary facilities within the Great Harbour and also that ROMACONS might be able to provide valuable new data to elucidate the many issues associated with his discovery. With his strong endorsement, he requested that our project be included in his excavation permit for 2007. The Egyptian Antiquities Department agreed, and we proceeded to collect cores from three different submerged installations during the period of May 5–13 (Fig. 4.36). Without his encouragement and generous logistical support, our fieldwork would never have happened. Unfortunately, at this writing Goddio's final report on the underwater excavations in the Great Harbour is still in preparation, but one should consult this report when it appears to better understand the background and context in which ROMACONS conducted its fieldwork (Goddio and Fabre, in preparation).

***4.7.2. ROMACONS fieldwork.*** The ROMACONS team, comprising Oleson, Brandon, Jonathan Cole, and Derek Klapecki, a graduate student at the University of Victoria, arrived in Alexandria on 5 May 2007 and the crate with all the drilling equipment was delivered on the evening of the 7th. On the 8th we received a permit to move the crate out to the "Princess Douda" moored within the eastern harbour, a German coaster converted to a dive support vessel that was Goddio's base of operations. The underwater coring took place on 8 to10 May, during which four cores were successfully extracted from the agreed permitted locations.

The key target for the first day was the concrete-filled caisson on the southern side of Antirhodos Island. The formwork appeared very similar to the caissons found in Area K on the northern end of the western mole at Sebastos, a fact that was confirmed by Brandon during the pre-season reconnaissance in 2006 (Fig. 4.36). The wood from the Alexandrian versions, however, had been $^{14}$C dated by Goddio to 250 BC, and described as lacking any pumiceous ash pozzolan (Goddio *et al*. 1998: 32–37, 56). The inspection of the block during the 2006 reconnaissance, however, suggested that the mortar did in fact contain pumiceous ash pozzolan and was similar to the maritime mortar mixes we had seen at other sites. The top of the concrete block was 4 m below sea level, although it was only 0.76 m thick; the first core (ALE.2007.01) was 0.75 m long. In order to take a second sample quickly, the coring frame was simply unclamped from the feet and rotated through 180 degrees, then re-fixed, enabling the second core to be drilled without re-setting the feet. ALE.2007.02 was extracted from a position 2 m to the west of ALE.2007.01 and the recovered length of the core was 1.03 m and was complete from the marine encrusted top to the timber impression on the base. The visibility in the harbour water was approximately 40 cm, making assembly and operation of the machinery difficult and underwater photography impossible.

On 9 May core ALE.2007.03 was taken from the largest concrete *pila* in a line of *pilae* that once probably formed a pier on the northern side of the harbour, now located just offshore from the Alexandria gun club and clay pigeon shooting range (Fig. 4.36). This area is now called the "Ball Trap." The top of the concrete block was approximately 2 m below sea level. The sea conditions on this occasion were the worst the team experienced in all the ROMACONS fieldwork. Although the water was calm, the pollution and sediments in this part of the harbour made the underwater visibility almost zero. It was difficult to see anything at all and the whole operation of fixing the frame and taking the core had to be carried out by touch alone. Nevertheless a 1.14 m core was successfully extracted.

On 10 May core ALE 2007.04 was drilled from a concrete jetty, designated J2 by Goddio, which extended north-northeast from the peninsula at the southern end of the Great Harbour (Fig. 4.36). The top surface of the concrete is now 6 m below the current sea level. A 1.03 m long core was recovered, representing the complete thickness of the remaining concrete.

When the weather deteriorated on 11 May we packed the crate for shipping back to Italy, while the cores were placed with the Egyptian Department of Underwater Archaeology under the Supreme Council of Antiquities, before being transported to Cairo for analysis and testing.

All cores consisted of a firm, bluish-green mortar with a rich pumiceous ash pozzolan additive; the coarse aggregate in the concrete was the local *kurkar* (calcarenite grainstone) (Figs. A3.69–78). Only a visual analysis of the cores was possible before the samples had to be sent to Suez Cement, an affiliate of CTG Italcementi, for scientific analysis (Fig. 4.37). To visual inspection the samples all bore a great similarity to cores taken at Caesarea, while the wooden formwork also appeared quite similar to the barges found in Area K at Caesarea. The assignment of the concrete and the concomitant wooden barges to the Hellenistic era seems incorrect based on the ROMACONS fieldwork and the archaeological and literary evidence that point to the discovery and first use of concrete in the Gulf of Naples region 200 years later.

***4.7.3. Scientific Analysis.*** See below Appendix 3.14, pp. 279–83 for the results of analytical investigations.

***4.7.4. Observations and conjectures.*** The concrete that was used in the caisson on the southern side of Antirhodos Island was made with a pumiceous ash pozzolan (ALE.2007.02, pp. 280–81). Fragments of wood from the barge form were found incorporated in the base of the concrete when the cores were analysed as part of the protocol adopted by ROMACONS. The $^{14}$C date range was 1960 ± 50 years (for a calendric age of AD 31 ± 54 years, or 23 BC to AD 84), which is more in keeping with comparative data collected by ROMACONS from other Roman maritime concrete sites. These data suggest that modifications were being made to the harbour on Antirhodos in the early Imperial period, after Strabo's visit. It is likely that a significant number of the additional moles, piers, jetties and docks that were added in the Imperial era around the Great Harbour were made with concrete using pumiceous ash shipped from the Gulf of Naples as ballast on the empty transport ships en-route to Alexandria to collect grain. A fragment of wood recovered from core ALE.2007.03 during testing at CTG Italcementi provided a $^{14}$C date of 1950 ± 50 BP, for a calendric age of AD 44 ± 56 years, or 12 BC to AD 100, suggesting that construction was going on along the northwest edge of the harbour as well during the first century of the Empire.

While the ROMACONS fieldwork in the Alexandria harbour did not provide incontrovertible evidence to disprove the Ptolemaic origin of the maritime concrete or the single-mission barges used in its placement, we did find sufficient evidence to suggest strongly that these concrete blocks dated to the Augustan era or during the Principate, *ca.* 200 years later than the proposed Hellenistic date for the formwork. The Hellenistic $^{14}$C date is itself an outlier, from a structure that Goddio otherwise dates to the Augustan era (Goddio *et al.* 1998: 37). At our suggestion, he did collect another wood

*Fig. 4.37. Oleson examining core ALE.2007.02 on the* Princess Douda *in Alexandria harbour.*

sample for the wooden forms that yielded the Hellenistic date, but unfortunately the $^{14}C$ dating of this sample by the Egyptian authorities yielded inconclusive results. Our study of the form revealed that in size and construction it was almost identical with the forms found at Caesarea: *ca.* 5 to 8 m wide, 10 to 15 m long, and 1 to 3 m high, and the surviving planks were edge-joined with pegged mortise and tenon joints (see pp. 210–13). Moreover, we were able to take a core from within the frame that provided this early date and discovered that mortar of this concrete block contained pumiceous ash pozzolan likely from the Gulf of Naples region, a most improbable circumstance if the third-century date was correct. At both Caesarea and Alexandria, local *kurkar* was used as aggregate rather than imported stone. The scientific analysis of the Alexandria and Caesarea concrete samples now provides further evidence of the physical and chemical similarities (see Chapter 7). These technical details make a very compelling argument that the concrete structures in both harbours were built at approximately the same time during the Augustan era and perhaps were even constructed under the supervision of the same Roman master builders, experts in building in the sea who had gained their experience at Portus Iulius or elsewhere along the Neapolitan coastline (Oleson *et al.* 2011: 115).

The transport of the raw materials for the pozzolanic concrete, plus wood for the frames or even prefabricated single-mission barges built somewhere along the marine corridor to Egypt, probably arrived on the large freighters sailing in ballast to Alexandria to pick up wheat for transport back to Rome (Hohlfelder 1999; Votruba 2007). A diversion to Caesarea and then on to Alexandria on the outbound run, when the cargo was pumiceous ash as ballast, other building materials, and miscellaneous cargo like pottery safely stowed in the loose pozzolan that also served as dunnage, was probably the prevailing protocol for delivering the huge amounts of volcanic ash required for construction projects at both ports.

The results of the ROMACONS fieldwork suggest a maritime connectivity between Alexandria and Caesarea during the Augustan age, and most probably well beyond. Obviously, King Herod's harbour existed in the long shadow of Roman Alexandria. What his hopes were for his port city of Caesarea and for its harbour Sebastos can no longer be determined (Oleson *et al.,* 2011a: 115–17). At the international level, was it his dream to eclipse or diminish the importance of Alexandria in the new world order that was emerging in the early Roman Empire? If so, his dream was never realized. Were his plans simply to enhance his own economic fortunes by providing his kingdom with an all-weather new harbour complex and Rome with another maritime window into the countries beyond the eastern Mediterranean coast? Was his intent also to provide Rome with a port of trade or a trans-shipment harbour along the major maritime trade corridor in the eastern Mediterranean and a safe port of call for grain ships beating their way back to Italy? Was Sebastos to serve his political agenda by providing another station in the Levant for the Roman navy or for his own navy to be available for use by Rome whenever and wherever the emperor required? Unfortunately, the surviving literary sources provide no insight into his motives, but they do imply at least that this maritime connectivity, first seen in the circumstances surrounding the building of Sebastos and the rebuilding and renovation of the Eastern Harbour of Alexandria, continued throughout the Roman and early Byzantine eras.

## 4.8. Chersonesos, Fieldwork September 2007 (C. J. Brandon, R. L. Hohlfelder)

***4.8.1. Background.*** Chersonesos (alternatively, Chersonisos or Chersonasos) was a Roman harbour founded on the site of a small Hellenistic haven located *ca.* 30 km east of Heraklion, on the western edge of the Bay of Mallia (Fig. 3.2). This minor Roman harbour (circa 270 m × 150 m in size) was sited in the lee of a headland called Kastri. The Roman improvements to the Hellenistic harbour, possibly dating to the reign of Augustus, comprised concrete moles added to the rubble breakwaters to the south and east, and quays along the shore (Fig. 4.38). In 1955 and 1956 the ancient harbour was surveyed by Leatham and Hood (1958/59: 263–73, pl. 64). According to them, ancient Chersonesos had the best harbour along the northern Cretan coast between Heraklion and Olous (modern Elounda) and served as the maritime gateway for the inland city of Lyttos (or Lyktos). Since their survey a new harbour and the resort of Limani Khersonisou have been developed and the majority of the Roman moles are buried under the modern breakwater and harbour wall. The mole to the south, however, and the quay on the west are untouched, although partially destroyed after 2000 years of battering by the sea, and they were the source of the samples taken by hand in October 2001 and of the cores drilled in September 2007. The southern mole is preserved for a length of 22.7 m in two parts and stands within 3.3 m of water at the seaward end to just below sea level. Concrete quays extend along the shoreline on the west of the harbour and remain in evidence for a length of 30 m and approximately 2.6 m wide. The long L-shaped eastern mole that now lies hidden under the modern concrete breakwater was originally 150 m long with a 30 m long return, and between 5.2 to 5.3 m wide. Leatham and Hood described it as being well preserved and faced with small squared blocks of stone that remained *in situ* at the level of the seabed. Along the inner surface of the mole were recorded a series of vertical recesses set at 6.8 m centres, alternately 1.0 m and 1.5 m deep and between 0.6 to 0.8 m wide. These were initially thought to have been either recesses that housed wooden steps or timber fenders. It is possible that these were the remains of the original formwork within which the concrete was cast.

Leatham and Hood mentioned that the original top surfaces of the moles remained in only a few places and were almost flush with the current sea level, although these too have been destroyed by modern construction. This, together with the

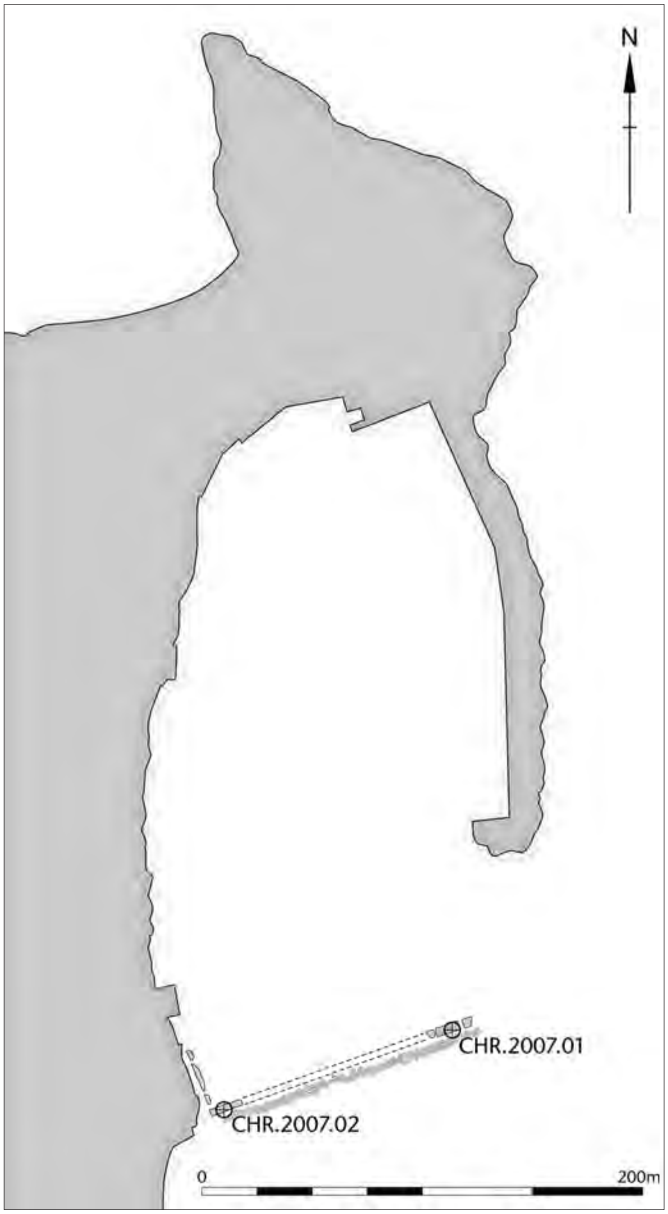


*Fig. 4.38. Chersonesos, plan of harbour and breakwater, with indication of coring locations (Will Foster Illustration).*

drowned fish-pond on the southeast tip of the Kastri headland, indicates that the relative sea level has risen approximately 1 m since the Roman era. The harbour is now fairly shallow, with a maximum depth of 3 m to a sandy bottom that has obviously silted up over the course of time.

***4.8.2. ROMACONS fieldwork.*** In October 2001, before the creation of ROMACONS, Brandon received permission from the Ephorate of Underwater Antiquities to take five small samples of concrete (3 cm × 10 cm) from concrete blocks on the two artificial breakwaters defining the Roman harbour that had not been immured in modern construction. The sampling technique involved hammering hardened stainless steel tubes into the concrete matrix or mortar and then extracting the probes by hand (Fig. 3.3). This method of collection was arduous, and in the end unsatisfactory. Although some fragmentary samples were obtained for analysis by C. Stern at the University of Colorado, Boulder, this experiment confirmed the limitations of manual collection of concrete samples and was a necessary antecedent for the protocols later developed and employed by ROMACONS (Brandon *et al.* 2005: 26–27).

The results of the analysis of these samples, however, were unexpected. Given the proximity of Santorini (ancient Thera, 100 km distant), where pozzolanic volcanic ash is readily available, it was surprising to discover that the volcanic sand that appeared in the concrete matrix had possibly been imported from the Gulf of Naples (Brandon *et al.* 2005: 25–29). Why would pumiceous ash pozzolan be imported from Naples for maritime concrete construction in Crete when alternative supplies of this critical material were available nearby? Were special circumstances involved? Could it also be that Roman builders in the sea, wherever their projects were located or however modest in scope they might be, always imported pumiceous ash pozzolan from the Gulf of Naples area in spite of the costs or other logistical efforts? These questions, spawned by Brandon's manual sampling, also informed the research design of ROMACONS. The ROMACONS team decided to collect larger cores that could be compared directly with the database of similarly sampled Roman concrete.

The ROMACONS fieldwork at Chersonesos took place successfully from 11–12 September 2007, although numerous technical challenges arose that almost thwarted the planned work. Initially there were delays in recovering the crate with the drilling equipment from Egypt. It only arrived in Brindisi at the end of August, leaving no time for the equipment to be serviced and repaired. The logistics of transporting it to Crete were complicated by regulations concerning driving the rental van out of Italy. Fortunately, they were solved by CTG Italcementi just as we were due to board the ferry to Patras. Although we had a permit issued by the Ephorate of Underwater Antiquities in Athens, to take core samples without an attendant inspector, the local harbour master at Chersonesos stipulated that we did need an official representative of the government to oversee the fieldwork. This unanticipated requirement, which was imposed at short notice, was a major problem, as there were no underwater archaeologists from the Ephoria on Crete, and the offices in Athens were shut over the holiday. Fortunately we managed to receive agreement from the harbour master that we could use an archaeologist from the Ephoria in Heraklion. We are truly grateful for the generous assistances provided by Director Maria Bredaki from the Ephorate of Prehistoric and Classical Antiquities in Heraklion and her assistant Mrs Eirini Karousou, who kindly agreed to attend the site and witness our work. We then found that neither the water pump nor the hydraulic pump worked, and both had to have their carburettors re-built. But far more serious, we found that all the hydraulic oil had been drained out of the pump when it had been shipped back from Egypt. Unfortunately because of the delays in transportation it had not been inspected at CTG Italcementi's laboratories either at Bergamo or Brindisi and the missing oil was only found on the day before we were due to start coring. After a series of frantic telephone calls we managed to locate a source of the oil and a specialist engineering shop in Heraklion that could repair both pumps.

We used a small local fishing caïque as the diving platform, kindly donated by Tolis Vougioukas of the dive centre, Creta Maris, who also generously provided us with diving tanks and air. As the caïque was very small and crowded with dive tanks, we needed to use a dingy that was towed behind it as the platform that held all the drilling machinery (Fig. 3.30). Fortunately, there were only three of us on the boat, Brandon, Derek Klapecki from the University of Victoria, and Khristos, the boatman.

On the first day, we selected to core the seaward end of the southern mole and chose a site on top of the mole in 1.2 m of water. The surface of the concrete, although approximately level, was extremely pitted, with lumps of marine encrusted rock aggregate. There was no evidence in the mass of concrete of any vertical piles (*destinae*) or horizontal tie beams (*catenae*) to suggest that it might have been cast within a prefabricated caisson.

Fixing the feet for the drilling frame was difficult. Although initially the fixings appeared very secure, they quickly became loose once the drill bit cut into the hard limestone aggregate and caused the frame to vibrate. There was little or no mortar between the stones, which meant that the expansion bolts were set into individual pieces of aggregate rather than the mass of the mortar, and any vibration in the system broke the rock free while still connected to the drill frame feet. The result was that the expansion bolts and feet had to be continuously re-set. This procedure was exacerbated by the large swell that washed across the shallow water on top of the mole, battering the drilling frame and the operators. Although the core tube penetrated 1.9 m into the block, only 0.5 m of material was recovered, almost entirely aggregate (CHR.2007.01).

On the second day, a core was taken from the western (shoreward) end of the southern mole (Fig. 4.39). The upper section stood above the water, making it much easier to work, despite the continuing swell. We successfully extracted a 1.49 m long core (CHR.2007.02; Figs. A3.51–52) after drilling into the block 1.52 m without any operational difficulties.

***4.8.3. Scientific analysis.*** The preliminary results of the microscopic, petrographic and chemical analyses of the mortar taken by Brandon in 2001 appear in Brandon *et al.* 2005: 28. Additional analyses appear below in Appendix 3.11, pp. 270–72 and Chapter 7.

***4.8.4. Observations and conjectures.*** The concrete on the seaward end of the southern mole is mostly aggregate with very little mortar. Brandon first observed this characteristic when he sampled the concrete in 2001 and failed to collect any mortar from the eastern end of the mole (Brandon *et al.* 2005: 28). The high proportion of aggregate was reconfirmed when core CHR.2007.01 was found to contain virtually no mortar. The material appears to be very similar in consistency to the consolidated rubble mole at Anthedon (Figs. 6.64–65). The concrete towards the shore end of the mole and along the quay was more in keeping with the Roman concrete studied at sites along the west coast of Italy and had a relatively high ratio of mortar to aggregate, nearly 75 to 25. If the outer sections of the mole were cast within wooden caissons, the Roman engineers might have considered it more economical to use a rubble mix with minimal amount of mortar, reducing the amount of pumiceous ash pozzolan that needed to be imported, in a similar manner to the mixture found in the centre of the concrete blocks found in Area K at Caesarea (Brandon *et al.* 1999: 169–78). The concrete on the shoreline would most likely to have been cast within Category 1 forms (see pp. 191–205), in which a maritime concrete rich in pumiceous ash pozzolan was cast within an inundated form. The regular vertical recesses recorded by Leatham on the side of the eastern mole could possibly be evidence of the caissons used in their construction.

*Fig. 4.39. Chersonesos, coring in progress at location of CHR.2007.02.*

The regular deep vertical recesses along the length of the outer mole could be the gap formed by the abutment of two caissons rather than for wooden steps, some form of mooring device, or fender as suggested by Leatham (Leatham *et al*. 1958/59, 267). The caissons would have been approximately 6.8 m long and between 5.2 and 5.3 m wide.

Leatham recorded that the original upper surface of the mole that extended south from the headland, to protect the eastern side of the harbour, survived in only a few places towards the shore on its northern end and also near the point where the mole changes direction. At these locations the top of the mole was just awash. Flush with modern sea level and running down the centre were a line of rectangular stone plinths 0.65 × 0.55 m on plan, spaced at between 8 and 9 m apart. Leatham suggested that these were mooring bollards, but they might also have been supports for some form of architectural embellishment such as bases for columns or statues, as on the Punta Terone concrete pier in Miseno. Unfortunately this structure is now completely capped by the modern concrete mole and sea wall, but a row of what appear to be the sockets for horizontal tie beams can still be seen here and there below the modern concrete, approximately at modern sea level.

The surviving section of the southern mole that abuts the shore and connects to the north-south quay is only 2.6 m wide, whereas the seaward end is 5.3 m wide. As this now stands approximately 1 m above sea level it may well be that the remaining portion of the full width of the mole is buried under the current rubble-filled harbour. It is surprising to find two very different concretes at either end of the same mole, the most likely reason being that they were cast in two different forms.

As noted elsewhere (pp. 224–26) the transport of massive amounts of pumiceous ash pozzolan to Caesarea Palaestinae and to Alexandria in the early Roman era probably was associated with the grain trade. Merchant ships involved in the grain trade, either *naves annonariae* or *naves onerariae*, appear to have sailed from Puteoli in the early empire with the local or regional volcanic sand as a commercially valuable ballast (Gianfrotta 1996; Hohlfelder 2000a: 252; Hohlfelder *et al*. 2007: 414). Although the import of grain was the *sine qua non* for maintaining political stability in Imperial Rome, many aspects of this most important element of Imperial Rome's maritime commerce remain poorly known. Not the least of these is the financial complexities of sending unknown numbers of ships each year to Alexandria, owned and operated by private individuals or *ad hoc* companies, with hulls empty, or nearly so, of items or commodities to sell in Egypt. Such inefficient capacity utilization must have been fraught with financial challenges (Scheidel 2011: 30).

But when such ships were commissioned in some way by a client king such as Herod the Great to bring Italian building materials and technical expertise to his new harbour at Caesarea Palaestinae, these problems were minimized owing to his wealth and connections with the Roman Imperial elite. Pumiceous ash pozzolan, and perhaps other building materials such as wood for the formwork, river rocks, or lime, were carried either as cargo or ballast on ships sailing from Puteoli to Alexandria. These bulk commodities could have been off-loaded both at Sebastos and then at Alexandria, where renovations involving maritime concrete were underway as well, sometime in the Augustan era, although we do not if they were synchronous or slightly later than the harbour engineering at Caesarea. It seems quite likely that the small harbour at Chersonesos may also have been constructed during the reign of Augustus as part of what might be seen as his master plan to renew and expand the maritime infrastructure of the Roman Empire.

The transport of pumiceous ash pozzolan to both Caesarea Palaestinae and Alexandria was in some way state sponsored, by Augustus and/or Herod in the case of Caesarea, and thus easy to understand. Gianfrotta (2011: 190) has suggested that there may have been transport of large quantities of pumiceous ash pozzolan to other major harbour projects sanctioned or endorsed by the emperor. For example, another Caesarea, in Mauretania, a port city ruled by another client king, Juba II, may also have received shipments of this material from the Gulf of Naples region (p. 138). Juba II, like his counterpart Herod in Judaea, might have been given easy access to all the necessary building materials and technical support from Italy.

It is much more difficult to explain how pumiceous ash pozzolan from the Naples region found its way to small harbours such as the one at Chersonesos, far removed from the great emporia of Augustan Rome. It was not on the main maritime corridor for grain shipments to Rome; it was very close to another source of volcanic sands on Santorini; and the financial patrons and their rationale for building permanent concrete harbour installations remain unknown. The appearance of pumiceous ash pozzolan from the Gulf of Naples in the mortar in the cores from Chersonesos was unexpected in the maritime installations of such a small port (Brandon *et al.* 2005: 28–29; Oleson *et al*. 2004a: 206).

Gianfrotta (2009, 2011) has recently provided a possible resolution of this conundrum. He notes that a considerable portion of Cretan territory in the area of Knossos was transferred to Capuan ownership during the Augustan principate. This spawned an extensive maritime trade in the early Imperial era between Crete and Capua, a city close by the source of pumiceous volcanic ash in the Campi Flegrei. The massive export of goods from Crete to Capua included wine from Lyttos, an inland city that used Chersonesos as a harbour. Remains of the Cretan amphorae that carried this wine are widespread throughout Campania (Gianfrotta 2011a: 190–91). It seems likely that the ships from Capua that carried the wine to Campania probably were primarily in ballast for the first leg of the trip from Italy to Crete, although possibly carrying some other miscellaneous cargo embedded in or on top of the volcanic ash ballast. If so, the appearance of Neapolitan pumiceous ash pozzolan in the Chersonesos *pilae* is not surprising. Thus, he concludes that Imperial economics and politics played their role at Chersonesos and in the building of its small harbour.

There is also another possibility, based solely on economics, that could also explain the rapid widespread use of pumiceous volcanic ash in maritime concrete throughout the empire. When the value of pumiceous ash pozzolan as a necessary ingredient for making maritime concrete became known (Wilson 2011b: 226 for Africa Proconsularis), it is possible that the businessmen of Puteoli and elsewhere in the Gulf of Naples realized that using volcanic ash products as ballast had considerable economic potential. Wherever the Naples-based freighters may have sailed, their ballast offered the possibility of unexpected sales and profit beyond the value of the primary cargo. Perhaps this type of material arrived at Chersonesos in such a manner, as an opportunistic cargo unconnected with Imperial plans or policy.

## 4.9. Egnatia, Fieldwork May 2009

***4.9.1. Background.*** Egnatia or Gnathia (modern Egnazia) was a small Adriatic maritime community located on the coastline of ancient Apulia north of Brindisium (modern Brindisi) and south of Barium (modern Bari) (Figs. 3.2, 6.1). In ancient times, its small, partially sheltered embayment served as a way station for coastal craft sailing north or south along the western Adriatic shoreline and the home of a small fishing enterprise. With little or no enhancement, this inlet seems to have served its maritime needs for centuries (Fig. 4.40). The city fell to the Romans in the early third century BC, during the Republic's expansion in Italy. In spite of its potential strategic significance as a debarking point for Rome's growing involvement and ultimate conquest of the Balkans, Egnatia seems not to been noticed by contemporary writers. Its cloak of near invisibility in surviving sources may reflect its modest role in the history of both the Republic and the Empire.

***4.9.2. ROMACONS fieldwork.*** Dr. Rita Auriemma of the Università di Lecce invited the team to take core samples from three concrete *pilae* in the ancient harbour, now submerged because of local coastal subsidence of *ca.* 3.0 m (Auriemma *et at*. 2004a: 19). Along with various colleagues, she has explored the submerged ruins of this small harbour on numerous occasions, primarily to gather data regarding local sea level changes in the Late Holocene (Auriemma *et al*. 2004a–b). Due to technical difficulties with the hydraulic oil compressor, only one core (EGN.2008.01) was recovered. It was from a large *pila* located near the terminus of the northern breakwater (Auriemma 2004: 44, fig. 21) (Fig. 4.41). The upper surface

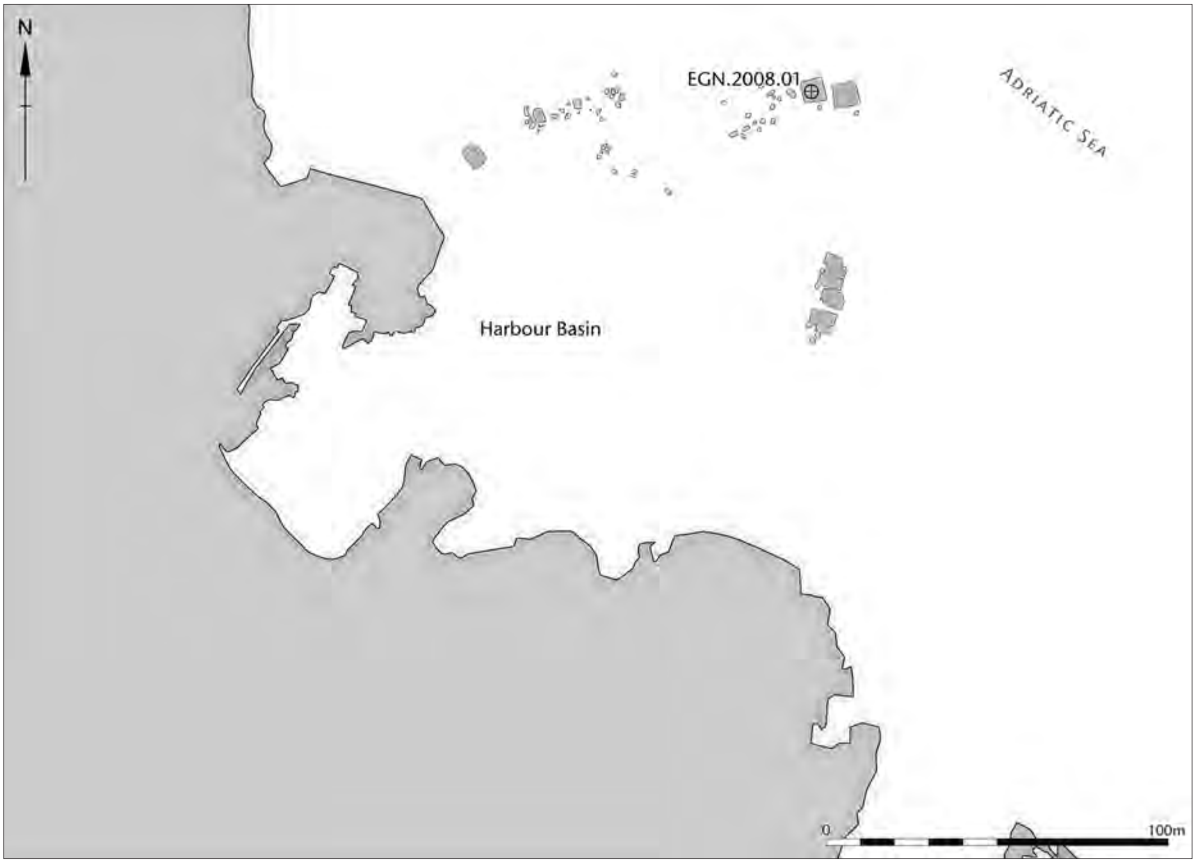


*Fig. 4.40. Egnatia, plan of harbour with indication of coring site (Will Foster Illustration).*

of this structure was *ca*. 3.2 m below modern sea level. The core, which did not penetrate the entire block, was *c*. 2.6 m in length. The mortar was very granular and porous and was distinguished by a variety of textures and colours. It also contained many lime inclusions, random fragments of red potsherds (probably not an intentional part of the mix), black lumps, and pumice lapilli (Figs. A3.41–42). The *caementa* were a local pale yellowish limestone of varying size with some large pieces included. Since the core did not reach the bottom of the pila, it is not clear whether it was resting on sand or bedrock. The deepest section of the lower exterior surface appears to have been faced with *opus reticulatum* even though the block seems to have been constructed underwater (Brandon 2011: 127, fig. 8) (Fig. 4.42). Similar facing has been found on the surface of submerged *pilae* in the Gulf of Naples area as well (see above p. 85).

***4.9.3. Scientific analysis.*** No preliminary description of this core has been published. See Appendix 3.9 for the final analysis (pp. 265–67) and Chapter 7 for analytical results.

***4.9.4. Observations and speculations.*** The date of the concrete structures defining the harbour of Egnatia has been assumed to lie sometime in the Augustan era, or perhaps a bit earlier (Gianfrotta 1996; Auriemma 2004: 52). The harbour would have had strategic significance during the civil war between Pompey and Caesar as a possible embarkation point for the movement of troops to the Balkans before the final engagement at Pharsalus (48 BC). It might also have had a similar role to play during the wars of the second triumvirate ending in the victory of Octavian over Antony and Cleopatra at Actium (31 BC). On the other hand, the enhancement of the natural inlet of Egnatia could have occurred sometime in the reign of Augustus as part of his building of a maritime infrastructure along the Adriatic coast of Italy.

Our core does provide an important datum to challenge this assumption. A small piece of wood embedded in the mortar of EGN.2008.01 provided a surprisingly early $^{14}$C date: 2120 ± 30 year BP, calibrated age 200 to 50 BC, Calendric Age BC 123 ± 45. This is, of course, only one $^{14}$C date and must be treated with caution. Having stated this caveat, we must mention that this is the earliest range of $^{14}$C dates obtained from any of the ROMACONS samples, including those from the Gulf of Naples, where it can reasonably be assumed Roman builders first developed proper maritime concrete. From only this one date, it might appear that Egnatia was the location where maritime concrete was first employed in the sea, but such an early use of this material here rather than in the Gulf of Naples or the adjacent coastlines makes little historical or archaeological sense. Egnatia's brief moment in the maritime history of Rome was later in the first century BC or even in the later part of the Augustan era. Thus, this early $^{14}$C date and the use of *opus reticulatum* near the base of the exterior face of the *pila* constructed beneath the sea remain two unsolved mysteries.

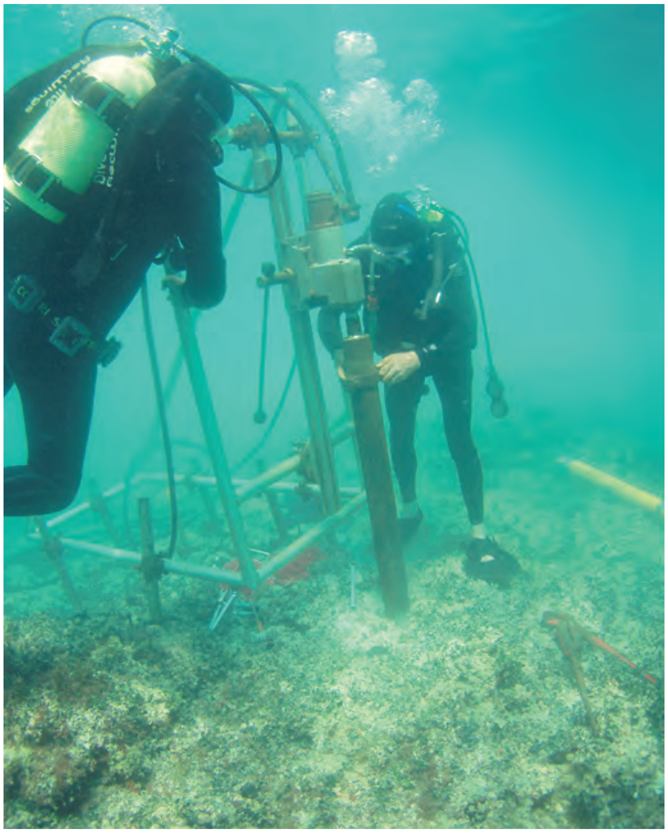


*Fig. 4.41. Egnatia, view of* pila *with coring in progress for EGN.2008.01.*

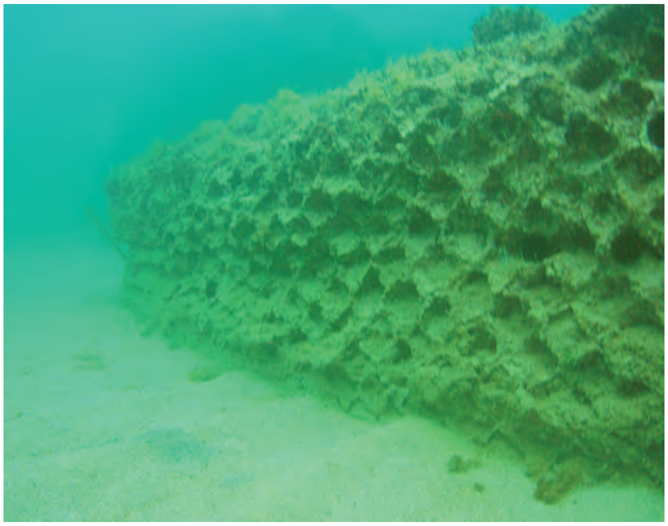


*Fig. 4.42. Egnatia,* opus reticulatum *facing on outer* pila.

## 4.10. Pompeiopolis, Fieldwork August 2009

***4.10.1. Background.*** The site of Pompeiopolis, located on the Mediterranean coast 10 km west of Mersin, Turkey, is now surrounded by the modern city of Mezitli (Figs. 3.2, 4.43). Excavations inland from the remains of the Roman harbour by R. Yagçı have uncovered Hittite and Late Bronze Age occupation levels on a small mound, most probably near an earlier course and perhaps the ancient mouth of what is now called the Mezitli River. The area around this river harbour settlement was probably occupied more or less continuously from the Bronze Age onward, because its location provided easy access to the timber and metal resources of the Taurus Mountains north of the site and an easy escape corridor if the settlement was threatened by an overwhelming attack from the sea. The Hellenistic settlement was named Soli. Over time, alluvium pushed the shoreline south of the original settlement to a point where the remains of a Roman harbour are still visible today (Fig. 4.44). Since these extant installations are Roman, we shall refer to the site as by its Roman name Pompeiopolis, while recognizing that it had a significant earlier history as well (Brandon *et al*. 2010a, 2010b).

ROMACONS had long been interested in testing the concrete in a Roman harbour in Turkey, and thanks to the kind collaboration of Professor R. Yagçı we had an opportunity to do so at Pompeiopolis. Professor Nicholas Rauh of Purdue University, a terrestrial archaeologist with considerable experience at various Cilician sites, plus several of Professor Yagçı's graduate students joined Brandon, Oleson and Hohlfelder on this occasion to assist in our fieldwork.

Pompey the Great founded the Roman city of Pompeiopolis in 67 BC on the remains of the Greek settlement of Soli following an unexpectedly rapid, successful campaign against the Cilician pirates. He settled some of his veterans in this strategic location and renamed his new city Pompeiopolis. The major archaeological feature that survives is a great harbour basin. Today, approximately three-quarters of it is landlocked, with portions of the western breakwater and its enclosed interior covered by encroaching sand dunes to the west, while most of the eastern breakwater has been reclaimed by the sea and now is submerged in a ruinous state (Fig. 4.45). All the remains that are visible today date from the city's refounding. The nature of the Greek harbour installations, if there were any at this location, remains unknown.

The western breakwater was constructed in part on a natural reef and has maintained a surprising integrity for approximately 160 m, up to the point were the bedrock ends and a sandy seabed begins (Fig. 4.46). Beyond, the inexorable force of the sea has reclaimed the structure, and its remains are scattered about on the sea floor. The eastern breakwater seems to have been built completely on a sandy seabed, and this entire structure has succumbed to the wind and waves over the past centuries. Using aerial photographs, recent surface surveys, and plans drawn by earlier travellers to the site, it is

Fig. 4.43. Map of harbour sites along the southern coast of Turkey (Will Foster Illustration).

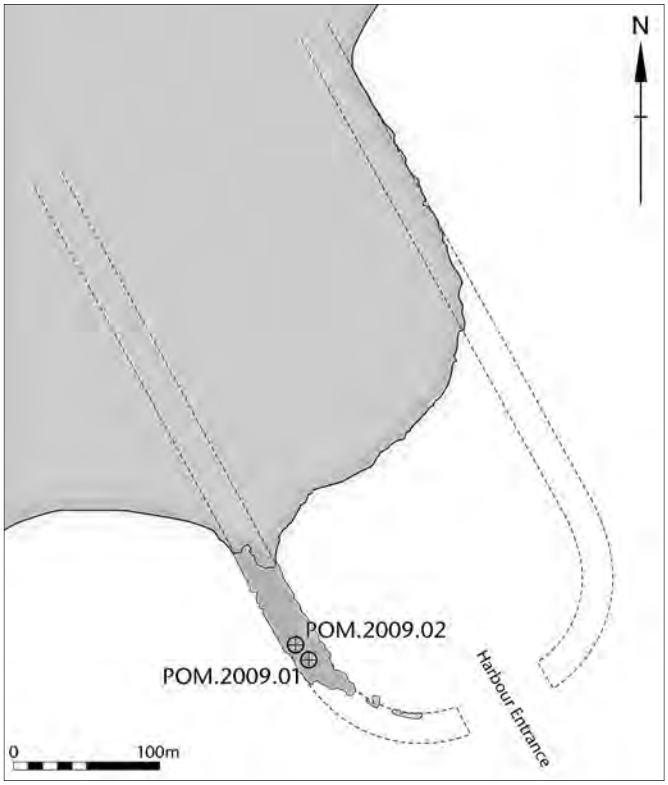


*Fig. 4.44. Pompeiopolis, plan of harbour with indication of coring sites (Will Foster Illustration).*

*Fig. 4.45. Pompeiopolis, aerial photograph of harbour and adjacent portion of city (Courtesy of R. Yagçı).*

*Fig. 4.46. Pompeiopolis, view of west breakwater, looking south.*

possible to estimate the dimensions of the breakwaters and the harbour area they enclosed. The basin created by these two opposed breakwaters, a rectangular shape with two rounded ends, was approximately 320 m in length with a width of 180 m, measured from the inside edge of each breakwater (each was *ca.* 23 m wide). The enclosed area of this harbour was more than *ca.* 5.50 ha, a medium-sized harbour somewhat larger than Republican Cosa (2.5 ha) but considerably smaller than Baianus Lacus (14 ha), Antium (25–30 ha), or Sebastos (20 ha) (Schörle 2011: 96, Table 5.1).

The seaward ends of both breakwaters have disappeared into the sea, creating an incoherent rubble and block scatter that provides no clues as to the configuration of the terminus of either mole, or the width of the harbour's mouth. Most probably they curved inward to define and narrow the harbour's entrance which otherwise would have been far too wide to afford adequate protection for the basin. The nature of any structures that stood at either terminus (lighthouse, customs station, statuary, temples, etc.) remains a mystery.

The Roman engineers constructed both breakwaters by building large boxes or cells made of ashlar blocks that were then filled with concrete. This was the first instance in our fieldwork that we encountered such a protocol to encapsulate concrete: the use of permanent stone formwork in place of expendable wooden forms that had a limited life span in the sea (Fig. 4.47). This placement system seems most likely to be a variant of a Vitruvian method of harbour construction identified by Brandon as Category 3 (pp. 205–8). The surviving section of the western breakwater is paralleled only by the probably Hadrianic breakwater at San Cataldo, Italy (p. 134).

Both moles were framed on the outside by double walls of ashlar masonry. Cross-walls constructed at irregular intervals divided the area into large boxes to be filled with maritime concrete, a type of permanent ashlar formwork. The lower portions of the outside walls appear to be up to 2.8 m thick. A well-preserved section of the outer wall of the western mole clearly shows the layout of a course of stone blocks (Fig. 4.48).

The design consists of two outer and inner stretcher blocks laid on either side of five headers followed by a double row of headers. The courses above appear to step in slightly, reducing the wall-thickness to 2.2 m while maintaining a vertical outer face. A distinctive feature is that each block was secured to the adjacent blocks with large butterfly-clamps set into the upper surface of the stone. No clamps have survived, but deep cuttings remain visible, 35 cm long by 5 cm deep, and varying in width from 6 cm at the ends to 3 cm at their midpoints (Fig. 4.49). There were up to 6 clamps per block. The extraordinary size of the clamp-sockets suggests that the clamps were made of wood rather than metal (Vann 1994: 72).

The upper surface of the western mole is 1.8 m above sea-level, and where stretches of the original paving-stones remain, they are 1.3 m long and 0.63 wide, laid out in alternating rows of header and stretcher. Four cross-walls are clearly visible on the exposed surviving length of the western breakwater, set at 34 m, 30 m, and 14 m apart to form the cells into which the concrete was placed. Most of the cross-walls are 1.6 m thick, built with alternating courses of headers and a line of double stretchers alternating with a header. One cross-wall on the landward end is only 60 cm thick on the upper course, consisting of a single line of stretchers, while it widens to a double row of stretchers at a lower level. The cells were probably built out into the sea one-by-one and in-filled with concrete as each was completed (Fig. 4.47). This form of enclosure was not watertight, and the compartments would have been flooded to sea level, requiring that the lowest stratum of the concrete be laid under water. The upper layer in each cell was paved with stone slabs (Brandon *et al.* 2010a: 393).

Where does the design of this breakwater fit in the evolution of Roman technology to build structures in the sea? It seems in some ways to be a fusion of the Greek technology of building harbours with ashlar blocks with the Roman method of employing wooden forms to contain maritime concrete until it cured. The stone walls, however, subsequently offer additional stability and protection beyond what wood could ever provide. Does this new technique date to Pompey's founding of the city in the mid-first century BC, which would make this breakwater one of the earliest Roman maritime concrete structures? Or, more likely, was this blending of Greek and Roman harbour technology a product of a much later moment in the evolution Roman harbour technology, perhaps dating from the reign of Antoninus Pius (AD 138–161) who issued a Pompeiopolis coin with a horseshoe-shaped harbour design as a reverse (Boyce 1958; Brandon *et al*. 2010a: 395) (Fig. 4.50). This coin issue may have commemorated an enhancement or remodelling of the harbour. Would the concrete at this location, so far from the Gulf of Naples, exhibit the same physical, chemical and mechanical properties as samples collected elsewhere, including the use of Neapolitan pumiceous ash pozzolan? If so, under what circumstances would this volcanic ash have been transported from the Phlegraean shore to this Cilician harbour? With these and other questions in mind,

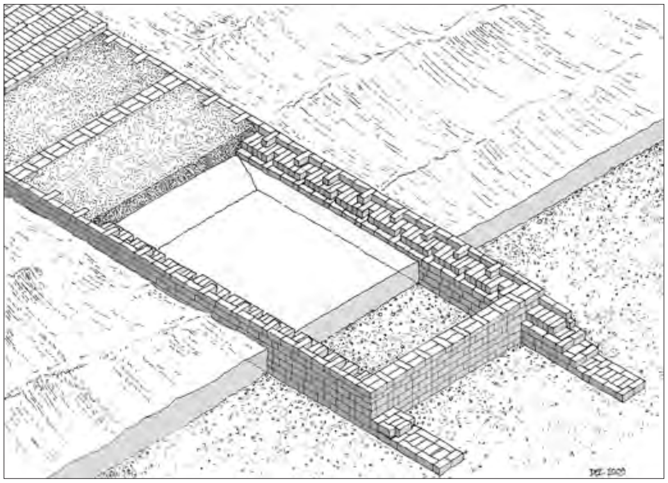


*Fig. 4.47. Pompeiopolis, west breakwater, reconstruction of cell containing concrete (C. J. Brandon).*

*Fig. 4.48. Pompeiopolis, detail of outer wall of west breakwater.*

*Fig. 4.49. Pompeiopolis, detail of clamp recesses on west breakwater.*

Fig. 4.50. Coin of Antoninus Pius representing the harbour of Pompeiopolis (Courtesy of the American Numismatic Society, Newell Collection).

we approached Pompeiopolis in August 2009 with hopes of collecting several cores from both breakwaters.

***4.10.2. ROMACONS fieldwork.*** In spite of the kind assistance and valuable counsel of Professor Yagçı, Rauh's knowledge of the intricacies of Turkish archaeological bureaucracy, and our best efforts to facilitate our project before and after arriving in Turkey, unanticipated licensing details, customs issues, and problems surrounding the transport of our drilling equipment from our storage facility at CTG Italcementi in Bergamo to Pompeiopolis reduced our planned fieldwork from a week to only two days. In reality, we had time to recover only two core samples, each extracted from easily accessible locations on the western breakwater (Brandon *et al*. 2010: 396, fig. 9). POM.2009.01 was drilled on the surface of the breakwater *ca.* 1.8 m above sea level (Figs. 4.51, A3.53–55). The hard river cobbles placed regularly throughout the mortar as aggregate slowed the progress of the coring. Nevertheless, we were able to extract a core *ca.* 4.4 m long that included a *ca.* 2.2 m section of bedrock, inadvertently cored since we were not sure we had reached to the bottom of the concrete.

Of particular interest was a stratum of fine river mud between the lowest level of concrete and the top of the bedrock. In fact, each time we removed a section of our drilling tube, mud infiltrated the core-hole. The best explanation for the presence of the mud on the bedrock is that it was deposited from the river that emptied into the sea before the breakwater was constructed. The concrete cells must have been placed on top of the river mud layer surmounting the bedrock. Its presence suggests that the Mezitli River debouched into the sea at one time before the artificial harbour was created and perhaps even after it was constructed. If so, the seated figure so prominent on the reverse of the Antoninus Pius coin might represent a local river god, instead of Portunus or Oceanus (Brandon *et al*. 2010a: 395). At this interface of land and sea, where ocean and river meet in a harbour, an ambiguous personification honouring all three entities would have been most appropriate.

The mortar in the concrete in POM.2009.01 was poorly compacted and had a micro-aggregate of small pebbles and beach sand. There were also many relict lime clasts as well as bits of pumice (Figs. A3.53–54). It was very friable and contrasted dramatically with the hard river cobble aggregate which also appeared in a much larger concentration than was normal for *caementa* in cores extracted elsewhere. The typical ratio in the ROMACONS samples was 40% aggregate to 60% mortar, whereas at Pompeiopolis the ratio was 64 to 54% aggregate to 36 to 46% mortar. Whatever the reasons were for such a different type of concrete – perhaps an abundance of good local aggregate in the form of cobbles from the Mezitli River – the final mix and application of the concrete produced an extraordinarily well-preserved structure.

The second core POM.2009.02 was extracted from a flat concrete surface at 0.49 m above sea level inside a row of blocks framing the lower part of the mole (Fig. 4.52). It seems to be the surviving layer of maritime concrete still left after the ashlar blocks of the external face of the cell had been breached. The core recovered was short, 0.80 m, but it contained diagnostic material. The mortar was clearly pozzolanic and even contained pieces of tuff likely from the Naples area (Figs. A3.56–57). It was homogeneous throughout, hard as opposed to the upper layers of friable mortar in POM.2009.01, and well mixed. A small piece of wood was recovered from the core at -0.75 m. This sample was $^{14}$C dated to 1864 ± 28 BP, with a calibrated calendrical date of AD 147 ± 48, buttressing the second-century date for the breakwater and eliminating the possibility that this surviving structure was from Pompey's era.

Fig. 4.51. Pompeiopolis, taking core POM.2009.01.

***4.10.3. Scientific analysis.*** Analyses of the two Pompeiopolis cores were published by Stanislao *et al.* (2011). Visual observations of both cores were made at the site and appear in Brandon *et al*. 2010: 397–98. For additional scientific analyses, see Appendix A3.12, pp. 272–74, and Chapter 7.

***4.10.4. Observations and conjectures.*** The size of the harbour may help us understand its *raison d'être*. The original Pompeian harbour may have been simply a riverbank installation with few if any artificially constructed additions. Its purpose was probably primarily military, to provide a friendly harbour if the Cilician pirate menace flared up again. Since that never did happen, its purpose over time would have changed. It probably became a station for coastal trading by smaller merchantmen, probably of *ca.* 50 to 70 tons capacity, moving commodities from the Taurus Mountains and the surrounding hinterland of Pompeiopolis to other similar-sized maritime communities along the southern Anatolian shore and the Levantine coast, as well as to and from Antioch, the closest major international emporium. Although the harbour was situated along one of the primary maritime corridors between the eastern and western Mediterranean, it seems unlikely it had any direct interaction with the long-distance commerce that sailed further out to sea. Pompeiopolis is not mentioned by Luke in his account of Paul's last voyage to Rome in *Acts* 27, although the coaster that Paul and his entourage were on must have sailed right by. Although this vessel would have stopped somewhere along the Cilician coast, perhaps its arrival and departure from whatever havens it entered and left were so routine that Luke consciously omitted such mundane events.

*Fig. 4.52. Pompeiopolis, taking core POM.2009.02.*

The $^{14}$C date provided by the wood extracted from POM.2009.02 most likely indicates that the restoration of the harbour was either completely the work of Antoninus Pius or it had been started during the reign of his predecessor Hadrian and then finished by him. Both emperors were known for their patronage of harbours (Brandon *et al*. 2010: 395). Either

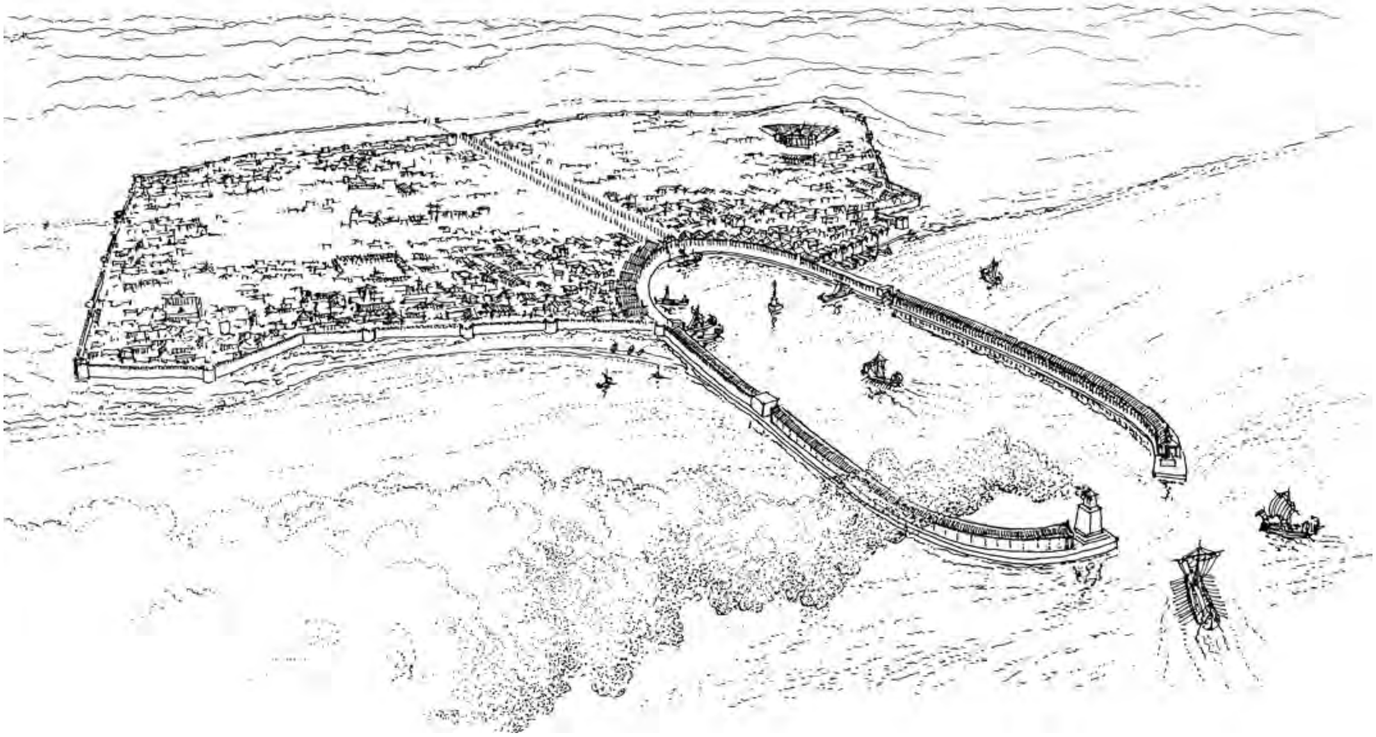


*Fig. 4.53. Reconstruction of Pompeiopolis harbour in the second century AD (C. J. Brandon).*

scenario is consistent with the coin issued by Antoninus Pius featuring the harbour of Pompeiopolis as the reverse type, which Boyce (1958) has suggested was struck in 143/44.

Since we now believe that either the Mezetli River or a canal from it ran through an open channel between the columns of a centrally positioned colonnade or under a street framed by the colonnade (the *cardo maximus*?) into the landward end of the breakwater (Fig. 4.53), river-borne alluvium entering the enclosed basin would have presented a serious and persistent problem for a functioning harbour, as would the deposition of sand driven into the harbour mouth by heavy seas. Routine dredging would have mitigated this problem, but the builders of the harbour might have tried to implement a sluicing system to combat silt and sand accumulation. We found no evidence of such system on either breakwaters, but at least one such cutting may have existed until recently. Sir Francis Beaufort, who surveyed this coast in 1811 and 1812, depicted one sluice channel in the eastern breakwater on his drawing of the harbour (Beaufort 1817: 248–56, fig. 3) (Fig. 4.54). R. L. Vann (1994), who visited and surveyed this site in 1993, reports the existence of a 3 m gap in the eastern breakwater, visible at that time but now concealed by a recently built restaurant. We believe some variant of a sluicing system may have been a common feature of artificially constructed Roman harbours, such as Sebastos (Raban 2009: 125–26), but its efficacy here or elsewhere remains debatable. More than one 3 m wide sluice channel would have been needed to provide an out-flowing current of sufficient strength to carry river-borne silt through the harbour entrance against inflow from the open sea. It may be that siltation was a constant problem that required frequent redress through dredging (*cf.* Wilson 2011a: 51 on the dredging of river ports).

The collapse of the eastern breakwater has allowed sand to accumulate against the eastern side of the west breakwater and throughout the section of harbour basin still in the sea. Without dedicated geological coring, it is now impossible to estimate the depth of water within the basin when it was functioning. Such information would help to determine the

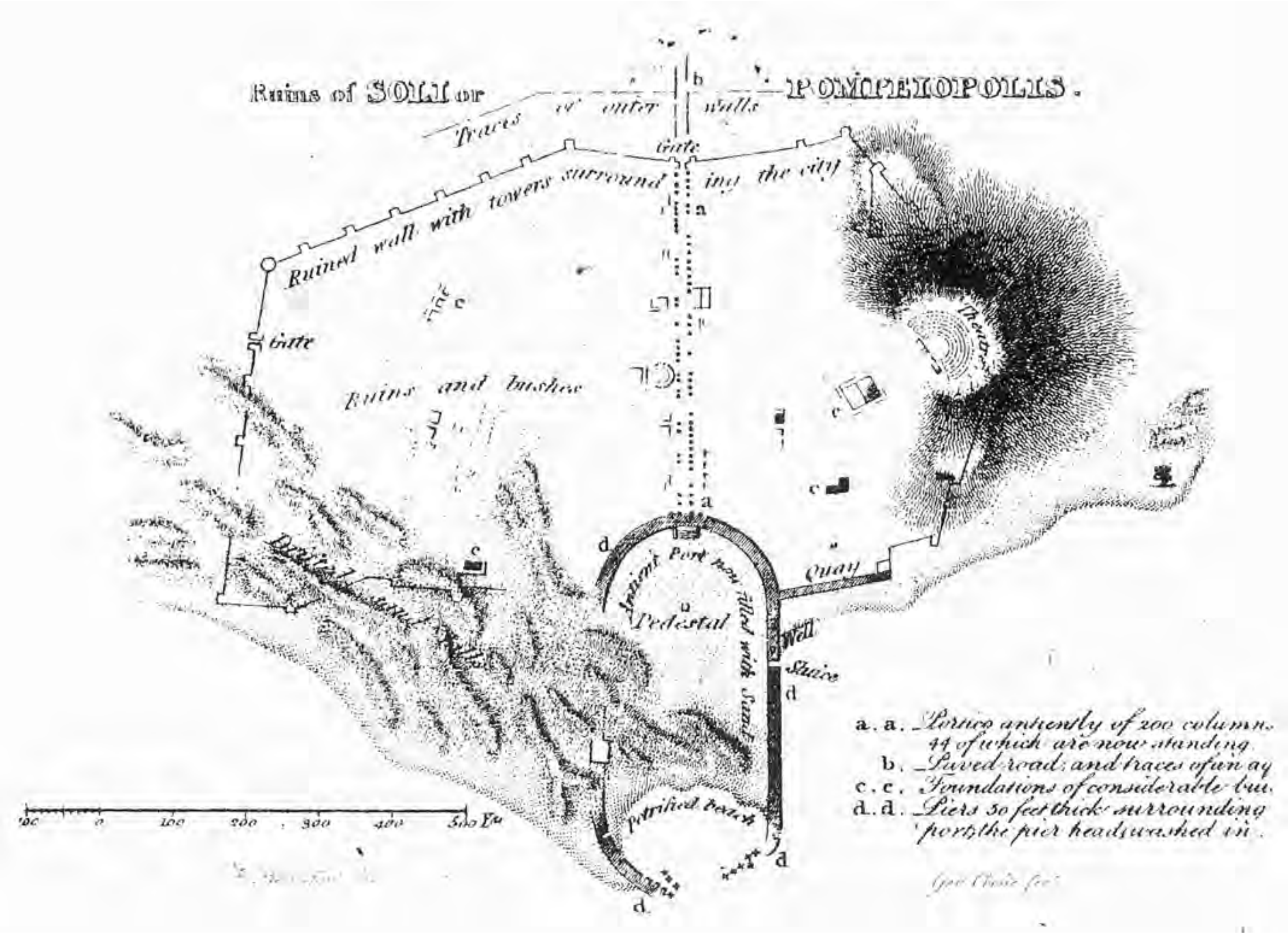


Fig. 4.54. Pompeiopolis, map of the harbour by Beaufort in 1811–12 (from Beaufort 1817: fig. 3).

size of ships that might have been able to use Pompeiopolis during its *floruit*.

The reasons behind the remodelling of the harbour commemorated by the Antoninus Pius coin are uncertain. Perhaps after a long period of neglect or deferred maintenance, river alluvium and sand transported by the east to west current that moves along the Anatolian shore may have rendered existing harbour facilities dysfunctional. A renovation with Imperial support or blessing might have had strategic significance by re-establishing or reconditioning a base for the Roman navy in the eastern Mediterranean should it be needed (Raban 2009: 184) and by providing another safe haven for *annona* ships transporting goods from the Levantine coast and eastern Anatolia to Rome. The rebuilding of this harbour was consistent with the maritime policies of both Hadrian (Cassius Dio 69.5) and Antoninus Pius, a policy that saw Imperial investments in other eastern Mediterranean ports (*e.g.* Andriake/Myra, Patara, Caesarea, Antioch), perhaps as an effort to enhance a *maritime façade* along this well-travelled coastline of an increasingly important sector of the empire.

# Chapter 5

# The Brindisi *Pila* Reproduction

## *J. P. Oleson*

The first years of ROMACONS fieldwork, conducted in 2002 and 2003 at Antium, Portus, Cosa, and Santa Liberata, produced high quality and informative cores of Roman marine concrete (Oleson *et al.* 2004a). Neither the resulting data nor the few descriptive passages from relevant ancient literary sources, however, provided precise information on the procedures Roman engineers used to build formwork in the sea, or to prepare and place the mortar and aggregate components of the concrete in these forms. Vitruvius preserves invaluable contemporary information about Roman harbour construction (see pp. 14–23, Passages 4–9), but he – and other authors such as Pliny the Elder and Strabo – are silent about many mundane but important matters. The ancient literary sources provide no explicit information on such important issues as the procedures for measuring and mixing the ingredients of the mortar, the use of salt or fresh water, and the methods used to place mortar and aggregate in inundated forms. Although the analysis of ROMACONS cores provided reliable information on the strength and constituents of Roman marine concrete, in 2004 there were still no data on how quickly the mortar set, or how long it took to achieve its maximum strength. Questions also remained regarding the practical difficulties involved in the erection of wooden formwork in the sea, whether the semi-liquid mixture of mortar and aggregate was compacted – as terrestrial concrete seems to have been – and how all these tasks might have been accomplished.

To address these issues and other related questions from a new perspective, Brandon, Hohlfelder, and Oleson undertook an experimental archaeological project from 13 to 21 September 2004. During this nine-day period, this small team constructed a freestanding, 8 cubic metre concrete *pila* in the inner harbour of Brindisi (Italy; Fig. 6.1) using to the extent possible only materials and tools that would have been available to Roman builders (Hohlfelder *et al.* 2005; Oleson *et al.* 2006). The problems encountered and the solutions taken were all very instructive. Subsequently, the team used the standard ROMACONS coring equipment to take cores from the *pila* in March 2005 (BRI.2005.01), November 2005 (BRI.2005.02), November 2006 (BRI.2006.01), May 2008 (BRI.2008.01) and November 2009 BRI.2009.01. These cores have provided unique data on the strength and evolving mineralogy of a Vitruvian type mortar and concrete as it cured, at intervals of six, 14, 26, 44, and 62 months. While it is not certain that our solutions for construction problems associated with the use of Roman marine concrete mirror precisely the practices of builders two millennia ago, the resulting structure and its materials bear a striking similarity to the ancient *pilae* ROMACONS has studied. There have been occasional attempts in the past to replicate Roman mortar, but all were on a very small scale, and most have been uninformed by recent archaeological work (Sersale and Orsini 1969; Costa and Massazza 1976, 1977). A recent, carefully designed project at the University of Melbourne showed more promise, but it has been abandoned because of funding difficulties (Goldsworthy and Min 2009; Goldsworthy, pers. com. 2013).

### 5.1. The reconstruction project: Methods and materials

Vitruvius provides us with our only detailed description of how Roman builders constructed concrete structures in and under the sea (*De arch.* 5.12; pp. 20–23). He outlines three techniques, with an engineer's eye for site and materials: placing marine concrete within an inundated form, prefabricating a block of marine (?) concrete above water, and placing concrete made without pozzolan in a double-walled cofferdam from which the water has been pumped. According to Vitruvius, the first technique was suitable for situations in which pumiceous ash pozzolan (*pulvis*) was available, the second for locations where rough sea conditions made it difficult to build formwork, and the third for situations in which pumiceous ash pozzolan was not available. Since the ROMACONS project is focused specifically on the Roman use of marine concrete within flooded formwork, as described by Vitruvius and reflected in archaeological remains, the team focused on that procedure. For ease of reference, the relevant portion of the passage is quoted here (see also above, pp. 21–23, Passage 9).

> (2) If, however, we have no natural harbour situation suitable for protecting ships from storms, we must proceed as follows. If there is an anchorage on one side and no river

> mouth interferes, then a mole composed of concrete structures or rubble mounds (*structuris sive aggeribus*) must be built on the other side. The harbour enclosure should be constructed in the following manner. Those concrete structures that are to be in the water must be made in this fashion. Powdery volcanic ash (*pulvis*; lit. "powder") is to be brought from the region that runs from Cumae to the promontory of Minerva and mixed in the trough in the proportions of two parts earth to one of lime. (3) Next, in the designated spot, formwork (*arcae*) enclosed by solid (*or* "oak") posts and tie beams (*stipitibus robusteis et catenis*) must be let down into the water and fixed firmly in position. Then the area within it at the bottom, below the water, must be levelled and cleared out, [working] from a platform of small crossbeams (? *ex trastilis* or *trastillis*). Afterwards aggregate broken in the trough (*caementis ex mortario*) and mortar (*materia*) mixed as specified above is to be placed within, until the space inside the form has been filled with the concrete structure.

This passage, the Vitruvian recipe for marine mortar discussed below, and archaeological data constituted the basis for our reconstruction of a *pila* in the sea.

We opted to build a test block of eight cubic metres, nominally a cube 2 m on each side. These dimensions are considerably smaller than those of the typical Roman maritime *pila*, which ranged around 400 m$^3$ and could be as large as 1100 m$^3$ (at Nisida north of Naples; Gianfrotta 1996: 71, fig. 4), but they are sufficiently large to ensure that the mortar aggregate mix would be representative and that core samples could be taken. The 2 m × 2 m footprint was also the smallest area that would provide safe access for a diver to prepare the sea floor and lay aggregate by hand if that proved necessary. The height of the form ensured that there would be enough bulk of concrete both above and below water level to enable us to observe any distinctions in construction procedures and performance of the mass after curing. In addition, it seemed that 8 m$^3$ of concrete was probably the upper limit of material that the small team could mix and place in a reasonable amount of time and at a reasonable cost to our sponsors. Finally, it would have been difficult to obtain permission to cast a larger block in the busy harbour of Brindisi and to leave it in position afterwards long enough to obtain data on curing and weathering. As built, the form was a rhomboid in plan due to obstructions in the harbour mud and other practical difficulties in construction, with final side dimensions of 1.83, 2.10, 1.94, and 2.12 m and an average height of 1.87 m, containing 7.44 m³ of concrete.

At the time, the Bergamo laboratory of the CTG Italcementi Group operated a marine concrete testing platform in the Lega Navale marina on the northern side of the Seno di Ponente in the harbour of Brindisi (Fig. 5.1). The marina director offered space for our experiment on the outer edge of the yacht basin, tucked into a corner alongside a floating dock leading to the Italcementi facility and a concrete quay leading to the local rowing club. The sea floor at the selected site (UTM 4503323) sloped slightly from west to east, with a water depth at the centre varying from 1.5 m to 1.7 m depending on the tide. In addition to the advantages of easy access, security, and sheltered conditions in all weather, the concrete quay was located immediately below a fenced parking area with space to store all the materials needed for the experiment (Fig. 5.2). The only disadvantage of the sheltered location was the condition of the water, which was heavily polluted. Sewage, associated plastic debris, and even dead animals floated by the formwork, so team members entered the water only when absolutely necessary. The concrete quay provided working space where mortar could be mixed in a shallow trough. The raw materials needed for each trough load – lime paste and *pozzolana*, or tuff aggregate – were lowered by rope in a rubber basket from the storage area in the parking lot to the concrete working quay 3 m below. The water used to mix the mortar was taken straight from the harbour, although when there were obvious spills of oil or petrol we waited until they had dissipated before using it, or we drew water from a location more exposed to currents.

*Fig. 5.1. Location of the completed* pila *reproduction in the marina (to the left).*

*Fig. 5.2. Tuff blocks and bags of* pozzolana *assembled for the reconstruction project.*

## 5.2. Formwork design

As far as is known, the wooden formwork prepared for Roman maritime structures was intended principally to contain the mortar and aggregate while they were being placed, and to protect the semi-liquid concrete mass from the waves and currents until it had set. Occasionally, Roman formwork may also have been intended to serve as a medium-term exterior cladding for the structure. In the lagoon at Cosa, both concrete formwork and excavation cofferdams were left in place after construction despite apparently being easily accessible (Figs. 8.29–30; Oleson in McCann *et al.* 1987: 100–1, pl. V.4–V.17). Studies of Roman maritime concrete sites around the Mediterranean show that there were many variations in the design of formwork and the method of building it, in addition to the differences Vitruvius specifies between those used to cast marine concrete and concrete made without pozzolans (see pp. 20–23). The single-mission barge forms used in Herod's harbour Sebastos at Caesarea Palaestinae are particularly striking (Figs. 8.51–52; Brandon 1996, 1997a–b, 1999), but many other variants, along with apparently *ad hoc* formwork solutions can be found around the empire (Felici 1993; Felici and Balderi 1997a–b). The technique most commonly seen in surviving harbour remains was intended for use with marine concretes; it consisted of vertical boards driven into the seabed to create the enclosing walls, secured with collar tie beams fixed to vertical pile posts and horizontal cross beams. Archaeological evidence documents variations in the width of the vertical board cladding from 0.095 to 0.5 m, with a preference for boards wider than *ca.* 0.25 m. Beams vary from 0.13 to 0.30 m on a side.

The clearest example of Vitruvian type formwork, and one that was the principal model for the *pila* experiment, was used to build Nero's harbour of Antium. Felici (2002) has accurately recorded the positions of beam impressions and postholes in the concrete remains, along with some timber found *in situ*, particularly the ends of the vertical timber sheet piling that lined the forms. These boards varied from 0.24 to 0.26 m wide and 0.075 to 0.08 m thick with edges that had not been squared. Felici's reconstruction shows them side-by-side (Figs. 8.16–17; Felici 2002: 110–13). His reconstruction of the eastern mole, however, indicates overlapping vertical planking along with internal vertical piles and horizontal tie beams (Felici 1993: 76). Felici has also found evidence for the vertical external piles that supported the horizontal beams securing the vertical planks of the form, matching Vitruvius' description (Felici 1993: 75–87; 2002: 110). Impressions of planked formwork with occasional overlapping planks are preserved at a number of sites: for example, on the lower portion of the concrete Pier 1 at Cosa, with impressions 0.10 to 0.15 m wide, 0.15 to 0.20 m deep (Fig. 4.12; Gazda 1987: 76–77; Felici and Balderi 1997); in the Claudian harbour of Portus on the north mole (Fig. 8.23; Testaguzza 1970: 114; Meiggs 1973: pl. XIXa); in the early imperial fish tank at Santa Severa, where evidence was found for vertical planks 0.10 to 0.40 m wide, 0.03 to 0.045 m thick (Fig. 6.17; Pellandra 1997: 21–6); and at Ponza, where vertical planking 0.27 to 0.36 m wide, 0.05 m thick lined the outer layer of a form, or possibly one wall of a double walled cofferdam (Gianfrotta 2002: 67–74).

Evidence for horizontal tie beams, most likely the *catenae* described by Vitruvius, is frequently seen on Roman concrete harbour structures, since the beams passed through the middle or across the top of the block, usually just above ancient sea level. Examples include the cruciform impression on the tops of square blocks on the South Breakwater at Caesarea (Figs. 4.28–30; 0.13 m, 0.18 m, and 0.29 m sq.; Raban 1989: 496–97); the piers at Cosa (Fig. 4.14; 0.10 to 0.15 m wide, 0.15 to 0.20 m deep; Gazda 1987: 76–77); the *Molo Sinistro* of the Claudian harbour of Portus (Fig. 4.3; Felici 1993: 94–95); the mole at Astura (Fig. 8.39; Felici 1993: 89–92); and the mole at Side in Turkey (0.30 m × 0.30 m, 2.0 m apart; Schläger 1971: 153–54; Knoblauch 1977: figs. 75–77). Examples of external horizontal collar beams and the vertical posts are not found as often, since they were outside the formwork and more easily lost. Upright beams outside vertical planks were found at Santa Severa (Fig. 8.14; D 0.20, 1.5 to 2 m apart; Oleson 1977: 305–7; Pellandra 1997: 21–6), Anzio (Fig. 8.5; Felici 2002: 110–11), and Side (0.15 m × 0.30 m, 0.80 m apart; Schläger 1971: 151, 155; Knoblauch 1977: fig. 74). Where preserved, the wood used for planks and beams has been identified as oak, spruce, pine, and fir.

Our experiment was not intended primarily to test formwork design, but rather to determine what problems might arise in constructing the formwork and placing the mortar and aggregate within it, and how the concrete set and cured. Consequently we were interested in the shape, installation, porosity, and stability of the walls and frame. It seemed less important that the timber should be identical in species or moisture content with that used by the Romans, and for reasons of expense and logistics we used timber that could be readily obtained from a local lumber yard: reconstituted, kiln-dried beams (0.15 × 0.15 m) and planks (0.3 m wide, 0.03 m thick) (Fig. 5.3). Roman builders most likely used green, unseasoned timber and lumber for marine formwork, because it was both more economical than seasoned lumber and – being less buoyant – easier to pile-drive or manoeuvre underwater. There is extensive archaeological evidence for the use of green (?) timber with bark still adhering, including at Caesarea and Misenum (Brandon 1997a: 45–58; Benini *et al*. 2010: 114–15). There is no explicit literary evidence for the use of green wood (*cf.* Blake 1947: 66–69, 345), but the soldiers shown on Trajan's column seem to cut trees and use the unseasoned timber immediately for their fortifications and the rough structures within the camps (Lepper and Frere 1988: scenes 31–46, 344–45; Meiggs 1982: 180). Formwork preserved in the drains beneath the Colosseum consisted of freshly cut, unseasoned oak (Picozzi 1974: 17). The Romans certainly knew that ships made with unseasoned wood were heavy (Caesar, *B Civ.* 1.58.3), and Roman sources report that timber was immersed in fresh or salt water to season it (Cato *Agr.* 31; Pliny *HN* 13.99; Meiggs 1982: 349–50). The factor of buoyancy proved to be more important than we anticipated.

Modern scholars often underestimate the importance of lime in ancient concrete work, focusing instead on the pumiceous ash pozzolan. The lime paste, however, drives the chemical reaction that produces the hydraulic effects, and the Romans recognized an array of limes with varying properties (above, pp. 16–17). Vitruvius emphasizes the need for selectivity (*De arch.* 2.5.1; *cf.* Pliny *HN* 36.174). Italcementi analysed some polished sections of the cores taken from Roman maritime structures with an X-ray micro-analyser connected to a scanning electron microscope in order to identify the small unburned residues of limestone (sometimes less than 50 µm) within the coarse white clusters of lime in the samples. As expected, the analysis revealed limestone of high purity, containing about one percent $SiO_2$ and $Al_2O_3$ by weight, and negligible MgO. In today's terminology the lime produced from this type of limestone would be defined as "air lime," indicating that it slowly hardens in air by reacting with atmospheric carbon dioxide. Air limes generally do not harden under water as they have no hydraulic properties, which must be supplied by a pozzolanic additive (c.f. European Normative on building lime EN 459–1). A source of the appropriate matching lime was commissioned by CTG Italcementi from Calce S. Pellegrino SPA in Palagiano near Taranto and delivered to the site in the form of slaked lime putty (*grassello di calce*) packaged in airtight 25 litre plastic bags (Fig. 5.4).

*Fig. 5.3. Reconstituted lumber ready for use in the formwork.*

*Fig. 5.4.* Grassello di calce *provided for the* pila *reconstruction.*

Vitruvius is very insistent that the pumiceous volcanic ash (*pulvis*, lit. "powder" or "dust") intended for maritime concrete should be sourced from the Bay of Naples (*De arch.* 5.12.2; pp. 20–22), or – more specifically – the area around Baiae (*De arch.* 2.6.1; p. 17). Strabo (5.4.6 pp. 24–26) also praises the "natural quality of the sand-ash (*ammokonía*)" at Puteoli for the construction of breakwaters, and Pliny the Elder (*HN* 35.166; p. 27) echoes his opinion. Both Seneca (*Q Nat.* 3.20.3; p. 26) and Pliny (*HN* 16.202; pp. 26–27) use the term *Puteolanus pulvis* for pumiceous volcanic ash from the Bay of Naples area near Puteoli. It seems likely that the practice of obtaining pozzolan from Vesuvian deposits was applied right across the Mediterranean, despite the presence of numerous pumiceous ash deposits elsewhere in central Italy, and even outside Italy, at Santorini or Melos, for example (see pp. 3, 90, 154–58).

The popularity of *Puteolanus pulvis* may have been the result of the proximity of the deposits in the Bay of Naples region to the sea, and the consequent ease of loading and transport around the Mediterranean. Another explanation may be the special cachet of materials originating in Italy, the centre of imperial power. It is also possible the Roman engineers recognized that the *pozzolana* found near Puteoli in fact has more reactive properties than most other Mediterranean deposits known in antiquity, and they applied this knowledge to sites elsewhere. In any case, it was crucial to the success of the ROMACONS experiment to use *pozzolana* from the specified area. Italcementi located a supplier that provided us with material from Bacoli, adjacent to Baia and well within the region specified by Vitruvius (Fig. 1.1).

The coarse aggregate for the experimental concrete was also sourced from Bacoli, in the form of machine-sawn tuff blocks (30 cm × 20 cm × 10 cm). Many of these broke during delivery, and the rest were broken up with a sledge hammer into irregular fragments averaging 0.10–0.15 m diameter (Fig. 5.5). It is not clear how tuff aggregate was produced in antiquity, although Blake speculates that much aggregate was scrap material (Blake 1947: 349–51; *cf.* Lugli 1957: vol. 1, p. 401). Most beds of tuff are somewhat uniform in character, generally without fissures that could be used to lever out large, irregular blocks for further reduction to aggregate by hammering. Pounding at the quarry face would have produced only dust and small fragments, unsuitable as aggregate. There is no literary or archaeological evidence from the Roman period for the use of saws to cut this soft stone, which is the method employed today. Blocks removed from the quarry face by the typical trench and break procedure (Adam 1994: 25–27) may have served as raw material for producing aggregate by means of tedious reduction of the quarried blocks by hammering. Quarry off-cuts and fractured blocks would have been an economical source of aggregate, but the uniformity of the aggregate in many concrete walls of the imperial period suggests a more organized method of production (MacDonald 1982: 100). The provision of sufficient aggregate clearly was an important logistical problem, since, wherever possible, Roman engineers recycled local building debris such as broken bricks and roof tiles, potsherds from discarded amphorae, and recycled *caementa* as coarse aggregate in their concrete for terrestrial structures (MacDonald 1982: 149; Lancaster 2005a: 59, 81–5). A local source of aggregate is nearly always used in modern concrete in order to reduce costs, and the same is true of the Roman concretes examined by the ROMACONS project.

## 5.3. Construction of the formwork

The initial design of the formwork followed the description given by Vitruvius (quoted above) and is supported by archaeological evidence. The first stage of the planned construction sequence at Brindisi called for four 2.5 m long beams (*stipites robustei*), 0.15 m square, to be driven vertically down into the harbour bottom, one at each corner of the projected form (*arca*). The bottom end of each pile beam was cut to a point, and the beam was held vertically in the intended position by two individuals standing on the dock and in a dingy. A third individual then attempted to drive the beam into the mud, first by pushing and twisting it, then by hammering the upper end with a sledge hammer, and finally by dropping one end of another beam on the upper surface. All these efforts were unsuccessful, because we could not drive the piles deep enough into the viscous mud to overcome the buoyancy of the light, kiln-dried wood.

In the initial plan four vertical corner piles were to support horizontal beams against which vertical sheet piled planks could be driven, then fixed to the inside faces. Since we could not install the piles, we reversed this sequence and began by driving planks down into the mud side by side with a sledgehammer until one side wall of the projected form was in position. The high ratio of surface area to buoyancy in the boards allowed the sticky mud to hold them in position until the entire wall was complete. The boards were then nailed to a horizontal collar beam placed outside the form at a height just above water level. The weight of this beam and the suction of the mud held the first wall in place, allowing the team to construct the opposite, facing wall of the form in the same manner, 2.0 m away. Once the second wall had been completed, two cross beams were fixed with bolts to the ends of the beams framing the walls, completing an enclosing collar frame (Fig. 5.6). Holes for the bolts were drilled with a large hand auger. Construction of the last two walls of the form was relatively straightforward, since the beams guided and braced the planks and stabilized the form, and work could be carried out while standing on the frame (Fig. 5.7). Vitruvius specifies that horizontal tie beams (*trastilla*?) were to be fixed across the open form to provide stability and to serve as a working platform, and archaeological evidence for such beams is common (see above). As built, however, the form was small enough to make such reinforcement unnecessary, and planks laid across the projecting ends of the collar beams made an excellent working platform.


*Fig. 5.5. Tuff blocks being reduced to* caementa *for the* pila *reconstruction.*

We found that it was not always possible to position each vertical wall plank tightly against the adjacent one, with a gap of less than 5 mm. Stones and debris on and within the harbour mud sometimes deflected the planks as they were being driven in, resulting in gaps of 1 to 3 cm between the planks, either side to side or front to back. In addition, the restrictions imposed by the pre-existing frame meant that installation of the boards for the third and fourth walls left a final gap narrower than the standard board width. Both types of gap, either of which might have allowed mortar to escape before it set, were remedied by driving in a plank inside the form that overlapped the boards on either side of the gap, a solution apparently often used in

*Fig. 5.6. First two plank walls in position; bolt hole being drilled in horizontal collar beam joint.*

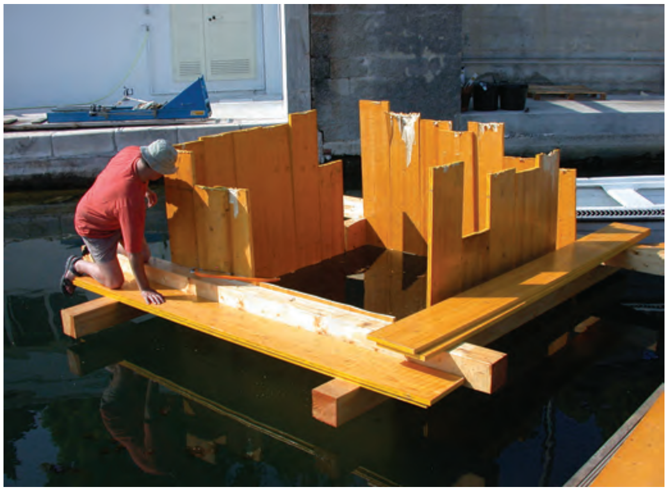


*Fig. 5.7. Trimming the formwork planks after installation of shuttering.*

antiquity as well (Figs. 5.16, 20, 8.32–33, 35) Modern engineers also comment on the need for tolerance towards variations in formwork design during construction (Franklin 1990: 9). At the end of the second day of construction, the top ends of the planks were trimmed to a uniform level (Fig. 5.7). It required 37.5 man-hours to erect the formwork, but an experienced team would have been much faster.

Because of the presence of modern debris such as steel cables and building debris, it was not possible to clear and completely level the seabed (harbour floor) within the form, as prescribed by Vitruvius. Instead, we removed the loose debris and covered the mud inside the form with a layer of beach sand 10 cm thick, to replicate more typical seabed conditions and to isolate the concrete from any modern contaminants.

## 5.4. Preparation of the mortar

Lugli (1957: vol. 1, p. 385) suggests that the mortar and aggregate were mixed prior to placement in the formwork, while Blake (1947: 351, and below) cites numerous examples that these two components were placed separately. DeLaine (1997: 135) also assumes separate, alternating placement. Assuming that the stiff mortar we mixed resembles the ancient formula, it would have been very difficult to mix mortar and aggregate effectively outside the form, and even with a softer mortar, the weight and bulk of the material would have made placement of useful amounts very difficult.

Neither Vitruvius nor any other ancient literary source specifies whether fresh water or sea-water should be used when making mortar for maritime concrete. Since Vitruvius is careful to specify the source and quality of the pumiceous volcanic pozzolan and the lime that constituted the mortar, he would certainly have indicated the use of fresh water for mixing concrete intended for maritime structures if the character of the water had been an issue. In a passage marvelling at the properties of *pozzolana* from Puteoli, Pliny (*HN* 35.166) seems to be describing a natural concrete formed where deposits of the material came into contact with sea-water, revealing that Roman "scientists" saw no natural impediment to the use of sea-water in mortar. Although the literary evidence is ambiguous, the use of sea-water for mixing mortar destined for marine structures is an obvious logistical and economic shortcut. Given the absence of comment by ancient engineers, we opted to use sea-water in the mix, but care was taken to exclude organic and plastic debris, as well as to avoid the occasional light oil slick from the marina. The decision was consistent with modern practice, since sea-water is allowed in the mix for natural marine cements and Portland cements designed for marine structures, as long as reinforcing bars are not part of the design (Lea and Desch 1956: 511, 553; Cornick 1962: 119; Franklin 1990: 25). Sea-water and natural pumiceous ash pozzolans were used, for example, in concrete produced for both the Suez and Corinth canals (Efstathiadis 1978: 19). Subsequent analysis showed that sea-water was in fact an essential part of the curing process (pp. 164–66).

The proportions of *pozzolana*, lime putty, and aggregate for the reconstructed mix were worked out from the formula given by Vitruvius (*De arch.* 5.12.2; pp. 20–23, Passage 9) and from analysis of the cores taken by the ROMACONS project. Similar calculations had been used to estimate the volumes of materials and amount of labour required for construction of the *pila* at Santa Liberata (Oleson *et al.* 2004b: 220–21). The 6 m long core taken from this *pila* in 2004 supported these calculations (SLI.2004.01, see Appendix 3.1). Based on a nominal 8 m$^3$ cube of concrete the quantities were calculated as follows:

- In the concrete cores recovered by the ROMACONS Project from Roman maritime structures between 2002 and 2004, the average proportion by volume of large aggregate to mortar/binder is 35:65. Therefore, production of an 8 m³ block requires 2.8 m³ of tuff aggregate and 5.2 m³ of mortar (after setting).

- Based on the evidence of nineteenth-century handbooks, DeLaine (1997:123) calculates that mortar made with *pozzolana* and slaked lime (lime putty) will shrink in volume by 25% as water is added (a figure verified in the CTG Italcementi laboratory), and that there was probably a further 10% loss in volume through ramming and settling of the mixture in the form. Based on these calculations, 5.2 m³ of set mortar requires 8.0 m³ of dry *pozzolana* and lime putty. Given Vitruvius' 2:1 proportion of *pozzolana* to lime for underwater construction, and assuming measurement by volume, the reconstructed *pila* required 5.33 m³ of loose *pozzolana* and 2.67 m³ of lime putty. Since quicklime can increase 350 to 400 percent in volume when slaked with water (Lancaster 2005a: 53), the original volume of quicklime required was somewhere around 0.67 to 0.76 m³.

Three important questions arose in the course of these calculations. Did Vitruvius calculate his 2:1 ratio by volume or by weight; did he calculate on the basis of wet lime putty or dry quicklime; and did he calculate on the basis of dry or wet *pozzolana*? Siddall (2000: 340) assumes that dry *pozzolana* was added to the dry lime before the slaking process (see pp. 65–67). Lancaster suggests that the lime should be slaked and aged before mixing (2005a: 53–54), and Blake (1947: 315), Lugli (1957: vol. 1, p. 393), and DeLaine (1997: 140, 175) assume that aged lime putty was mixed with the *pozzolana* immediately before placement. Ancient and modern sources praise the quality of slaked lime aged for months or years (Cowper 1927: 30–31, 55; see below). In fact, Vitruvius explicitly states that the lime should be slaked before it is added to the mortar mix (*De arch.* 2.5.1; pp. 16–17, Passage 6): "Once the lime has been slaked, mix the mortar (*materia*) according to these formulae: if it is quarry sand (*harena fossicia*), mix three portions of sand to one portion of lime." (Cum ea [*calx*] erit extincta, tunc materia ita misceatur ut si erit fossicia, tres harenae et una calcis infundatur…). This is the hydraulic mix for structures on land; for marine structures, the Vitruvian ratio was two to one (*De arch.* 5.12.2). For structures on land, Pliny (*HN* 36.175) specifies a hydraulic mortar with a ratio of four to one. Although succinct, Vitruvius' comments on the mixing of mortar for a harbour structure seem to imply that the (slaked) lime and *pozzolana* are to be mixed in the trough immediately before use (*De arch.* 5.12.2): "let *pozzolana* be brought...and mixed in, so that in the trough the proportions are two to one" (*uti portetur pulvis…isque misceatur, uti in mortario duo ad unum respondeant*). This procedure does not allow for the slaking of quicklime. Furthermore, it is difficult to store quicklime, which becomes inert if it is allowed to absorb atmospheric $CO_2$ (Blake 1947: 315; Lancaster 2005a: 54). Roman engineers may well have preferred to slake quicklime immediately after it was produced, to avoid this problem. Recent traditional lime-burners keep slaked lime "fresh" in a pit near the kiln by covering it with a layer of soil or water (Cowper 1927: 30–31; Adam 1994: 72). After attributing building collapses in first-century Rome to skimping on lime, Pliny (*HN* 36.176) refers to "old building laws" requiring the ageing of *intrita* – which in the context should be slaked lime putty – for three years prior to use (see p. 28). Using a petrographic microscope, Pavía and Caro (2008: 9–10) documented the use of aged lime in samples of Roman mortar dating from 100 BC to AD 500.

Finally, we decided that the Roman engineers put the *pozzolana* into the mixing trough dry. Vitruvius (*De arch.* 2.4.3) specifies that *pozzolana* should be used soon after it is dug from the pit, because weathering makes it "earthy" (*terrosa*) and incapable of bonding with the aggregate. The implication is that the natural moisture of *pozzolana* direct from the quarry is the standard condition. Nevertheless, we tested this interpretation (and the sensitivity of the mix) by mixing the final 16 batches of mortar with slightly different proportions, being 2.7 of dry *pozzolana* to 1 of lime. The point at which this change was made corresponded to the low tide water level. Since *pozzolana* shrinks in volume by approximately 25% when dampened (DeLaine 1997: 23), whereas lime putty undergoes little or no volume change, a mix of 2.7 of dry *pozzolana* to 1 of lime putty is the equivalent to 2 measures of wet *pozzolana* to 1 of lime putty. Tests of Core 1 from the *pila* revealed that the chemical composition of the concrete made with the 2.7:1 mix was closer to that of the ROMACONS samples of ancient concrete than the 2:1 mix (see Chapter 7). In consequence, it seems likely that the Romans wet their *pozzolana* before measuring it out into a trough for mixing mortar. This procedure probably also facilitated the mixing of the lime and *pozzolana*, since we found that the lime paste tended to roll up into balls surrounded by a crust of *pozzolana* if the latter was added while dry. Natural *pozzolana* mortars for maritime use in Italy prior to the early twentieth century had a *pozzolana* to lime putty ratio of 2:1 by volume (Maura 1996: 50–1), but experimentation showed that a ratio of 3:1 or 3.5:1 gave better results (Lea and Desch 1956: 368).

There is no explicit statement in the Roman authors that the components of the mortars and plasters they describe were to be measured by volume rather than weight, but measurement by volume seems the most likely interpretation. Roman concrete architecture consisted of masses of mortar, coarse aggregate and facings carefully shaped to form practical and symbolic volumes of space. Except in the most daring structures – such as the Colosseum, or the Pantheon, in which the density and perhaps the proportion of aggregate varied from the foundation to the rim of the oculus (Blake 1973: 3–4; Taylor 2003: 207–8; *cf.* Delaine 1997: 159; Lancaster 2005a: 62, 77, 167, 2005b: 77) – the weight of the concrete was of little concern. Instead, contractors needed to consider the volume of the empty formwork scheduled to be completed in a particular work period. Marine structures in particular started off as large, empty, box-like forms, and Vitruvius focuses on "the space left within the form" (*De arch.*

5.12.2). The easiest way to organize such a task was to calculate the required volume of each component, arrange for delivery of the materials in bulk at the appropriate times, and marshal the appropriate number of workers and foremen (MacDonald 1982: 154, 157–59; DeLaine 1997: 174–94). The regular brick bonding courses through concrete walls in terrestrial structures may have been intended to allow easy calculation of the amounts of concrete and numbers of bricks required for a known structural unit (Taylor 2003: 105–6). In the absence of steam shovels, front-end loaders, conveyor belts, or even wheelbarrows, workers had to empty barges or transport wagons with baskets and sacks. It would have been simple for a foreman to count and direct porters carrying *pozzolana* and mortar in containers of known, standard volume to a specific trough where a calculated volume of mortar was to be mixed. Calculation by weight requires an extra step, special scales, and a greater opportunity for error. In her detailed analysis of the construction of the Baths of Caracalla, DeLaine (1997: 93–94, 123, 184) assumes calculation by volume divided into basket loads, and Lea and Desch (1956: 368) report the traditional calculation of the ingredients of marine pozzolanic mortar by volume. The mortar used for the Suez and Corinth Canals contained Santorini Earth and lime putty, measured by volume, and mixed with sea-water (Efstathiadis 1978: 19).

In view of this evidence, we calculated the mortar mix by volume and assumed that Vitruvius was referring to dry *pozzolana* and slaked lime. Although the decision to use dry *pozzolana* may have been mistaken, the use of slaked lime putty must be correct. If we had used dry *pozzolana* and quicklime in Vitruvius' ratio of 2:1, the final *pozzolana* to lime ratio after water was added would have been the equivalent of 2:3.5 or 2:4, reversing the proportions and resulting in an extremely rich ("fat") mortar. Wet *pozzolana* and quicklime would have given the equivalent of 2.5:3.5 or 2.5:4, still very heavy in lime. Conversely, measuring the components by weight would have significantly diminished the proportion of lime in the mix. In ordering the raw materials we allowed for a small amount of wastage and for loss of mortar in suspension in the water or by leakage through the side wall joints in the form (Table 5.1). The supply of *pozzolana* and tuff was just sufficient for the experiment, while only one-third of the beach sand was used. Ninety-two 25 litre bags of lime were used, totalling approximately 2,300 litres.

*Table 5.1: Materials procured for the* pila *reconstruction.*

| | |
|---|---|
| Lime putty | 3 m³ |
| *Pozzolana* | 6 m³ |
| Tuff aggregate | 3.5 m³ |
| Beach sand | 1 m³ |
| Timber | 36 no. 30 × 3 cm planks 2.5 m long<br>6 no. 15 × 15 cm beams 3.5 m long<br>4 no. 15 × 15 cm beams 2.5 m long |
| Tools | 1 hand auger, 2 bow saws, 2 hammers, 2 spades, 2 mattocks, 2 large rubber buckets, 3 wicker baskets, miscellaneous nails, spikes, and bolts. |

A mixing trough with sides 0.71 m × 2.5 m and 0.3 m high and a capacity of 0.525 m³ was built on the concrete quay next to the formwork, immediately below the car park where the *pozzolana*, lime, and tuff aggregate were stored. On Day 3 we began to mix the mortar (Fig. 5.8). Each batch was composed of 6 measured buckets containing 16.5 litres of dry *pozzolana* (totalling 99 litres or 0.099 m³) and two 25-litre bags of lime (0.05 m³) forming the desired 2 to 1 mix. The mortar was mixed by hand with mattocks, rakes and spades, all tools readily available to Roman builders (White 1967; Adam 1994: 73–76). The lime was folded into the dry *pozzolana* sand while sea-water was added in small amounts. Although there is no ancient evidence regarding the stiffness of mortar intended for submarine construction, modern handbooks for this type of work all recommend a stiff mix with little slump (Cornick 1962: 119, 134–35). In consequence, the amount of water used was kept to a minimum, approximately 12 to 16 litres of sea-water for 149 litres of dry mix. Mixing the mortar was very hard work until the *pozzolana* grains had been thoroughly moistened by the water and lime, and even then the resultant mix was very stiff with virtually no slump. A ball of mortar (diam. 0.07 m) compacted in the hand would keep its shape. Each batch produced approximately 0.1 m³ of wet mortar, light grey in colour, with occasional nodules of unmixed lime putty (Fig. 5.9). The caustic lime putty caused painful burns if allowed to contact bare skin, reminding team members of Theophrastus' warnings of the heat produced in slaking lime (*On Stones* 66; p. 12, Passage 1). Nevertheless, we seem to have been more scrupulous than the ancient (slave?) workers in attempting to obtain a uniform mix, since the cores of the reproduction concrete contained a markedly lower percentage of large lime nodules than the relict lime clasts seen in the cores of ancient concrete (pp. 267–70). Over the six full days that we laid the concrete we mixed 44.5 batches (4.45 m³) of wet mortar.

## 5.5. Placement of the mortar and aggregate

Unfortunately, Vitruvius does not elaborate on how the mortar and *caementa* should be placed underwater in the formwork he describes, simply stating that the aggregate and mortar should be heaped up (*congerendum*) in the empty form until it is full. Leather tubes, similar to the tremie tubes sometimes used when pouring modern concrete underwater, would not have been suitable for the viscous mortar used by the Romans or for the large, irregular *caementa*. The suggestion of Roman tremie tubes was first made by Dubois (1902: 452–54); for tremies and skips used in modern underwater concreting, see Franklin *et al*. 1990: 12–16; Allen 1998: 275–76. In any case, we would expect some explanation by Vitruvius, or some other evidence for the use of tremie tubes by the Romans, if such a procedure was envisioned. These tubes, or bottom-dumping hoppers ("skips") hoisted by a crane, are necessary when

*Fig. 5.8.* Pozzolana *and lime putty in the mixing trough.*

*Fig. 5.9. Detail of the mortar after mixing.*

*Fig. 5.10. Reconstruction of workers lowering mortar into formwork at Sebastos (Hohlfelder 1987: 264–65) (National Geographic Society, used with permission).*

placing modern concrete in inundated forms both because this concrete is prepared in a very liquid form, and because the aggregate (much smaller than Roman aggregate) and mortar are mixed together in carefully calculated proportions prior to placement. If poured directly into an inundated form, the mortar of a modern concrete is diluted and the aggregate accumulates in distinct, uncemented layers (Cornick 1962: 119; Franklin *et al.* 1990: 12, 22–23; Allen 1998: 276).

Although the stiff "Roman" mortar that we mixed held together quite well when tossed into the inundated form, there was some erosion of the lumps, and the pumice *lapilli* that form inclusions in the *pozzolana* tended to float away and be lost. It was also difficult to distribute the mortar evenly across a form by tossing, since the lumps, irregular in shape and only slightly heavier than water, descended in unpredictable directions, and the murky water within the form did not allow visual inspection of the result. Since baskets were a standard container for excavated earth and for building materials at Roman construction sites on land, it is likely baskets were used to carry mortar to fill the forms for a maritime structure. Remains of what could be basketry withes were found in five of the ROMACONS cores (Appendix 3, POR.2002.02, SLI.2004.01, BAI.2006.02 and 04, ALE.2007.01). Oleson proposed the use of such baskets, supplied with a rope on each handle and a trip-line attached to the base, for placing mortar in the formwork at Sebastos, the harbour of Caesarea Palaestinae

(Fig. 5.10; Oleson 1985; Hohlfelder 1987: 264–65). In theory, the baskets were filled at a mixing trough, then carried to the edge of the form by one or two individuals who lowered the basket to the selected spot with the two handle ropes, then emptied its contents by means of the tip rope.

There are several clear iconographic records of baskets in use at Roman construction projects; the most legible examples are found on Trajan's column (Fig. 5.11; Lepper and Frere 1988: scenes 30, 32–33, 45–46, 100, 131, 139–40, 145–46, 161–62). The baskets the Roman soldiers use, for the most part to shift earth, are tall and made of woven wickerwork, possibly willow withes (White 1975: 73–74). They do not have handles, but thick, rounded rims that the soldiers grip with their hands. A similar basket is shown in use by Hercules to clear the Augean Stables in an early Imperial relief from the amphitheatre at Capua (Pesce 1941: pl. 22b). Vegetius (*Mil.* 2.25) lists "baskets (*cophini*) for carrying earth" as part of a soldier's equipment. Other representations seem to show more shallow baskets, similar to the *goufas* made from recycled automobile tires used in many developing countries today to move dirt or construction materials. A third-century mosaic now in the Bardo shows one man pouring water from an amphora into a heap of dry material that another worker is mixing (Fig. 5.12; Adam 1994: 76, fig. 164). Two low baskets with upright ear handles sit nearby. Such workers may have been called *caementarii* (Blake 1947: 327–28). An inscription from Misenum mentions a *caementarius* who served with the fleet, perhaps constructing harbour installations (*CIL* 10.3414; p. 36, Passage 32). A fourth-century fresco in the Tomb of Trebius Iustus on the Via Latina in Rome depicts the construction of a brick-faced concrete wall (Fig. 5.13; Marucchi 1911, fig. 5; Blake 1947: 318). One worker mixes the mortar with a long-handled hoe. Another worker climbs up a ladder to a mason on the scaffolding, carrying on his shoulder what appears to be a low basket with heavy loop handles, filled with white mortar. A similar basket is visible beneath the scaffolding, next to the man mixing mortar. A third worker approaches the ladder carrying on his shoulder a tall basket without handles, similar to those illustrated on the Column of Trajan. This basket is heaped up with small, dark lumps that could be *caementa*.

DeLaine (1997: 93–94, 107; *cf.* White 1975: 73–74) compares the baskets on Trajan's column with nineteenth-century builders' baskets, which had an average capacity of one bushel (*ca.* 0.03 m³). She assumes that the Romans used baskets with a capacity of 2 *modii*, one cubic Roman foot, (*ca.* 0.026 m³). Two baskets similar to those depicted on the Column of Trajan were found in the Roman harbour of Pisa (Bruni 2000: 111, 115), one of them (V6) associated with a rope for suspension or handling. The capacity of the better preserved

*Fig. 5.11. Trajan's column, Cichorius Scene XII. Soldiers using baskets to shift earth (P. Rockwell, used with permission).*

*Fig. 5.12. Bardo Museum, third-century mosaic showing construction scene (J. P. Oleson).*

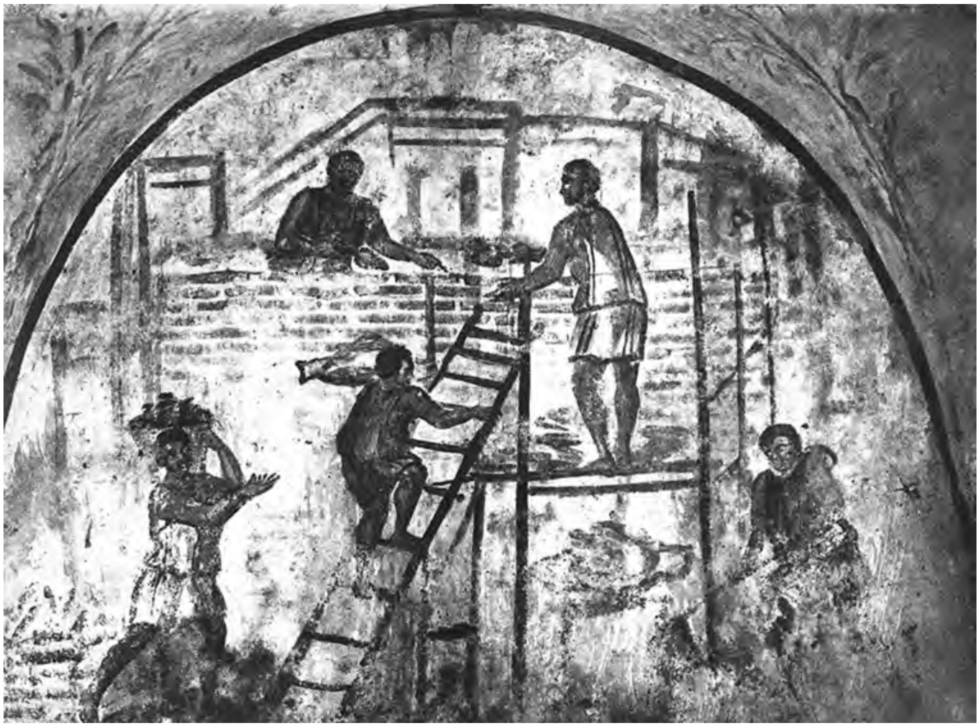


*Fig. 5.13. Tomb of Trebius Iustus, on the Via Latina, Rome. Fresco depicting construction of a brick-faced concrete wall (Marucchi 1911, fig. 5).*

example (V10) can be reconstructed as approximately 0.037 m³. There do not appear to be any traces of handles. The Pisa V10 design was used as the model for the Brindisi baskets, made to order from willow withes at a shop in Tunbridge Wells, Kent (H 0.35 m, upper D 0.43 m, lower D 0.28 m), but with the addition of two upright loop handles to assist transport to the form and lowering into the water (Fig. 5.14). The capacity of the reconstructed baskets was approximately 0.031 m³. In fact, the handles were vulnerable to damage and loss. The Romans could easily have carried the baskets by their thick rims, and tied the ropes through the thick basketry rim.

At the Brindisi construction site, two of the baskets were fitted with three ropes, one on each carrying handle and one tied to the centre of the base, to serve as a tip rope. The third basket was kept back as a spare. At the mixing trough we filled the baskets approximately two-thirds full (*ca.* 12.5 litres, *ca.* 20 kg) of wet mortar, an amount that both the basket and the porters could manage without breaking down. Two porters carried the basket to the edge of the formwork, grasped the ropes tied to each handle and manoeuvred the basket over the appropriate spot within the form (Fig. 5.15). It was a surprise to see that the positive buoyancy of the wicker basket nearly compensated for the slightly negative buoyancy of the mortar, allowing the two porters to manoeuvre the basket easily with their ropes. Once in position, the basket was allowed to sink to the bottom and the tip rope was gently pulled, dumping the mortar on the construction face as a coherent mass. The basket

*Fig. 5.14. Reproduction basket with load of mortar and ropes for lowering and dumping.*

then floated to the surface of its own accord and was pulled out of the water with the tip rope (Fig. 5.16). Once the workface became visible in the latter stages of work, it could be seen that the inverted mortar lumps carried the impression of the interior of the basket, as with soft ricotta cheese (Fig. 5.17). It required 356 basket loads of mortar, followed alternately by addition of the aggregate, to fill the form. The baskets proved very durable: one lasted for approximately 150 loads, the second for approximately 200.

It cannot be proven but seems reasonable that a similar procedure was used by Roman engineers to place mortar in inundated forms. Lowering the basket and emptying it with ropes involves little more effort than simply tossing basket loads of mortar into the water within the formwork, and it both preserves the integrity of the mortar and allows precise distribution of the input. We were able to manoeuvre the loaded baskets of mortar easily in the water, using the handle ropes, and the load of mortar slipped easily out of the basket once the trip-rope was pulled; since the wicker work is porous, there was no suction to overcome.

There is no evidence concerning the placement of mortar in Roman maritime structures, other than what has been related above. We assumed that the Roman engineers would require deposit of the basket loads in a regular pattern across the bottom of the form, to ensure that the whole area was covered with a layer of uniform thickness prior to the addition of aggregate. Since most Roman concrete seems to have been tamped (Adam 1994: 73–76; Taylor 2003: 100–1), after placing a day's worth of mortar (a layer *ca.* 0.18 m thick) we used a long-handled rake to spread the mortar into the corners and compact it across the form. This tool was light and difficult to manoeuvre, and it is unlikely that these efforts made any significant difference to the consistency of the concrete. The mortar nevertheless settled well. Compaction of the mortar tended to release numerous rounded, pumice *lapilli*, inclusions in the *pozzolana* that had not bonded with the mortar in the course of mixing (see Figs. 5.16, 19). Inclusions of this type are frequently seen in the cores taken from Roman maritime structures, and our experience indicates that they should be considered part of the *pozzolana* admixture rather than intentional small aggregate.

The irregular pieces of tuff *caementa* (D *ca.* 5 to 15 cm) were loaded into rubber baskets and lowered from the parking lot to the trough used to mix the mortar. The trough was used as a means to measure the quantity of large aggregate added to the mortar (Fig. 5.18). We initially allowed 20 percent for voids and estimated that a full trough contained 0.42 m³ of aggregate. After filling the form, we were able to calculate that the voids occupied only about 14 percent, and that each trough actually contained 0.53 m³ of aggregate. In consequence, the average aggregate to mortar ratio in the Brindisi concrete was 37:63 rather than the design ration of 35:65. We do not believe that this discrepancy had any significant effect on the result, since the ratio varies even more in our Roman concrete samples (See Appendix 3, Table A3.1). Samuelli Ferretti (1997:

*Fig. 5.15. Basket of mortar floating in the inundated form.*

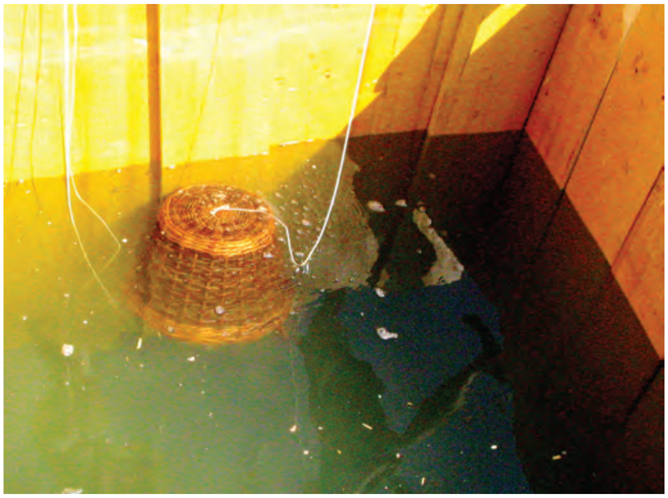


*Fig. 5.16. Empty basket returning to the surface. Note tip rope attached to base.*

*Fig. 5.17. Basket loads of mortar visible in shallow water in formwork.*

*Fig. 5.18. Trough filled with measured volume of tuff* caementa.

*Fig. 5.19. Surface of the concrete after settling overnight.*

*Fig. 5.20. Final upper surface of the concrete within the formwork.*

71) also recorded significant variation in samples taken from Trajan's harbour at Portus: aggregate to mortar ratio 54:46, 38:62, and 35:65.

After each day's batch of mortar had been dumped and spread, the aggregate was placed by casting the fragments of tuff into the water one by one from the edge of the form in a random pattern throughout the enclosed area. We feared that delivery with a basket in the same manner as the mortar would have left small, isolated lenses of aggregate. Once the measured quantity of aggregate had been added, we tamped it down into the mortar as best we could with the same long handled rake that had been used to compact the mortar. In Roman concrete structures on land the aggregate usually appears to have been placed in a similar random manner, particularly prior to the first century AD, then tamped (Blake 1947: 329–35, 351, 1959: 160; Lugli 1957: vol. 1, p. 385). Tamping imparts extra strength to many modern concretes as well (Wilby 1977: 142). There are also many Roman terrestrial structures in which the aggregate is very uniform in size and character and so regular in its placement that the individual *caementa* must have been laid by hand (Blake 1947: 335–38, 341, 344, 1959: 160). The *caementa* in the upper level of concrete at Pompeiopolis were laid by hand in a regular pattern (Fig. 4.48). Some structures show evidence of both procedures (Blake 1947: 339). Obviously, it would have been very difficult, frequently impossible, for Roman workers to lay aggregate by hand in an inundated form in zero visibility or at significant depths, and their efforts would have reaped little reward in terms of increased structural stability.

After three days of hard work, the upper surface of the concrete was visible in the morning below the surface of the sea before we recommenced work. The generally smooth surface indicated that the mortar was settling and to some extent self-compacting overnight, and incorporating the aggregate (Fig. 5.19). Mortar laid below water level still had not completely set twelve hours after placement, while mortar laid above water level set overnight but still was easily scratched with a fingernail. The process of filling the form with alternating layers of mortar and aggregate was repeated over the course of 6.5 days until the concrete reached to within 10 cm of the upper edge of the formwork (Fig. 5.20). It had taken 210 man hours to mix and lay 7.06 m$^3$ of concrete, approximately 30 man hours per m$^3$. Finally, the *pila* was capped with paving blocks (50 cm × 25 cm × 10 cm thick) of a local calcareous tufa, laid on a bed of mortar (Fig. 5.21).

We have no information concerning the removal of accessible portions of the wooden formwork from Roman maritime structures once the concrete had set or partially cured, but it seems a reasonable economy to reuse as much lumber as possible for a series of structures at one site. DeLaine (1997: 92) assumes the reuse of lumber from formwork above the foundation level at the Baths of Caracalla, and Schläger (1971: 151) assumes salvage and reuse of the accessible parts of the submarine formwork at Side. Although remains of the wooden formwork are often found beneath, within, and sometimes around the base of Roman concrete structures in fresh and salt water (see Chapter 8), the outside faces of the structure are usually bare. These are at once the areas where the formwork lumber could most easily have been recovered for reuse and where the wood would most quickly have been lost to marine borers and the force of the sea. It is conceivable that accessible planks forming the exposed faces of a form were left in place for several weeks or months to ensure the mortar had cured sufficiently to withstand the erosive forces of the sea. By this time, the lumber might not have been suitable for recycling. On terrestrial Roman structures, any formwork used would be removed for cosmetic reasons, if not also for recycling. The removal of the lagging or easing of the centring from vaults would have required more care, since the structures were more complex and the degree of curing was more critical, but the wood was always removed (Taylor 2003: 97–106, 182–86; DeLaine 1997: 157–69; Lancaster 2005a: 22–50). In any case, we left the formwork of the Brindisi *pila* in place in order to document its decay, only cutting off the ends of the collar beams in order to make more room for passage of boats in the marina. In November 2005, 13 months after construction, the wood of the form appeared solid below sea level, but heavily encrusted with mussels (Fig. 5.22). By May 2008, 3 years and eight months after construction, the submerged portion of the planks looked significantly weakened by marine borers and rot. If the *pila* had been located in an area exposed to significant wave action, the planks probably would have been torn away within 12 to 18 months.

*Fig. 5.21. Completed pila with paved upper surface.*

*Fig. 5.22. Condition of the formwork planks at low tide, November 2005.*

## 5.6. Conclusions from the reconstruction experiment

Once complete, the ROMACONS *pila* constituted a small-scale but convincing replica of an ancient maritime structure. The wooden formwork that encased the concrete had the same degree of irregularity as can be seen in ancient formwork and formwork impressions, and we were able to use the beams to support scaffolding planks for working, as suggested by Vitruvius. Seepage of mortar through the seams in the planking was minimal, despite the decision not to use caulking. Although there were several small gaps here and there in the formwork, only a small amount of mortar leaked out from the east face of the form at the level of the harbour floor. It is apparent that the mortar retained its integrity in the sea, owing both to its thick, viscous nature and the method of placement. Brandon's study of Roman forms has not so far revealed any evidence of sealants, except for the use of battens closing the seams between vertical planks on the interior of formwork at Miseno (Figs. 8.23, 8.36). The forms at the harbours of Caesarea Palaestinae (Figs. 8.63–65, 70–71; Brandon 1999) and Carthage (Hurst 1976), and a bridge footing at Chalon-sur-Saône (Figs. 8.56–57; Bonnamour 2000; Brandon 2001) were edge-joined laboriously with pegged mortise and tenon joints, like those in a ship's hull (Figs. 8.63–65). This arrangement would have strengthened the form and at the same time prevented leakage of the mortar. There is an obvious link between ship construction and the construction of the barge forms at Caesarea (Brandon 1996, 1997a–b, 1999) and at Chalon-sur-Saône (Bonnamour 2000), probably enforced by the exposed character of the sites. Elsewhere, shipwrights may well have been put to work constructing stationary formwork as need required. The "wall first" construction followed for the form at Brindisi would have been a natural solution for a shipwright trained in the Greco-Roman "hull first" method of ship construction. The forms at Caesarea and Chalon-sur-Saône were designed as single-use barges, but at Carthage this extraordinary structural precaution may be the result of fears that mortar might leak from between the planks because of exposure to the waves of the sea. The Carthage formwork may also be an example of excessive caution by a workforce unfamiliar with marine mortars.

While we constructed the formwork as carefully as possible, the difficulties in placing the beams and planks resulted in design irregularities similar to those observed in ancient formwork, for example at Cosa (Figs. 8.29–30) and San Marco di Castellabate (Fig. 8.19). In our case, and in antiquity as well, these variations reflect problems encountered in the construction of the shuttering and the solutions employed to solve them. The replication experience suggests that, given the composition of the mortar used, the basic design of the formwork is very forgiving and can tolerate minor design imperfections. It was not necessary to ensure that the hollow wooden container for marine concrete was watertight.

Visual representations strongly suggest that Roman builders used wicker baskets to carry mortar from the mixing area to its place of deposition, and lowering such baskets into inundated formwork and tipping them with ropes makes sense. We have shown that such a system of transport and placement in an inundated form works extremely well, although this is not proof that it was used in antiquity. The method of placing the mortar and the aggregate sequentially at Brindisi, however, may not have been correct. It is quite possible that a larger and more experienced Roman building crew would have added measured baskets of mortar and aggregate simultaneously. Nevertheless, distributing the aggregate by random tossing seems to be a satisfactory alternative to raking it.

The quick setting of the concrete above the water line was striking. Within 12 hours of the final placement of mortar and aggregate, the concrete had set sufficiently to allow the construction team to walk on the surface of the *pila* without any shifting or sinking of the aggregate. It is likely, however, that in situations where concrete blocks were exposed to heavy wave action wooden cladding may have been left in place after the concrete set in order to protect it from erosion as it cured. It is possible the wood may never have been removed but simply rotted away or was sucked away by the waves. *Pilae* were utilitarian in purpose, and most or all of their bulk was hidden beneath the sea. The wood may have been viewed as an expendable commodity not worth the effort of recovery for possible reuse after sufficient curing had occurred.

After successfully completing construction of the *pila*, we arranged to core it at intervals of six and twelve months in order to obtain information concerning the rate at which the concrete cured (Fig. 5.23). In consequence, cores were taken on 19 March (BRI.2005.01), 17 November 2005 (BRI.2005.02), 22 November 2006 (BRI.2006.01), 14 May 2008 (BRI.2008.01) and lastly, in November 2009 (not listed in Table 5.2; see pp. 172–180) with the same equipment used on the ancient concrete structures. The results of mechanical and chemical tests are presented in Chapter 7; only the results of visual examination relevant to the mixing and placement of the mortar and aggregate appear here.

*Fig. 5.23. Coring the completed* pila *in March 2005.*

The visual appearance of the cores is remarkably similar to that of the cores collected from ancient Roman structures. Voids appear with slightly greater frequency in the reconstructed concrete than in the ROMACONS ancient core samples, suggesting that the ancient concrete may have been tamped more frequently or more thoroughly, or placed with greater skill. It is interesting to see that no day joints were visible marking the successive additions of mortar at Brindisi, although possible day joints were observed in several of the ancient cores (PCO.2003.04, SLI.2003.01, CAE.2005.01). The absence of wave action around the Brindisi *pila* may explain the difference. This type of mortar clearly settles and self-compacts to a significant extent. On the other hand, there was a markedly lower frequency of small nodules of relict lime clasts in the modern mortar, either because of more thorough mixing, or because the lime had been more uniformly burned and slaked, or because of the much shorter curing period compared to the ancient concrete (see pp. 164–68). The ratio of binder to larger ash particles (D > 5mm) as percent by volume also varies significantly among the cores, and varies from the ratio of those materials placed in the form (63/37, or 1.7:1, mortar to aggregate) (Table 5.2; Appendix

*Table 5.2: Statistics for the Brindisi* Pila *Cores.*

| Core | Hole depth | Core Length | % of Core Recovered | % Mortar | % aggregate | Mortar to Aggregate Ratio |
|---|---|---|---|---|---|---|
| BRI.2005.01 | 1.75 | 1.75 | 100% | 67.0% | 33.0% | 2.0 |
| BRI.2005.02 | 1.65 | 1.65 | 100% | 75.7% | 24.3% | 3.1 |
| BRI.2006.01 | 1.00 | 0.80 | 80% | 77.1% | 22.9% | 3.4 |
| BRI.2008.01 | 1.75 | 1.75 | 100% | 72.2% | 27.8% | 2.6 |
| | | | | | | |
| Average | 1.54 | 1.49 | 95% | 73.0% | 27.0% | 2.8 |
| StD | 0.36 | 0.46 | 10% | 4.5% | 4.5% | 0.6 |
| | | | | | | |
| | | | **Materials** | 63.0% | 37.0% | 1.7 |

3, Table A3). The difference of values can be explained by the relatively unstructured method by which the aggregate was added combined with the small size of the core samples relative to the total volume of the block. It is reassuring that similar variations in the mortar to aggregate ratio appear in cores taken from single blocks of ancient concrete: for example PCO.2003.02 (57%/43%, 1.3:1), compared with PCO.2003.03 (77%/23%, 3.3:1), both taken from *Pila* 2 at Portus Cosanus. In the Antirhodos block at Alexandria, however, the ratios are much closer: ALE.2007.01 (55.5%/44.5%. 1.2:1), compared with ALE.2007.02 (56.6%/43.4%, 1.3:1). Visual examination of the ancient cores also confirms that there is variation in vertical distribution of the aggregate. Overall, one must conclude that the method for adding aggregate to the mortar mix in inundated Roman formwork resulted in a much less uniform result than usually seen in terrestrial structures, and that the Brindisi *pila* reflects the same irregularity.

The *pila* was originally planned with a mix of 65:35 (1.86 mortar to 1.0 aggregate) based on the averages measured from cores extracted from the concrete Claudian and Trajanic moles and quays at Portus, the harbour mole at Anzio (Antium) and at Cosa (Oleson et al 2004a: 215). Samuelli Ferretti calculated similar ratios for Trajan's harbour (1997: 71). For reasons explained above, the materials used actually created a mix of 63:37 (1.7:1 mortar to aggregate). Subsequently, we took a 6 m long core from a *pila* associated with the Villa of the Domitii Ahenobarbi at Santa Liberata (SLI.2004.01) in which the average mortar to aggregate ratio was 55:44 (1.25:1 mortar to aggregate) over its total length but varied considerably within it.

The random pattern of aggregate to mortar found in the Brindisi core appears to be reasonably representative of the distribution found in Roman structures. There are occasional mortar beds up to 0.18 m thick in the Brindisi pila, while the Santa Liberata core (which is 300% longer than BRI.2005.01) shows two mortar beds approximately 0.10 m thick and one approximately 0.20 m thick. The 2.0 m central portion of the core from the Santa Liberata *pila*, however, appears to have a lower proportion of aggregate than the upper and lower sections. Since both these samples are very small compared with the sectional area of their respective *pilae*, we cannot at present determine whether Roman builders added aggregate frequently as the work progressed, or as a separate procedure after the placement of a sufficient measured quantity of mortar.

The results of this unique experiment in Roman construction are manifold. We have shown that the Vitruvian formula for pozzolanic concrete in fact produces the appropriate result, as long as lime paste and wetted *pozzolana* are used, measured by volume, and prepared as a stiff mixture. Questions remain as to whether the lime was added as dry quicklime or wet slaked lime (see pp. 165–67). Furthermore, the hypothetical placement method involving baskets with a tip rope works well and seems as effective as any other method available to the Romans. The procedure for adding coarse aggregate is not certain, but Roman engineers could easily have orchestrated the alternate placement of mortar and aggregate according to the desired proportions. Finally, the resulting concrete sets relatively rapidly below and above water and reaches most of its strength within six to twelve months. One of the significant differences between the cores taken from Roman concrete maritime structures and the core taken from the *pila* at Brindisi is the evidence of the quality of the mix. The Romans took less care in how thoroughly they mixed the lime and *pozzolana* together, as is evident from the extent of unmixed relict lime clasts. The other interesting fact is how successful they were in compacting the mortar and aggregate even at depths in excess of 5 m underwater, achieving better results than those of the relatively shallow Brindisi experiment.

Prior to this experiment we had assumed that the rate of constructing concrete structures underwater was governed by the actual laying of the mortar and aggregate within the formwork. We now realise that placement of the concrete is easier than the laborious task of mixing the mortar in the trough. The difficulty of mixing the stiff mortar by hand raises questions about the logistics of mixing large amounts of mortar for placement in caissons in open water conditions, as at Caesarea Palaestinae. In such situations, could the mortar have been mixed in barges moored over the forms, or would smaller boats have transported to the forms mortar mixed on land? Whatever the procedure, the rate of construction would have been far slower, or far more expensive in labour, than construction on land.

This reconstruction of a *pila,* as far as we know the first large-scale experiment relevant to ancient maritime concrete ever carried out with carefully duplicated Roman materials and construction technology, has answered some of the questions not addressed in the surviving literary sources. Experimental archaeological reconstruction has demonstrated a method that Roman builders might have employed to transform Vitruvius's directives into reality.

# Chapter 6

# Maritime Concrete in the Mediterranean World

### *C. J. Brandon*

## 6.1. Important sites not sampled by ROMACONS

A principal objective of the ROMACONS project was to identify the source, or sources, of the key raw material, pumiceous ash pozzolans from the Bay of Naples, used in maritime or underwater concrete throughout the Roman world. The study was limited to the Mediterranean, as there is no recorded use of Roman marine concrete outside this immediate area, other than in the *piscina* at Quarteira in Portugal (Figs. 3.2, 6.2–3). Another goal was determination of the geographic spread of the technology and identification of any local or regional variations in the design and methodology of forming, mixing, and laying concrete in submerged or semi-submerged situations.

The selection of sites to sample was based on several considerations: the historic importance of the site; the extent and quality of the concrete remains; the geographical location; and that the sites were readily accessible and appropriate permits could be obtained. Initially the focus of our fieldwork was on sites along the coast of Toscana, Lazio, and Campania in Italy, as there were a considerable number of locations that could be readily accessed from CTG Italcementi's bases at Bergamo and Brindisi (Fig. 6.1). Obviously, it was necessary to sample sites elsewhere in the Mediterranean as well, in order to obtain a representative sampling of data.

Because of the importance of Caesarea Palaestinae in the history of Roman maritime harbour engineering, and the involvement of Brandon, Hohlfelder, and Oleson with the study of its harbour over many years, its harbour *Sebastos* was selected as the first objective after the initial Italian campaign. This was followed by Alexandria, because of its historic importance, and then sites in Greece and Turkey as far as permits could be obtained. The lack of potential sites from the western Mediterranean was immediately apparent. There were no surviving Roman harbour sites in Spain that made use of marine concrete, and only one on southern coast of Portugal, at Quarteira. This Roman structure, probably a fish-pond eroded from the coastline, had been broken up by fishermen in the 1930s, but some large fragments were recovered in 1998 and stored in the forecourt of the museum at Loulé (Figs. 6.2–3). Preliminary analysis of the mortar by SEM (Scanning electron microscopy) confirmed the presence of altered, vitrified particles with vacuolar shapes and chemical compositions similar to those of pozzolana from Pozzuoli (E. Gotti, pers. comm. 16 March 2007). The fragmentary nature of the lumps of concrete would have made coring difficult, but we were prepared to make the attempt, given the important location of the concrete outside the Straits of Gibraltar. In the end, however, the authorities responsible for the remains lost interest. The only other potential prospects for the northwest coast of the Mediterranean were Marseille and Fréjus, on the south coast of France (Figs. 6.6–8). The concrete quay excavated between 1992 and 1993 in Marseille was subsequently destroyed during the construction of an underground car park on the site (Hesnard 2004: 175–203; Hesnard *et al*. 1999: 45–49). The large block of concrete exposed during drainage improvements alongside Le Chemin des Horts in the harbour of *Forum Julii* at Fréjus proved to have been made without any addition of pumiceous ash pozzolan to the mortar. The southern quay, however, might provide useful core samples (Gebara and Morhange 2010).

Although several key sites have been destroyed by modern coastal development, there are many Roman harbour sites making use of marine concrete along the southern coast of the Mediterranean, several of them spectacular in scale and well preserved. Accessing them during the fieldwork phase of the ROMACONS project was not feasible, however, as the political situation made it impossible to obtain permits to core. We also felt that logistics and security would be difficult in the region.

The sites that hold great promise include the Algerian sites of Cherchel (Fig. 6.83) – an important Roman naval base with concrete *pilae* at the harbour entrance, similar to Misenum – and Tipasa, where there is a large concrete block, collapsed *pila*, or concrete filled caisson similar to those found in Area K at Caesarea (Fig. 6.82; Yorke and Davidson 1969). Coring of the harbour installations at Lepcis Magna and Sabratha in Libya would also provide important information if the future brings more stability and security. The concrete portion of the 990 m long mole at Thapsus, recorded by Davidson and

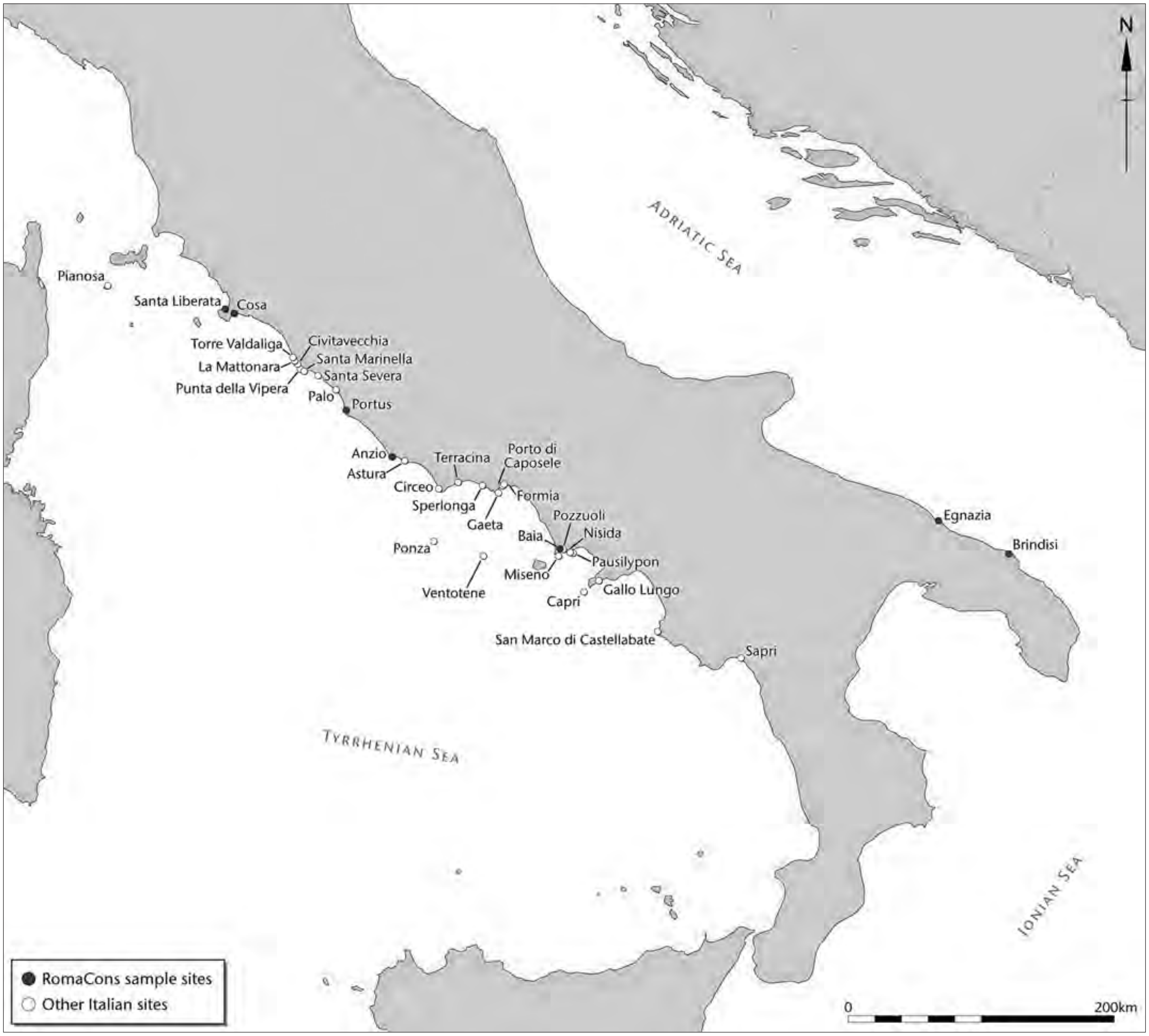


*Fig. 6.1. Map of coring sites in Italy, and sites with marine concrete (Will Foster Illustration).*

Yorke (2014) as more than 130 m long (Fig. 6.76), has now been mostly buried under a massive rubble breakwater of a modern marina, leaving only the rubble built seaward end exposed. The extensive concrete structures of the important harbour of Carthage, which were recorded by Yorke, Davidson and Little in 1973 and 1975, are now partially lost through recent development in the area (Fig. 6.77–78; Yorke and Little 1975; Yorke and Davidson 1976).

While the ROMACONS Project assembled a reasonably representative sample of cores from the eastern Mediterranean, there remains a shortage of samples from the North African coast. Hopefully this shortcoming can be made good at some future date when political stability returns to the region and samples of concrete can be collected from Cherchel, Tipasa, Lepcis Magna and Sabratha. While the ROMACONS project has focused on maritime structures, it would be worthwhile for future researchers to investigate submerged or semi-submerged fresh-water sites as well. This would include coring the concrete on the southern shore of Lake Nemi and from the Roman quays along the River Tiber in Rome and around Ostia. Access to the river embankments in Rome may be difficult, as the excavated sites have now been backfilled.

## 6.2. Catalogue of maritime concrete structures around the Mediterranean and Portugal

The harbours, fish-ponds, and other elements of Roman maritime concrete infrastructure are briefly catalogued here in geographic sequence starting from Portugal, outside the Straits of Gibraltar, proceeding in a clockwise direction around the Mediterranean and ending in Algeria, the most western area on the North coast of Africa in which Roman harbour remains have been reported. Structures that are likely to have been made of marine concrete, such as *piscinae* along the coast of Latium and Campania that have been reported without details concerning materials, but which the ROMACONS team could not verify as made of marine concrete, have not been included. The catalogue, however, does include a few structures that were once thought to have been built of Roman maritime concrete but are now known not to be; the re-evaluation is noted here. Also included are known sites that have disappeared, either from human or natural destruction. Where possible, the approximate location of the concrete structures, in longitude and latitude coordinates, has been added. The entries begin with the modern name of the site, where there is one, with the ancient name (where known) in parentheses. Minimal bibliography is provided, focussed mainly on recent discussions of the designs and materials of the structures involved. Although this catalogue is undoubtedly incomplete, and the annotations are brief, the sheer number of sites recorded and their geographical spread provide striking testimony to the accomplishment of the Roman harbour engineers (Table 6.1). Structures that are physically separate but part of the same complex (such as the harbour facilities at Portus proper) are counted as a single entry. It is remarkable that 65 percent of the sites are in modern Italy, nearly all those on coastline of Toscana, Lazio, and Campania.

*Table 6.1: Number of sites with Roman marine concrete structures, by modern country.*

| Country | Number of sites |
|---|---|
| Portugal | 1 |
| Spain | 1 |
| France | 2 |
| Italy | 62 |
| Greece | 5 |
| Turkey | 8 |
| Lebanon | 1 |
| Israel | 2 |
| Egypt | 1 |
| Libya | 2 |
| Tunisia | 6 |
| Algeria | 2 |
| **Total** | 93 |

### *6.2.1. Portugal*

*Quarteira*. Between 37° 3’41.41” N; 8° 6’20.67” W, and 37° 3’41.67” N; 8° 6’20.62” W, their original location in the sea. Now at 37º 8’22.30’’N; 8º 1’ 25.09’’W, their present location in the Loulé museum

Five large fragments of concrete were recovered from the sea off the city of Quarteira on the southern coast of Portugal between Olhos de Água and Vale de Lobo (Figs. 6.2–3). The site was called Quarteira Submersa. Believed to be the remains of a Roman fish-pond submerged through coastal erosion, several intact walls were dynamited by fishermen in the 1930s. The chunks of concrete, recovered in 1998 and now stored in the forecourt of the Loulé museum, were originally part of one large wall section that broke during transportation. Several sections show the use of amphorae embedded in the walls as nests for the fish. The concrete has been identified by CTG Italcementi

*Fig. 6.2. Location map of Quarteira.*

*Fig. 6.3. Two fragments of concrete wall from the Quarteira* piscina*, now in the Loulé Archaeological Museum. The near fragment is a cross-section showing the use of an embedded amphora body as a nesting pot.*

to contain *pozzolana*. The fish-pond may have been associated with a first-century Roman villa now 2 km from the submerged site. Simplício and Barros 2006.

### *6.2.2. Spain*

*Cadiz* (Gades). 36° 31' 18.31" N; 6° 17' 15.8" W. On the beach near the end of the peninsula of Cadiz are the eroded remains of a line of large blocks of concrete (Fig. 6.4). These have sometimes been identified as Roman, but they are in fact the remains of a modern sea defence wall built to retain the coastline to the southwest of the old city, perhaps in the nineteenth century. Raban 2009: 181.

*Ampurias* (Emporiae). 42° 08' 11.87" N; 3° 07'16.60" E. The Roman concrete and ashlar masonry wall on the beach at Ampurias although frequently referred to as being a harbour breakwater, is in fact part of the city wall (Fig. 6.5). Nieto *et al.* 2005: 71–100.

### *6.2.3. France*

*Marseille* (Massalia). Place Jules-Verne. 43° 17' 47.90" N; 5° 22' 09.92" E. Quay F120. Roman marine concrete, made with pumiceous ash pozzolan, forming a foundation to a quay 1.3 m wide and 3.5 m tall (Fig. 6.6). Excoffon and Dubar (2011: 178) imply that this is from the Vesuvian region. The remains are now buried or destroyed beneath a modern underground car park. Hesnard *et al*. 1999: 45–47; Hesnard 2004: 175–204.).

*Fréjus* (Forum Iulii). Le Chemin des Horts. 43° 25' 52.92" N; 6° 44' 30.17" E. Concrete East Quay alongside Le Chemin des Horts, on the east side of the harbour basin of *Forum Iulii* (Fig. 6.7). A sample taken by Brandon and analysed by Italcementi consisted principally of a lime and sand mortar without pozzolan that set in air with a rubble aggregate. On the basis of more extensive samples Excoffon and Dubar (2011), however, identify pumiceous volcanic ash and tuff from the Vesuvian region. Rivet *et al.* 2000: 293–301; Gébara and Morhange 2010: 36–91.

The South Quay. 43° 25' 46.19" N; 6° 44' 38.61" E. The South Quay is mostly buried under Le Chemin de la Lanterne d'Auguste, but the edge of a large concrete platform is visible to the northeast of the Lanterne d'Auguste (Fig. 6.8). To our knowledge this concrete has not yet been sampled or analysed. Rivet *et al.* 2000: 293–301; Gébara and Morhange 2010: 36–91.

### *6.2.4. Italy*

*Island of Pianosa* (Planasia). *I Bagni di Agrippa*. 42° 35' 34.83" N; 10° 05' 37.95" E. Two circular fish-ponds cut from the bedrock, with added concrete walls (Fig. 6.9). Schmiedt 1972: 38–47; Higginbotham 1997: 72–76.

*Island of Giglio* (Aegilium Insula), *Il Bagno del Saracino*. 42° 21' 23" N; 10° 55' 06.04" E. Rectangular fish-pond cut from the rock, with added concrete walls. Schmiedt 1972: 32–39.

*Santa Liberata* (Domitiana positio) *Bagni di Domiziano*. 42° 26' 11.08" N; 11° 09' 9.54" E. Rectangular fish-pond with four *pilae*, two on the shore to the West and two in the sea (Fig. 6.10). Core samples from the *pilae* were collected by ROMACONS in 2003 and 2004; see pp. 69–73. Schmiedt 1972: 22–26; Higginbotham 1997: 76–80; Lafon 2001: 339; Oleson *et al.* 2004a: 199–229; Gambogi 2008: 255–63.

*Cosa* (Portus Cosanus). 42° 24' 27.05" N; 11° 17' 36.60" E. A row of concrete *pilae* stretches from the shore out to the end of a submerged rubble mole. (Fig. 6.11). Core samples were extracted from Piers 1, 1.5, 2, and 5 by ROMACONS in 2003; see pp. 63–69. Schmiedt 1972: 25–31; McCann *et al.* 1987; Gazda 1987: 74–97; 2008: 265–90; Felici *et al*. 1997a: 11–19; Ciampoltrini and Rendini 2004; Oleson *et al*. 2004: 199–229.

*Cosa* (Portus Cosanus). 42° 24' 35.92" N; 11° 17' 37.01" E. A long lagoon behind the coastal dunes contained numerous walls, piers, and a spring house structure, at least the lower portions of which were made with marine concrete (Figs. 8.29–30). Gazda 2008: 265–90; Oleson 1987: 98–128.

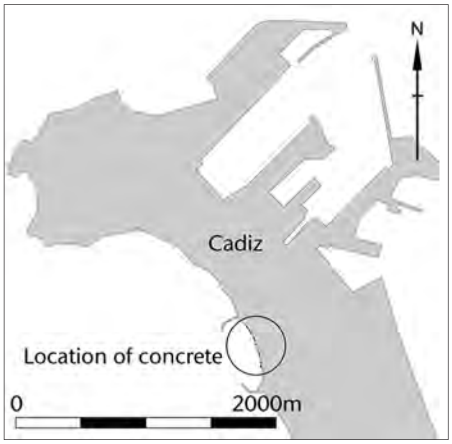


*Fig. 6.4. City area of Cadiz, with location of concrete.*

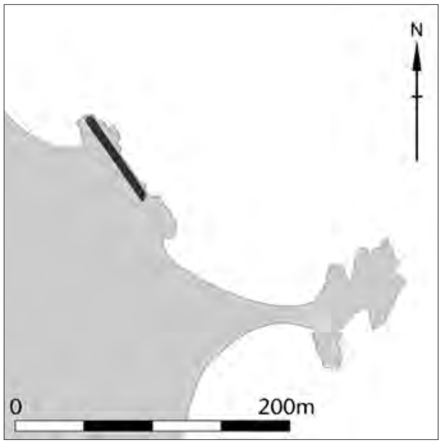


*Fig. 6.5. City area of Ampurias, with location of concrete wall.*

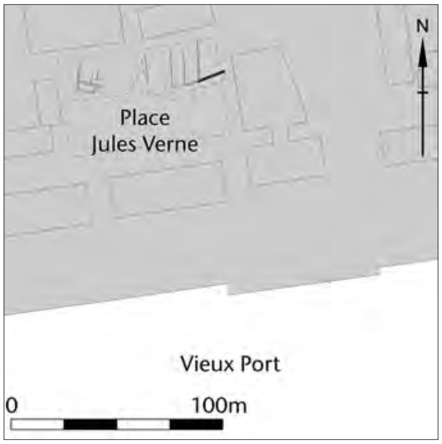


*Fig. 6.6. Marseilles, Place Jules Verne area, with location of concrete wall.*

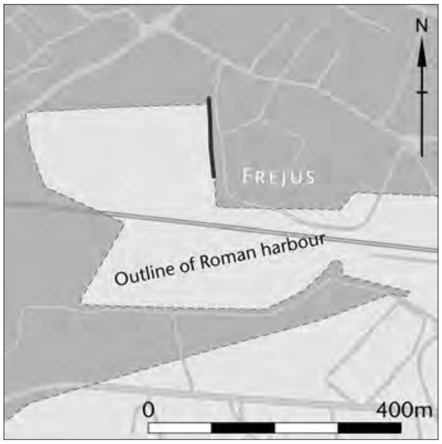


Fig. 6.7. Harbour area of Forum Iulii, with location of East Quay.

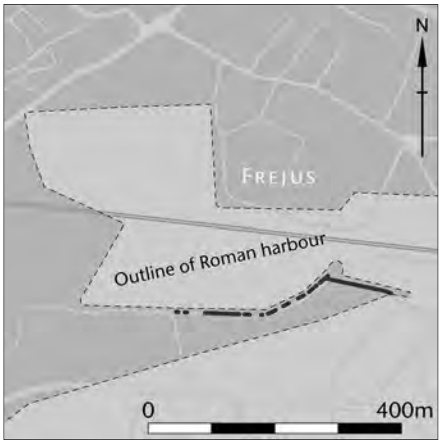


Fig. 6.8. Harbour area of Forum Iulii, with location of South Quay.

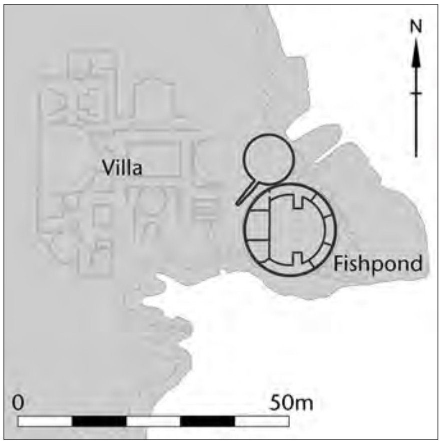


Fig. 6.9. Pianosa, circular fish-ponds.

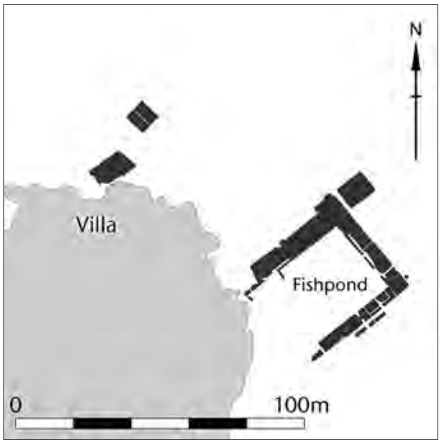


Fig. 6.10. Santa Liberata, fish-pond and pilae.

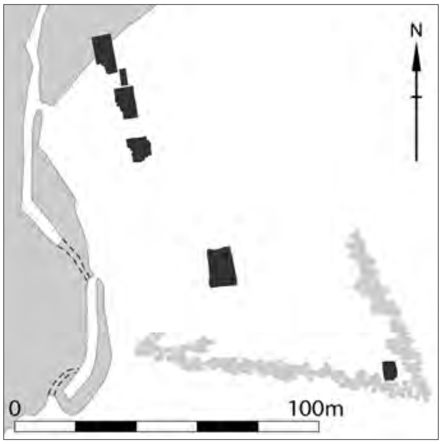


Fig. 6.11. Cosa, harbour with pilae.

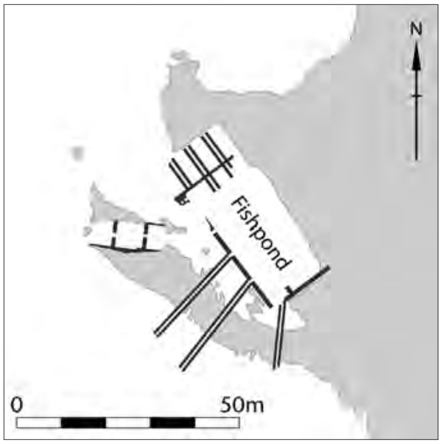


Fig. 6.12. Torre Valdaliga, fish-pond with concrete walls.

*Pian di Spille* (Quintianum). 5.5 km N of the ancient port of Graviscae. A series of circular and rectangular concrete fish-ponds on the shoreline that have been badly damaged by erosion and subsequently by the military. Higginbotham 1997: 87–88; Lafon 2001: 346.

*Martanum*. 3 km N of Graviscae. Two fish-ponds in the sea, one rectangular, the other U-shaped, constructed of marine concrete but badly damaged by erosion. Schmiedt 1972: 93–95; Higginbotham 1997: 88–90.

*Torre Valdaliga*. 42° 07’ 26.20” N; 11° 45’ 30.28” E. Rock-cut fish-pond with concrete walls and partitions (Fig. 6.12). Schmiedt 1972: 64–67; Higginbotham 1997: 90–93; Rustico 1999: 58–66.

*La Mattonara.* 42° 06’ 59.04” N; 11° 46’ 05.80” E. Rock-cut fish-pond with concrete walls and partitions (Fig. 6.13). Schmiedt 1972: 68–79; Higginbotham 1997: 93–96.

*Punta San Paolo*. 1.7 km N of Civitavecchia. Square concrete fish-pond with dividing walls, in the sea off Punta San Paolo. Now built over by modern industrial development. Schmiedt 1972: 61, fig. 63; Higginbotham 1997: 96–97.

*Civitavecchia* (Centum Cellae). 42° 05’ 36.72” N; 11° 47’ 10.29” E. Roman harbour structures now mostly buried under the modern port, although an original section of Roman marine concrete foundations still exists beneath the arched mole at the Lazzaretto (Fig. 6.14). Quilici 2004: 111–18; Felici 2008: 369–76.

*Punta della Vipera*. 42° 02’ 55.34” N; 11° 49’ 10.82” E. Rectangular fish-pond (55 m × 34 m) with thick concrete outer walls that face the sea (Fig. 6.15). The northern wall is 3.12 m thick, the west wall 2 m thick, and the southern side is 2.25 m wide. The inner dividing or partition walls are formed in *opus reticulatum* faced concrete. Schmiedt 1972: 75–87; Higginbotham 1997: 97–101.

*Santa Marinella* (Punicum), *Fosso Guardiole.* 42° 01’ 58” N; 11° 51’ 53” E. Large, rectangular concrete fish-pond with numerous interior compartments. Schmiedt 1972: 88–90.

*Santa Marinella* (Punicum), *Le Grottacce.* 42° 01’ 58.23” N; 11° 51’ 53.77” E. Semicircular concrete fish-pond with a diameter of approximately 55 m (Fig. 6.16). Schmiedt 1972: 89–92; Pellandra 1997: 21–33; Higginbotham 1997: 105–7.

*Santa Severa* (Pyrgi). 42° 00’ 56.64” N; 11° 57’ 21.44” E. A 27 m square concrete fish-pond, or possibly the foundations for a tower, built on the Etruscan rubble breakwater (Fig. 6.17). Schmiedt 1972: 63, fig. 64; McCann and Oleson 1974: 398–402; Oleson 1977: 298–308; Higginbotham 1997: 107; Pellandra 1997: 21–33.

*Torre Flavia*. 1.3 km northwest of the Torre, 4.5 km northwest of Palo. Circular brick or *opus testaceum* faced concrete fish-pond, 22.2 m in diameter, partially buried on the beach. Higginbotham 1997: 107–8.

*Palo* (Alsium). 41° 55’ 58.34” N; 12° 06’ 02.73” E. Large rectangular fish-pond, 110 m × 50 m protected on the three seaward sides by a wide concrete wall (Fig. 6.18). The walls are approximately 4 m thick and stand 2 m above sea level. A second curvilinear pond existed to the north, although it is now no longer visible. Higginbotham 1997: 109–11.

*Rome* (Roma), Portus Tiberinus. 41° 52’ 56.77” N; 12° 28’ 28.52” E. Concrete dock on the left bank of the Tiber River south of Ponte Sublicio, in front of two rows of vaulted warehouses. Covered by a footpath in 2006. Castagnoli 1980: 35–42; Colini 1980: 43–53; Mocchegiani Carpano 1999.

*Ostia* (Ostia), Tiber River Embankment. Concrete river embankment on the Tiber opposite Tor Boacciana. Meiggs 1973: plate VI.d.

*Ostia* (Ostia), Tor Boacciana. 41° 45’ 10.08” N; 12° 16’ 40.17” E. Concrete base to a building, possibly a lighthouse at the mouth of the Tiber in the Roman era, now landlocked.

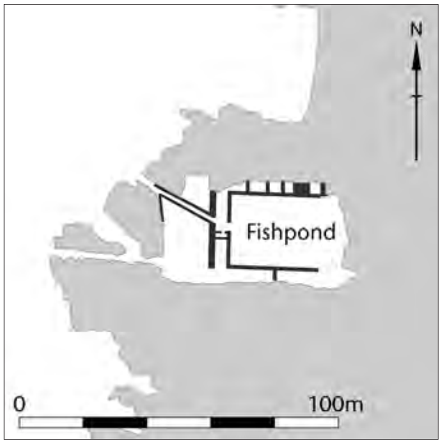


*Fig. 6.13. Torre Mattonara, fish-pond with concrete walls.*

*Fig. 6.14. Civitavecchia, plan of ancient harbour with conjectured position of breakwaters.*

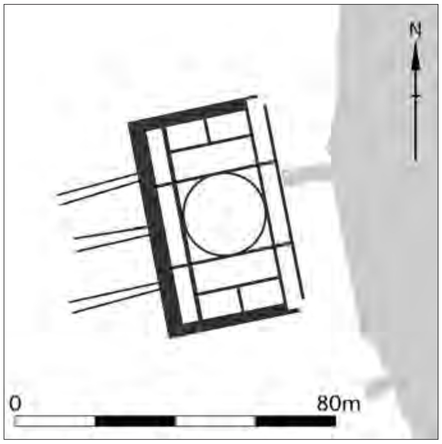


*Fig. 6.15. Punta della Vipera, fish-pond with thick concrete outer walls.*

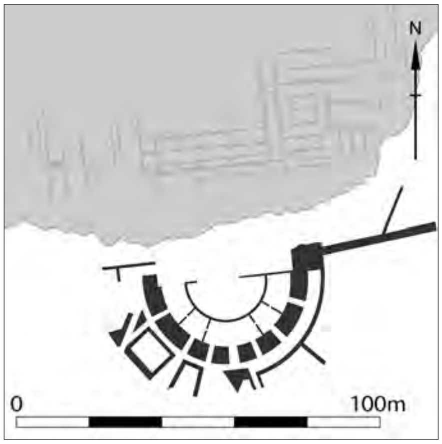


*Fig. 6.16. Santa Marinella, semicircular concrete fish-pond.*

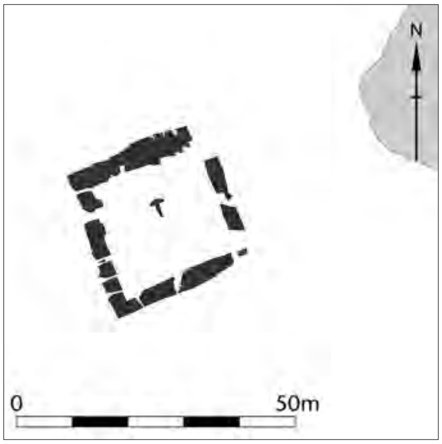


*Fig. 6.17. Santa Severa, concrete fish-pond.*

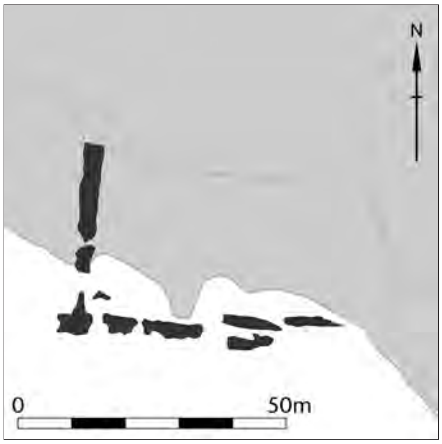


*Fig. 6.18. Palo, concrete fish-pond.*

*Ostia* (Portus), Claudian Harbour. There are several concrete structures in this complex. Testaguzza 1970; Schmiedt 1972: 94–103; Meiggs 1973: 149–71; Felici 1993: 94–98; Oleson *et al.* 2004a: 199–229; Keay *et al.* 2005.

Between 41° 47' 13.92" N; 12° 15' 10.04" E and 41° 47' 02.15" N; 12° 14' 39.48" E. A concrete mole (*Molo Sinistro*), approximately 750 m long, runs in a westerly direction from the Museum of the Roman Ships (Fig. 6.19). Concrete sampled by ROMACONS in 2002; see pp. 55–61.

Between 41° 46' 36.45" N; 12° 15' 11.89" E and 41° 46' 44.18" N; 12° 15' 06.09" E. A 350 m long concrete mole on the western side of the *Darsena* with an alleged site for a leading light (mark) on its northern end (Fig. 6.20). Concrete sampled by ROMACONS in 2002; see pp. 256–57.

Between 41° 46' 39.76" N; 12° 15' 15.84" E and 41° 46' 42.03" N; 12° 15' 21.44" E. A 250 m long concrete mole on the northern side of the canal leading to Trajan's basin (Fig. 6.21).

At 41° 46' 44.73" N; 12° 15' 29.75" E. Sloping concrete embankments and walls to the waterways and basins within the *Darsena* and harbour areas (Fig. 6.22). Concrete sampled by ROMACONS in 2002; see pp. 55–61.

*Lake Nemi* (Nemorensis Lacus) 41° 42' 19.88" N; 12° 42' 00" E. Concrete embankment along the southern shore of Lake Nemi. This is not strictly speaking a marine structure, but both the concrete embankment and the pleasure barges of Caligula were constructed with the same materials and on the same standards as if they were to be positioned in the sea. Ucelli 1952: 119–27; Ghini 1996: 192–93.

*Anzio* (Antium). "Harbour of Nero." West mole: 41° 26' 38.91" N; 12° 37' 20.77" E. East mole: 41° 26' 35.39" N; 12° 37' 53.14" E. The remains of the enclosing concrete moles are visible on the west and east sides of the harbour, projecting from the shoreline for over 110 m on the west and 60 m on the east from beneath the modern harbour breakwater (Fig. 6.23). ROMACONS sampled the concrete on the eastern mole in 2002; see pp. 61–63. Schmiedt 1972: 104–7; Felici 1993: 71–104; Felici *et al*. 1997b: 11–20; Felici 1998: 275–340, 2002: 107–22; Oleson *et al*. 2004: 199–229.

*Nettuno*, *Nettuno A*. 41° 27' 19.93" N; 12° 39' 09.13" E. Rock-cut fish-pond finished in concrete. Located in the sea opposite the Villino del Adolfo Nesi, it covered an area approximately 42 m × 22 m, with an external wall 1.5–2.7 m wide. Now buried under a tourist beach. Gianfrotta 1997: 21–24; Higginbotham 1997: 131–33; Lafon 2001: 364.

*Nettuno B*. 41° 27' 20.99" N; 12° 39' 21.86" E. A rock-cut fish-pond, 32.5 m × 37.5 m, finished with concrete, located on a rock shelf in the sea below the walls of the Castello di San Gallo. Now buried under a tourist beach. Gianfrotta 1997: 21–24; Higginbotham 1997: 133–35; Lafon 2001: 364.

*Nettuno C*. 41° 27' 22.02" N; 12° 39' 38.29" E. A square concrete fish-pond 22 m × 22 m with walls 1 m wide. The pond was protected by a sea-wall 3 m wide and 36 m long which ran east to west 11 m south of the pond. Located at the east end of the city. Now buried under a modern car park and marina. Gianfrotta 1997: 21–24; Higginbotham 1997: 135; Lafon 2001: 364.

*Astura*, La Saracca. 41° 25' 14.98" N; 12° 44' 42.87" E. A semicircular concrete fish-pond constructed on a rock shelf, 2.1 km north-west of the Torre Astura complex (Fig. 6.24). The pond is protected by a concrete wall 3.5 m thick defining a semi-circle 90 m in diameter; there are interior concrete partition walls 0.60 m thick. Two 4 m wide concrete walls, 25 long, form an external channel that projects towards the south. Schmiedt 1972: 114–20; Higginbotham 1997: 135–40; Rustico 1999: 55–61.

*Astura*, La Banca. 41° 25' 02.12" N; 12° 44' 57.60" E. A rectangular concrete fish-pond 33.2 m × 20.3 m on a rock outcrop 1.6 km northwest of Torre Astura (Fig. 6.25). The concrete was cast in stages, side by side to build up the thickness

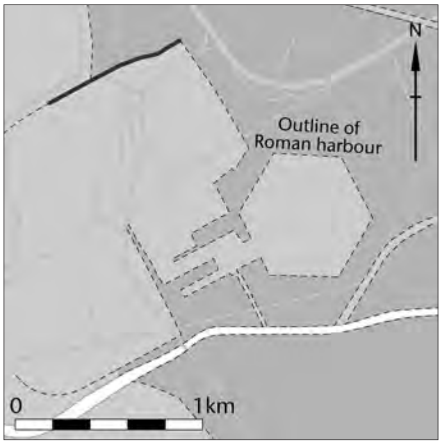


*Fig. 6.19. Portus, location of* Molo Sinistro.

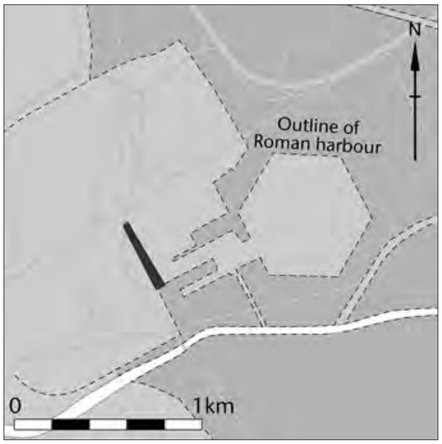


*Fig. 6.20. Portus, long concrete mole on the western side of the* Darsena.

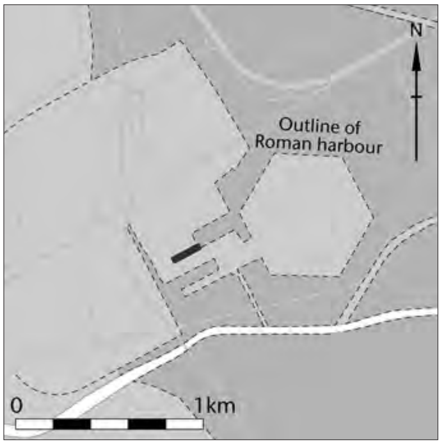


*Fig. 6.21. Portus, concrete mole along northern side of the canal leading to Trajan's Basin.*

of the walls up to 3.44 m thick. Higginbotham 1997: 140–43; Lafon 2001: 364.

*Torre Astura*, Punta di Astura. 41° 24' 30.42" N; 12° 45' 54.50" E. Large fish-pond situated on the southern end of the Punta di Astura. The rectangular fish-pond measured 172 m × 125 m, enclosed by concrete walls 2.4 m thick (Fig. 6.26). On the southern side there is a 42.6 m × 37.5 m rectangular projecting enclosure with concrete walls 2.5 m thick. The larger portion of the fish-pond was left without partition walls. The central area was enclosed by three concrete walls over 1 m thick, the space in-between divided into tanks with thin concrete walls and walkways. Schmiedt 1972: 108–14; Higginbotham 1997: 143–51; Lafon 2001: 364.

*Torre Astura*, Porto di Astura. 41° 24' 21.23" N; 12° 46' 03.29" E. Two long concrete moles enclose a harbour on the east side of Torre Astura (Fig. 6.27). Felici 1993: 89–92; 2006: 59–84.

*Ponza* (Pontia), Porto di Ponza. 40° 53' 43.23" N; 12° 57' 54.23" E. Section of modern harbour mole overlying a Roman mole with *quasi-opus reticulatum* faced concrete (Fig. 6.28). Gianfrotta 2002: 67–90; Pellandra 2002.

*Ventotene* (Pandateria). 40° 47' 48.82" N; 13° 26' 06.21" E. Concrete structures within a rock cut fish-pond (Fig. 6.29). Zarattini *et al.* 2010.

*Circeo* (Circei), Lake Paola Canal. 41° 14' 49.93" N; 13° 02' 04.47" E. Large concrete mass at the end of one of a pair of concrete jetties marking the entrance to the canal (*emissarium*) leading into Lake Paola at Circeo (Fig. 6.30). Schmiedt 1972: 120–22; Felici 1993: 93, pl. II.

"*Piscina di Lucullo*." 41° 15' 00.77" N; 13° 02' 31.23" E. Circular concrete fish-pond 32.5 m in diameter, divided into four quadrants by concrete radial walls 0.60 to 0.80 m wide,

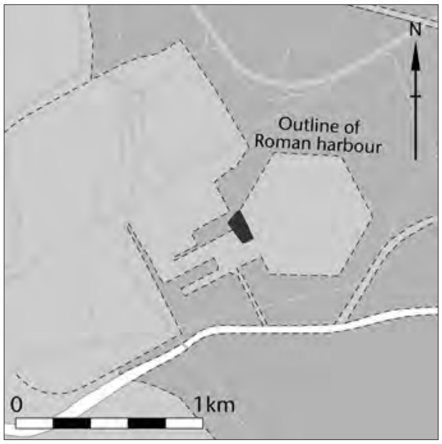


*Fig. 6.22. Portus, concrete embankment near the "Severan Warehouses."*

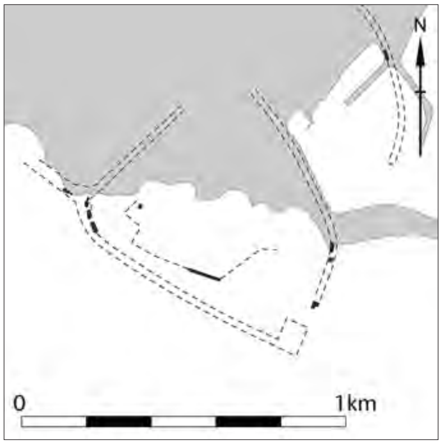


*Fig. 6.23. Anzio, plan of harbour.*

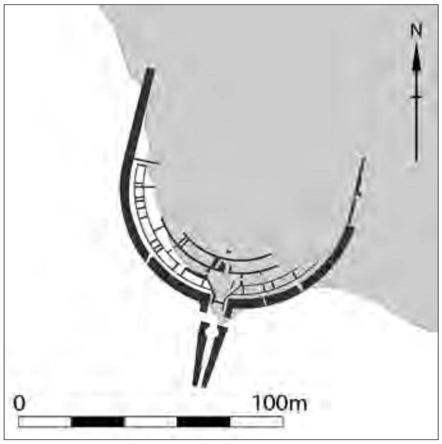


*Fig. 6.24. Astura, La Saracca, semicircular concrete fish-pond.*

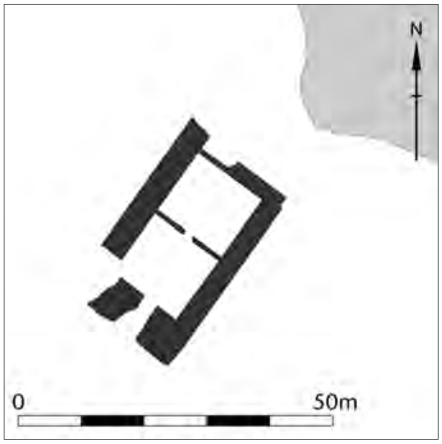


*Fig. 6.25. Astura, La Banca, rectangular concrete fish-pond.*

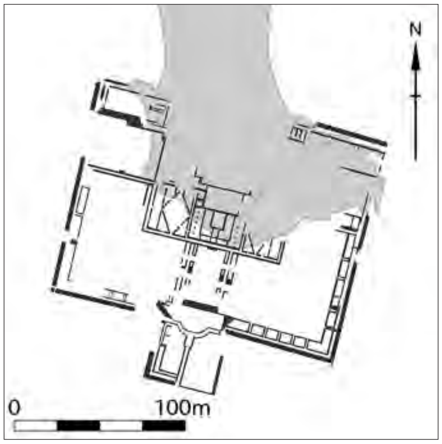


*Fig. 6.26. Torre Astura, Punta di Astura, rectangular concrete fish-pond.*

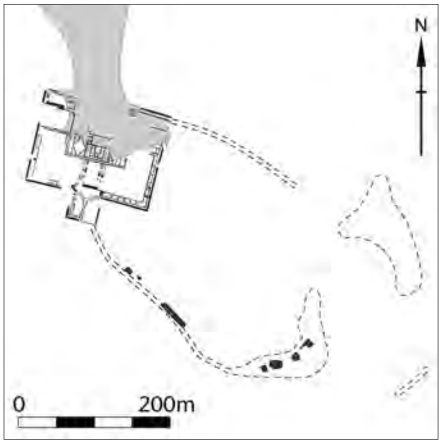


*Fig. 6.27. Torre Astura, Porto di Astura, two long concrete moles enclosing a harbour on the east side of Torre Astura.*

with two small additional tanks on the northern side of the main pond (Fig. 6.31). The pond is linked to the channel that connects the Lago di Paola to the sea by means of a canal. Schmiedt 1972: 123–33; Higginbotham 1997: 152–57; Lafon 2001: 368.

*Terracina* (Tarracina). 41° 16' 56.84" N; 13° 15' 14.47" E. Circular concrete mole that formed the outer edge of the Roman port of Terracina, now completely buried or destroyed by the modern sea defences and coastal road (Fig. 6.32). Blake 1973: 292–93; Felici 1998: 275–76.

*Sperlonga* (Speluncae), Grotto of Tiberius (*Grotta di Tiberio, Villa Tiberii*). 41° 15' 00.95" N; 13° 26' 59.68" E. Concrete and rock cut circular and rectangular fish-pond built in front of a natural grotto and linked to the sea by a canal (Fig. 6.33). Higginbotham 1997: 159–63; Lafon 2001: 380.

*Gaeta* (Caieta), *La Catena*, *La Nave,* or *Villa di Fontania*. 41° 12' 30.45" N; 13° 33' 11.31" E. A row of five concrete *pilae* protecting a fish-pond, in alignment with a concrete structure on the shoreline (Fig. 6.34). Schmiedt 1972: 134–35; Ciccone 1996: 16–18; Lafon 2001: 380, fig. 113; Felici 2008: 369–76.

*Porto di Caposele*. 41° 15' 02.95" N; 13° 35' 53.17" E. Concrete foundation for a quay, on the western side of the small harbour (Fig. 6.35). Nicholas Wood, pers. comm. 2002; Coarelli 1982. There is also a fish-pond; Ciccone 1996: 18–19.

*Formia* (Formiae). 41° 15' 19.72" N; 13° 36' 31.26" E. A rectangular concrete fish-pond, 59.4 m × 29.7 m, partially obscured by the modern roadway and quayside above, in the sea opposite the Giardino Publico (Fig. 6.36). The depth of the pond has been estimated at 3 m, and it is surrounded by enclosing concrete walls 2.5 m thick on the south and west sides, and 2.9 m on the east. Internal partition walls range from 1 m to 0.60 m thick. Three adjacent ponds that were visible a century ago are now buried or destroyed. Schmiedt 1972: 137–41; Ciccone 1996 19–21; Higginbotham 1997: 163–67.

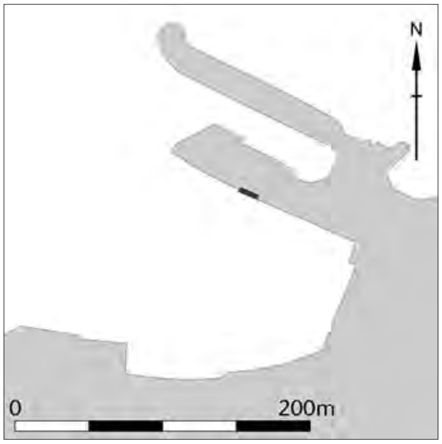


*Fig. 6.28. Ponza, Porto di Ponza, modern harbour mole overlying a Roman concrete mole.*

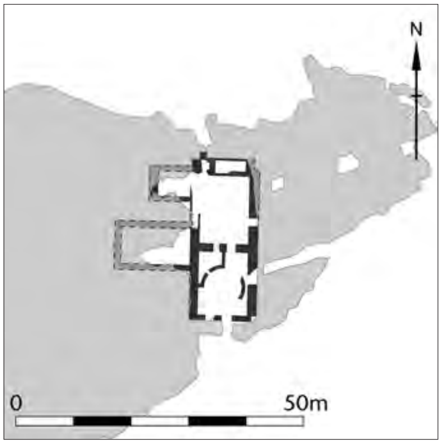


*Fig. 6.29. Ventotene, concrete structures within a rock cut fish-pond.*

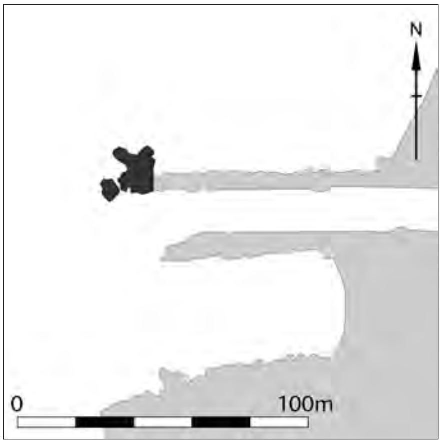


*Fig. 6.30. Circeo, Lake Paola Canal, large concrete mass on one of a pair of concrete jetties at entrance to the canal.*

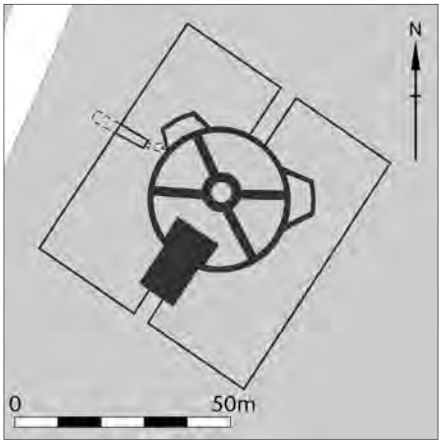


*Fig. 6.31. Piscina di Lucullo, circular concrete fish-pond.*

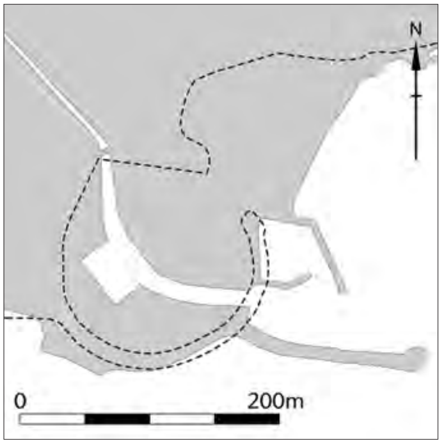


*Fig. 6.32. Terracina, concrete mole forming outer edge of Roman port.*

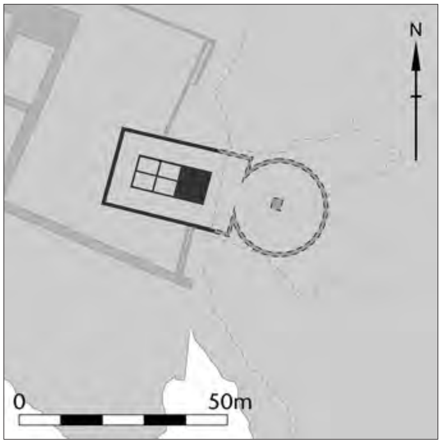


*Fig. 6.33. Sperlonga, Grotta di Tiberio, concrete and rock cut fish-pond.*

*Porto di Giánola*. 41° 14’ 52.01” N; 13° 40’ 29.30” E. Concrete moles forming the outer edge of the small harbour of Giánola, overlaid with ashlar walling. Schmiedt 1972: 142–43; Cassieri 1995; Ciccone 1996: 21–22; Lafon 2001: 385.

*Miseno* (Misenum), Punta Sarparella. 40° 47’24.88” N;14°04’58.42” E. A straight concrete jetty, approximately 60 m long by 5 m wide, with mooring blocks within the harbour (Fig. 6.37). Scognamiglio 2006: 65–77.

*Miseno* (Misenum), Punta Terone. 40° 47’15.62” N;14°05’20.69” E. A row of eight concrete *pilae* in a line outside the modern breakwater on the southern side of the harbour entrance (Fig. 6.38). Partly below the modern breakwater is a concrete mole with a semi-circular head, with the remains of mooring stones and steps: 40° 47’17.99” N; 14°05’21.60” E. Günther 1903b: 274; Caputo 1996: 237–41; Gianfrotta 1996: 70–74; Scognamiglio 2006: 65–77; Felici 2008: 369–76; Benini *et al*. 2010: 109–17.

*Miseno* (Misenum), Punta di Pennata. There are several structures in this complex.

*Pilae*. 40° 47’ 23.93” N; 14° 05’ 22.12” E. Concrete *pilae* on the south-eastern end of Punta di Pennata, at the eastern end of the submerged quay, opposite the Punta Terone mole (Fig. 6.39). Gianfrotta 1996: 71, fig. 10; 1999: 84–86; Scognamiglio 2006: 65–77; Felici 2008: 369–76; Benini *et al*. 2010: 109–17.

Quay. 40° 47’ 26.34” N; 14° 05’ 22.45” E. A concrete quay runs on the northern side of the harbour alongside Punta Pennata (Fig. 6.40). Scognamiglio 2006: 65–77; Benini 2008: 89–94; Benini *et al*. 2010: 109–117.

*Pilae*. 40° 47’ 29.15” N; 14° 05’ 06.87” E. A line of *pilae* extends north-south on the western end of the Punta di Pennata quay (Fig. 6.41). Benini *et al*. 2010: 109–17.

*Baia* (Baiae), Castello di Baia. 40° 48’ 32.86” N; 14° 04’ 59.26” E. and 40° 48’ 38.04” N; 14° 04’ 59.69” E. 14 concrete *pilae*

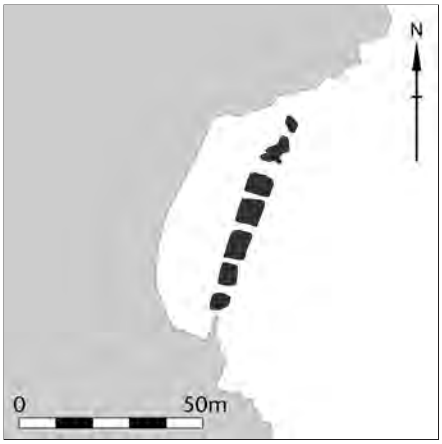


*Fig. 6.34. Gaeta, La Catena or La Nave, row of five concrete* pilae*.*

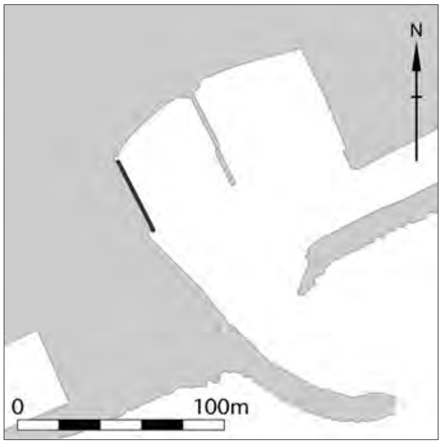


*Fig. 6.35. Porto di Caposele, concrete foundation for a quay.*

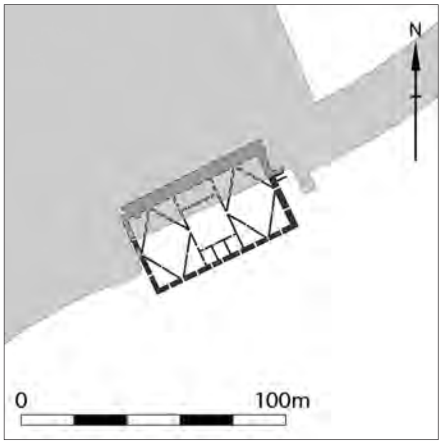


*Fig. 6.36. Formia, rectangular concrete fish-pond.*

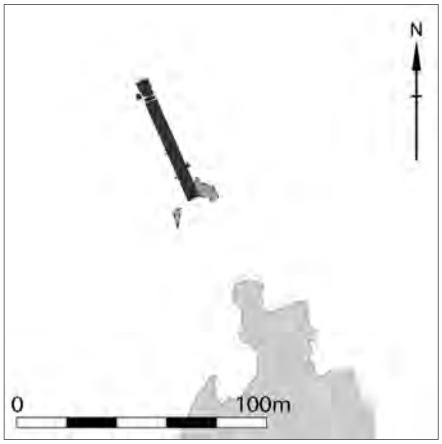


*Fig. 6.37. Miseno, Punta Sarparella, concrete jetty.*

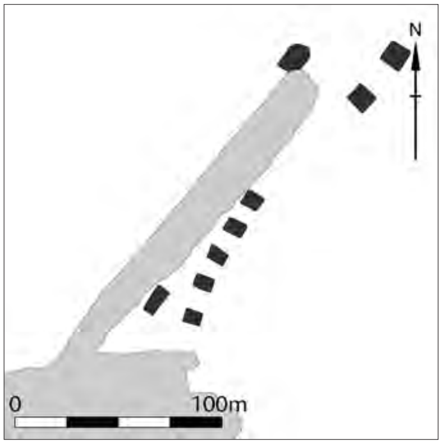


*Fig. 6.38. Miseno, Punta Terone, row of eight concrete* pilae*.*

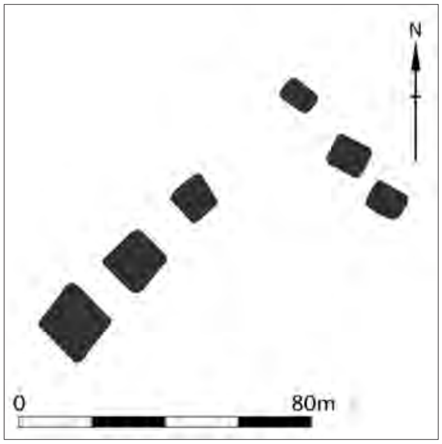


*Fig. 6.39. Miseno, Punta di Pennata, concrete* pilae*.*

offshore below the Castello di Baia, arranged in two clusters (Fig. 6.42). Fraia 1993: 21–48; Scognamiglio 1997: 35–45; Felici 2008: 369–76.

*Baia* (Baiae), Cantieri di Baia. 40° 48’ 56.12” N; 14° 04’ 38.62” E. 3 concrete *pilae* offshore from the Cantieri di Baia (Fig. 6.43). Fraia 1993: 21–48; Felici 2008: 369–76.

*Baia* (Baiae), Entrance channel to Baianus Lacus. 40° 49’ 06.59” N; 14° 04’ 36.01” E. Two concrete moles define the entrance channel (Fig. 6.44); the northern mole is 209 m long, the southern mole 232 m long. The moles are approximately 9.5 m across and define a channel 32 m wide. Concrete from the southern mole was core sampled by ROMACONS in 2006; see pp. 81–85. Scognamiglio 2002: 47–55, 2009b; Brandon *et al.* 2008: 374–92.

*Baia* (Baiae), Villa dei Pisoni. 40° 49’ 10.93” N; 14° 04’ 48.12” E. A row of concrete *pilae* originally protected the Villa dei Pisoni (Fig. 6.45). Fraia 1993: 21–48; Scognamiglio 1997: 35–45; Felici 2008: 369–76.

*Baia* (Baiae), Secca Fumosa. 40° 49’ 21.67” N; 14° 05’ 17.17” E. A cluster of approximately 30 large concrete *pilae* offshore from Lago Lucrino (Fig. 6.46). ROMACONS sampled the concrete from one of the *pilae* in 2006; see pp. 81–85. Scognamiglio 2002: 47–55; Felici 2008: 369–76; Brandon *et al.* 2008: 374–92.

*Baia* (Baiae), Entrance to Portus Iulius. 40° 49’ 33.72” N; 14°05’ 41.76” E. A row of large concrete *pilae* at the end of the western mole, and a single *pila* on the eastern mole, defining the entrance channel to *Portus Iulius* (Fig. 6.47). ROMACONS sampled the concrete from one of the *pilae* in 2006; see pp. 81–85.

40° 49’ 38.10” N; 14° 05’ 37.35” E. Two 220 m long concrete moles between 20 and 30 m across with a channel width of

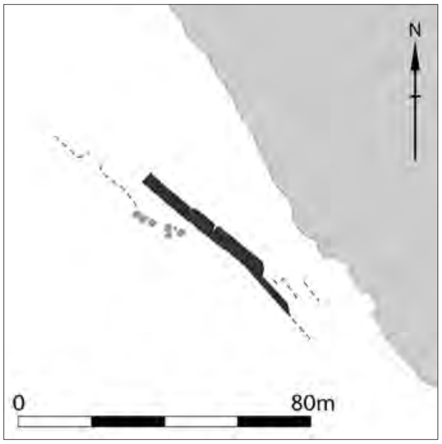


*Fig. 6.40. Miseno, Punta di Pennata, concrete quay.*

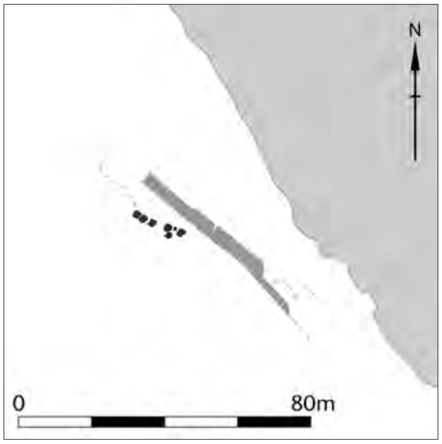


*Fig. 6.41. Miseno, Punta di Pennata, concrete* pilae.

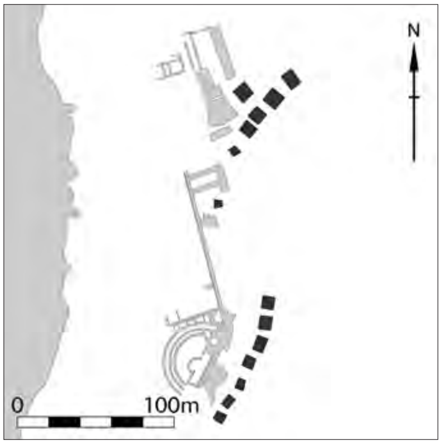


*Fig. 6.42. Baia, Castello di Baia, 14 concrete* pilae *offshore.*

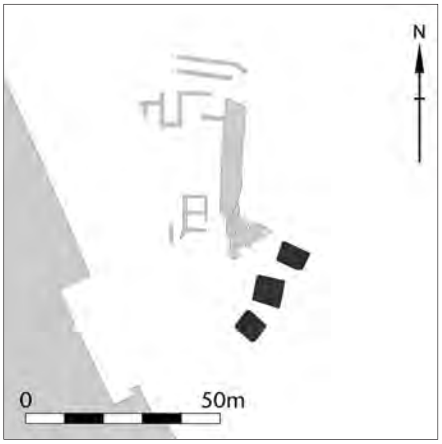


*Fig. 6.43. Baia, Cantieri di Baia, 3 concrete* pilae *offshore.*

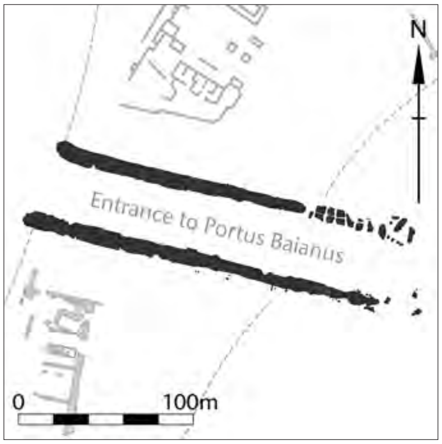


*Fig. 6.44. Baia, two concrete moles forming entrance channel to Baianus Lacus.*

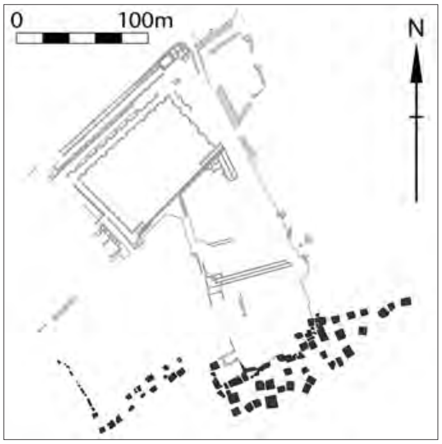


*Fig. 6.45. Baia, Villa dei Pisoni, cluster of concrete* pilae.

40 m (Fig. 6.48). ROMACONS sampled the concrete from both moles in 2006; see pp. 81–85.

40° 49’ 38.57” N; 14° 05’ 40.54” E. A row of five concrete *pilae* on the east side of the eastern mole defining the original shoreline (Fig. 6.49). Günther 1903b: 274–75; Scognamiglio 2002: 47–55, 2009a; Felici 2008: 369–76; Brandon *et al.* 2008: 374–92.

*Pozzuoli* (Puteoli), main harbour. 40° 49’ 17.74” N; 14° 06’ 55.45” E. Thirteen concrete *pilae*, originally fifteen or more, that formed the foundations for the row of arches of a 372 m long pier (Figs. 6.50, 2.2), now destroyed or buried under the modern pier in the harbour of Pozzuoli. Günther 1903b: 270–72; Dubois 1907: 249–68; Gianfrotta 1996: 65–76; Felici 2008: 369–76.

*Pozzuoli* (Puteoli), *pilae.* Between 40° 49’ 14.37” N; 14° 07’ 04.86” E and 40° 49’ 08.80” N; 14° 07’ 08.44” E and 40° 49’ 13.67” N; 14° 07’ 31.62” E. Concrete *pilae* along the coastline, to the south of the headland of Pozzuoli (Porta di Città) (Fig. 6.51). Dubois 1907: 249–68; Gianfrotta 1996: 65–76; Higginbotham 1997: 189–91; Felici 2008: 369–76.

*Nisida* (Nesis). 40° 47’ 46.13” N; 14° 10’ 08.14” E. Four concrete *pilae* are visible in a line projecting from the end of a modern rubble breakwater on the east side of the island (Fig. 6.52); originally there were seven but three of them are now buried. The outer *pila* is particularly large, being 9.50 m tall with sides of 7.70, 9.02, 14.20, and 15.20 m. Two other lines of *pilae,* a double row now buried under the modern causeway linking Nisida to the Lazzaretto and the mainland, and a double row to the north are buried under the modern harbour mole. Günther 1903b: 276; Gianfrotta 1996: 68–71; Felici 2008: 369–76.

*Pausilypon* (Pausilypon), *Gaiola* (Palaepolis). 40° 47’ 26.96” N; 14° 11’ 10.79” E. A long concrete wall connected to a mass of concrete and *pila* offshore from the western end of the

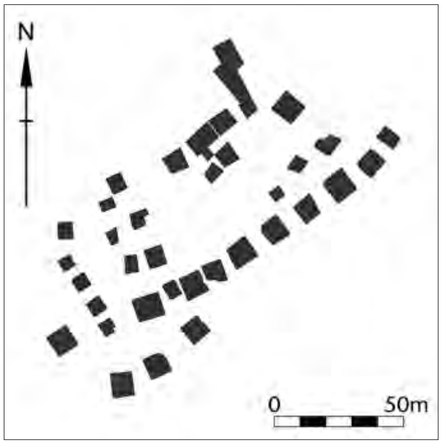


*Fig. 6.46. Baia, Secca Fumosa, 30 concrete* pilae *offshore.*

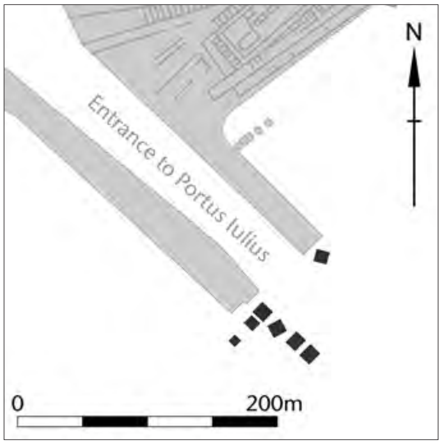


*Fig. 6.47. Baia, row of concrete* pilae *at entrance to Portus Iulius.*

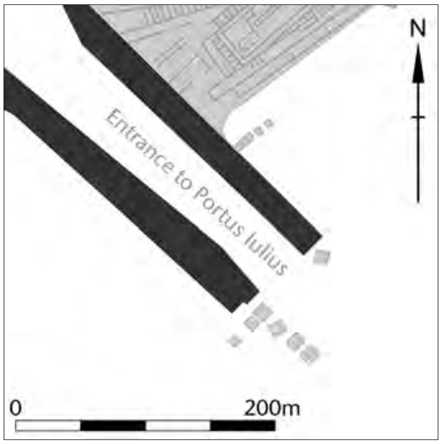


*Fig. 6.48. Baia, two concrete moles forming entrance to Portus Iulius.*

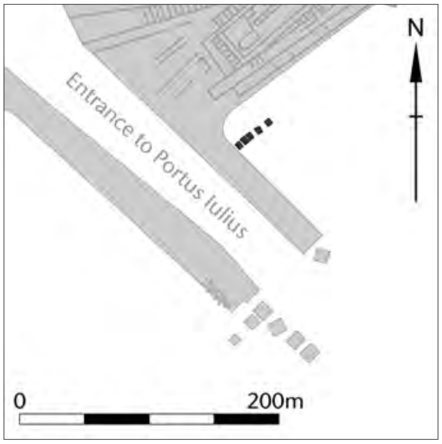


*Fig. 6.49. Baia, Portus Iulius, five concrete* pilae *on the east side of the eastern mole.*

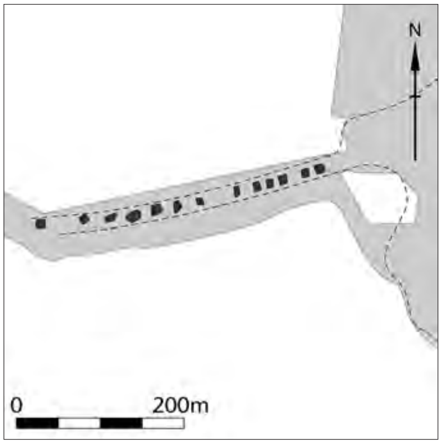


*Fig. 6.50. Pozzuoli, 13 concrete* pilae *forming foundation for main harbour breakwater.*

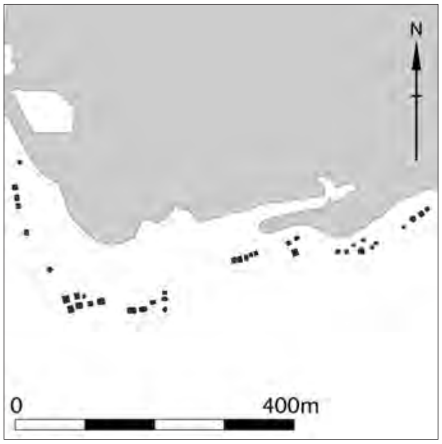


*Fig. 6.51. Pozzuoli, concrete* pilae *along the coastline, to the south of the headland of Pozzuoli.*

peninsula (Fig. 6.53, left side). Günther 1903a: 529 and plan 5; Günther 1913: 163–70; Felici 2008: 369–76.

*Pausilypon* (Pausilypon), harbour. 40° 47' 33.93" N; 14° 11' 22.82" E. A small harbour protected by a row of concrete *pilae* (Fig. 6.53, right side). Günther 1903a: 519–21 and plan 5; Günther 1913: 163–70; Felici 2008: 369–76.

*Pausilypon* (Pausilypon), Marechiano harbour. 40° 47' 41.60" N; 14° 11' 36.04" E. A small harbour protected by a concrete mole 5 m wide (Fig. 6.54, right side). Günther 1903a: 512–13 and plan 4; Günther 1913: 163–70; Felici 2008: 369–76.

*Pausilypon* (Pausilypon), Regio Marechiano. 40° 47' 36.21" N; 14° 11' 30.11" E. A line of three 5 m square rectangular *pilae* and a fourth irregular shaped pier on a reef offshore (Fig. 6.54, left side). Günther 1903a: 521 and plan 6; Günther 1913: 163–70; Felici 2008: 369–76.

*Pausilypon* (Pausilypon), Regio Rosebery. 40° 47' 52.85" N; 14° 12' 19.48" E. Four *pilae* each approximately 7 m square (Fig. 6.55). Günther 1903a: 502–9 and plan 1; Günther 1913: 163–70; Felici 2008: 369–76.

*Naples* (Neapolis). 40° 50' 49.29" N; 14° 15' 57.11" E. C. Morhange (pers. comm. 2012) reports having seen a concrete structure with wooden formwork in the excavations at the ancient harbour. One of the Roman ships found in the harbour contained the remains of a cargo of lime (Giampaola 2005, 2010: 127).

*Sorrento* (Surrentum), *Villa del Capo di Sorrento*. 40° 38' 02.38" N; 14° 21' 03.94" E. Concrete quay. D'Arms 1970: fig. 12.

*Capri* (Capreae), Palazzo a Mare East, "Bagni di Tiberio." 40° 33' 27.75" N; 14° 14' 11.33" E. Concrete *pilae* (Fig. 6.56). Scognamiglio 2010: 117–28.

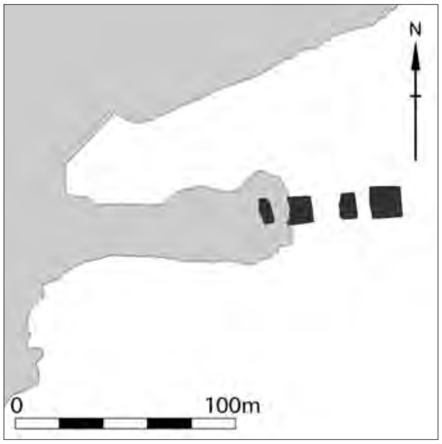


*Fig. 6.52. Nisida, four concrete* pilae.

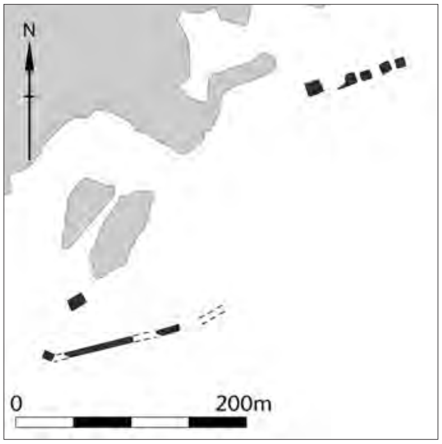


*Fig. 6.53. Pausilypon. Left side: Gaiola (Palaepolis), concrete wall, mass, and* pila. *Right side: small harbour protected by a row of concrete* pilae.

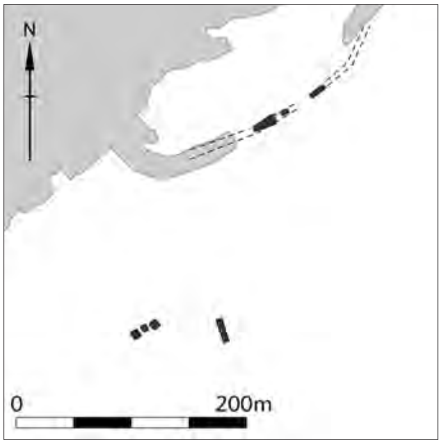


*Fig. 6.54. Pausilypon. Right side: Marechiano harbour with concrete mole. Left side: Regio Marechiano, three concrete* pilae *and irregular pier.*

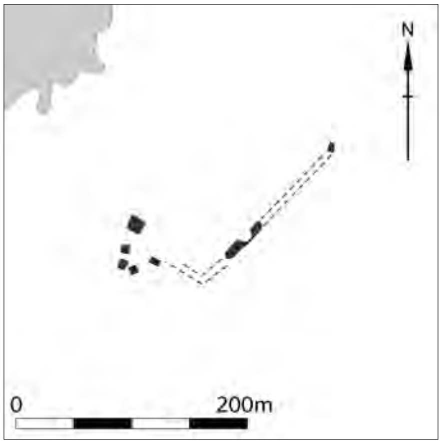


*Fig. 6.55. Pausilypon, Regio Rosebery, row of concrete* pilae.

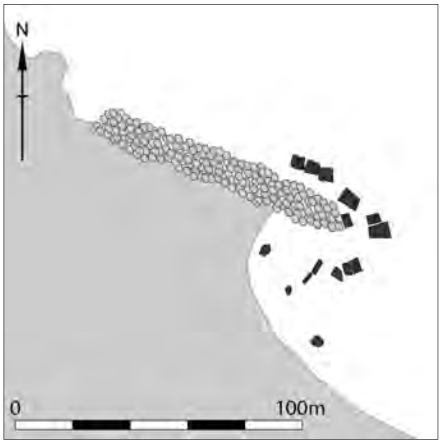


*Fig. 6.56. Capri, Palazzo a Mare East, concrete* pilae *and landing stages.*

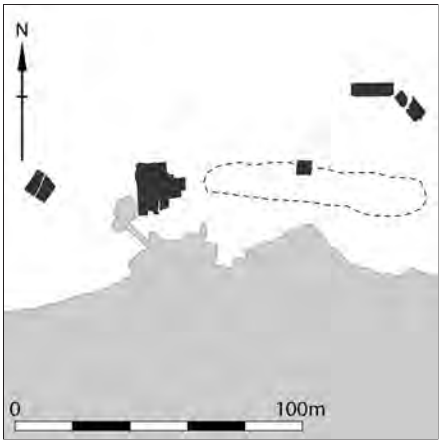


*Fig. 6.57. Capri, Palazzo a Mare West, concrete* pilae *and landing stages.*

*Capri* (Capreae), Palazzo a Mare West. 40° 33' 34.60" N; 14° 13' 43.60" E. Concrete *pilae* and landing stages (Fig. 6.57). Scognamiglio 2010: 117–28.

*Capri* (Capreae), Tragara near Scoglio del Monacone. 40° 32' 35.20" N; 14° 15' 22.32" E. Concrete *pila* with quasi-reticulate facing. Gianfrotta 1999: 86.

*Capri* (Capreae), Marina Piccola, near Scoglio delle Sirene. 40° 32' 40.34" N; 14° 14' 05.54" E. Rectangular concrete structure made in several stages with formwork, with *opus reticulatum* facing. Gianfrotta 1999: 86.

*Island of Gallo Lungo* (Sirenes). 40° 34' 57.40" N; 14° 26' 01.14" E. A row of concrete *pilae* of unknown function on the southern side of the Isle of Gallo Lungo, 3 km off the Amalfi coast, southwest of Positano (Fig. 6.58). Lafon 2001: 429, fig. 164.

*San Marco di Castellabate*. 40° 16' 04.56" N; 14° 55' 58.44" E. Concrete mole, more than 80 m long and approximately 4.5 m wide (Fig. 6.59). Gianfrotta 1999: 87; Benini 2002: 39–46.

*Sapri* (Skidros). 40° 04' 19.73" N; 15° 37' 20.17" E. Concrete arched pier, approximately 60 m long by 8 m wide (Fig. 6.60). Scognamiglio 2008: 139–49.

*Otranto* (Hydruntum). 40° 08' 55.08" N; 18° 29' 46.05" E. Medieval concrete mole under and outside the modern mole. Crupi 2008: 91–137; A. Cossa, pers. comm. 2012.

*Lecce*, San Cataldo, "Porto Adriano." 40° 23' 22.13" N; 18° 18' 25.45" E. Concrete core of a mole originally clad in ashlar (Fig. 6.61). Felici 2001a: 168; Auriemma 2004: 155–56, figs. 113–14.

*Egnazia* (Egnatia). 40° 53' 25.62" N; 17° 23' 33.41" E and 40° 53' 23.96" N; 17° 23' 33.94" E. Remains of two concrete moles project from rock headlands that once formed the small harbour of ancient Egnatia (Figs. 6.62, 4.40–42) . The northern mole extends for a length of 105 m although it is only easily visible at the end where two concrete *pilae* are sited. The southern, 70 m long mole is more in evidence, with a 25 m long stretch of concrete. In 2008 ROMACONS core sampled

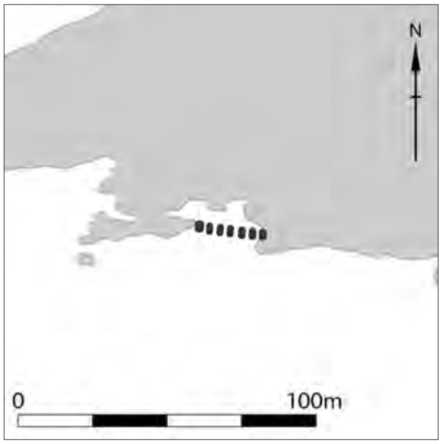


*Fig. 6.58. Island of Gallo Lungo, row of concrete* pilae.

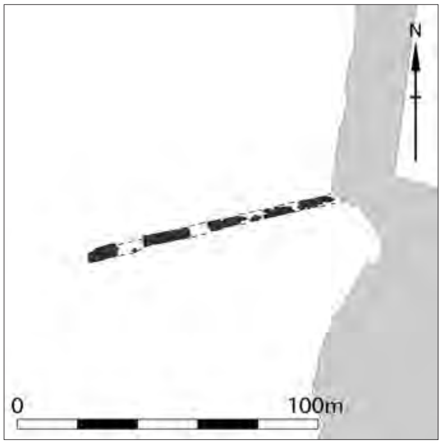


*Fig. 6.59. San Marco di Castellabate, concrete mole.*

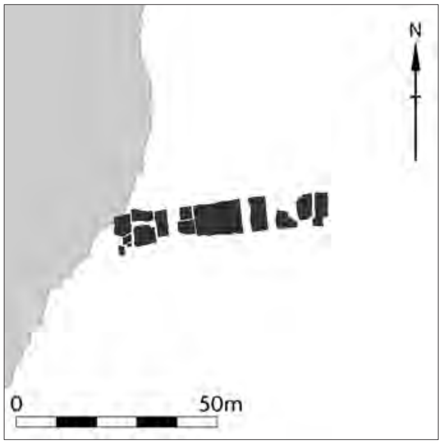


*Fig. 6.60. Sapri, concrete arched pier.*

*Fig. 6.61. Lecce, San Cataldo, "Porto Adriano," Hadrianic mole (D. Klapecki).*

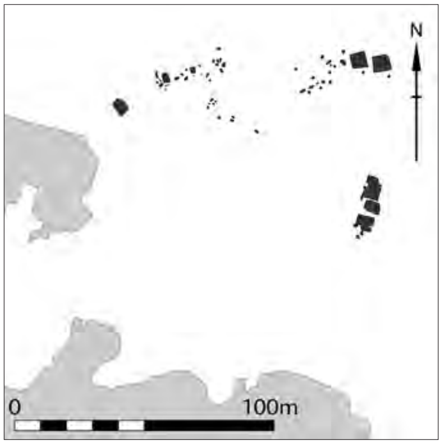


*Fig. 6.62. Egnazia, two concrete moles and several* pilae.

the concrete from the larger *pila* on the northern mole; see pp. 93–94. Gianfrotta 1999: 88; Auriemma 2003: 77–97.

*Adria* (Hatria, Adria), Torre del Cerrano. Several *pilae* formerly part of a harbour complex. Gianfrotta 1999: 89.

*Aquileia* (Aquileia). An ashlar-faced concrete embankment survives along the river harbour (Porto Fluviale) adjacent to the city centre (Marchiori 1989; Bertacchi 2003: 35–36). Although apparently not discussed in the literature about the site, traces of the concrete are visible here and there along the embankment where blocks have come out (J. P. Oleson, pers. comm. 2009). The date is also poorly documented, but the structure most likely was built in the third or fourth century.

### *6.2.5. Greece*

*Mavra Litharia* (Aigeira). 38° 08' 33.32" N; 22° 22' 51.93" E. (Fig. 3.2). Harbour breakwaters originally thought to be constructed in concrete. Extreme tectonic activity has uplifted and fractured the harbour moles by as much as 4 m. ROMACONS surveyed the harbour in 2007 but found no evidence of any mortar between the stone rubble. Features that have been wrongly interpreted as harbour structures in marine concrete in fact consist of round cobbles bonded together with a natural calcarenite grainstone (beachrock) concretion (Fig. 6.63). Papageorgiou *et al.* 1993; Stiros 201.

*Lechion* (Lechaion). 37° 55' 59.59" N; 22° 53' 29.29" E. (Fig. 3.2). The western port of Corinth. Ashlar faced concrete lining the channel leading from the sea into the inner cothon harbour basin. Shaw 1969; Stiros *et al.* 1996; A. Papafotiou, pers. comm. 1999.

*Anthedon* (Anthedon). 38° 30' 03" N; 23° 26' 45" E. Rubble behind clamped ashlar marginal walls (Figs. 3.2, 6.64–65). ROMACONS surveyed the harbour in 2007 and found no convincing evidence of any man-made marine mortar bonding the stone cobbles together. The mortar appears to be a natural calcarenite grainstone ("beachrock") concretion. Schläger *et al*. 1968: 21–98.

*Khersónisos*, Limani Khersonesou (Chersonesos), Crete. 35° 19' 12.53" N; 25° 23' 35.59" E. Two concrete moles at right angles to each other enclosed the small harbour at Chersonesos (Figs. 3.2, 4.38–39, 6.66). The northern mole now lies under

*Fig. 6.63. Mavra Litharia, natural beachrock formation with raised concrete wall in background.*

the modern breakwater, although the original Roman concrete can be seen underwater along the inner, western face. The southern mole is preserved in two parts for a length of 22.7 m. In 3.3 m of water near its termination it rises to just below sea level. Concrete quays extend along the shoreline on the west of the harbour. ROMACONS sampled the mortar in 2001 and 2007; see pp. 89–93. Brandon *et al. 20*05: 25–29.

*Ierapetra* (Hierapytna), Crete. 35° 00' 22.69 N; 25° 44' 24.45" E. (Fig. 3.2). Two projecting moles framed an outer basin, from which a channel led to an inner basin within the city walls. According to Lehman-Hartleben (1923: 202) the moles rested in part on reefs and in part on concrete made with "Puzzolanmörtel."

### 6.2.6. Turkey

*Istanbul* (Constantinopolis), Yenikapı. 41° 00' 22.22" N; 28° 57' 10.60" E. (Fig. 3.2). Concrete foundation, possibly non-hydraulic, to the pier within the interior of the harbour of Theodosios in the Yenikapı neighbourhood of Istanbul. Director Zeynep Kızıltan, Vice-Director Rahmi Asal, and Metin Gökçay, pers. comm. 2008. Basaran 2008.

*Eski Stambul* (Alexandria Troas). 39° 45' 27.63" N; 26° 08' 26.93" E. Several breakwater structures, built late 1st century BC to early 1st century AD, were constructed of marine concrete. A mole in the inner basin was constructed with "pozzolanic" mortar to just above sea level, then of "non-pozzolanic" mortar. With *opus reticulatum* facing. Feuser 2011.

*Kyme*, near Aliağa. 38° 45' 35.24" N; 26° 56' 05.85" E. (Fig. 3.2). Concrete mole lined with marginal walls of ashlar masonry with a mass of concrete on the outer, terminal end (Fig. 6.67). Schäfer and Schläger 1962; Esposito *et al.* 2002: 1–37.

*Tekirova* (Phaselis). 36° 31' 31.08" N; 30° 33' 13.01" E. (Figs. 3.2, 4.43). Concrete and rubble breakwater on the north and northeast side of the central harbour of Phaselis. Blackman 1978: 838; Schäfer *et al.* 1981: 63–67, pls. 22–28.

*Selimiya* (Side). 36° 46'N; 31° 23'E. 230 m long concrete mole in four sections on the northern edge of the ancient harbour (Figs. 3.2, 4.43, 6.68). Knoblauch 1977.

*Corycus*. 36° 27' 45.15" N; 34° 09' 01.19" E. (Figs. 3.2, 4.43). Mole of boulders and concrete 125 m long on the western side of the land castle at Corycus. L. Vann, pers. comm. 2000.

*Elaeusa-Sebaste*. 36° 29' 02.18" N; 34° 10' 38.68" (Figs. 3.2, 4.43). E. Concrete quay or wharf in the lee of the northern tip of the now land-locked island. Waelkens 1987: 100.

*Mezitli* (Soloi-Pompeiopolis). 36° 44' 18.68" N; 34° 32' 28.11" E. Two concrete moles lined with marginal walls of ashlar masonry (Figs. 3.2, 4.43–54, 6.69). ROMACONS sampled the concrete on the west mole in 2008; see pp. 95–101. Vann 1994: 68–73; Brandon *et al*. 2010a: 390–99.

### 6.2.7. Lebanon

*Saïda* (Sidon), Zire Island, Port Exterieur. 33° 34' 16.22" N; 35° 22' 06.33" E. (Fig. 3.2). Concrete layer, above an earlier foundation of stone blocks, on the pier projecting from the south-east side of Zire Island. Poidebard *et al*. 1951: 73–74; Frost 1973: 75–94; Frost 2000: 69–73.

Port Intérieur. 33° 33' 54.77" N; 35° 22' 05.55" E and 33° 33' 51.01" N; 35° 22' 03.73" E. Remains of concrete repairs or additions to the earlier enclosing moles of the inner harbours of Sidon now destroyed and buried beneath the modern harbour. Poidebard *et al*. 1951: 56–73; Frost 1973: 75–94; Frost 2000: 69–73.

*Fig. 6.64. Anthedon, naturally concreted rubble behind clamped ashlar marginal walls.*

*Fig. 6.65. Anthedon, naturally concreted rubble, detail.*

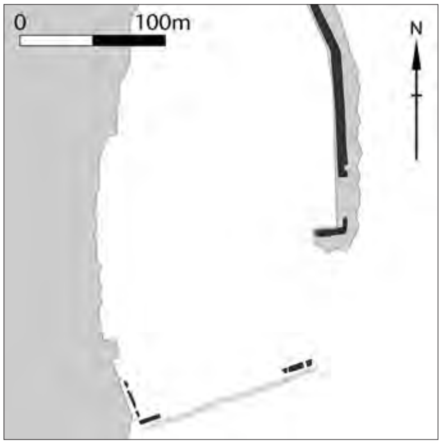


Fig. 6.66. Chersonesos, concrete moles.

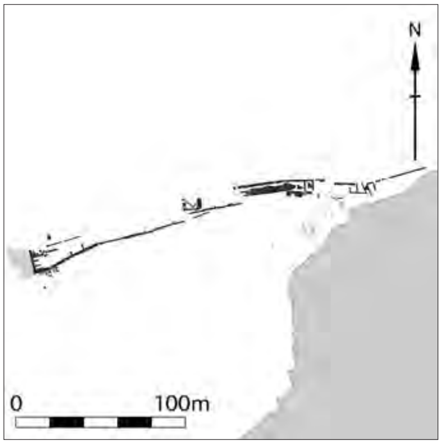


Fig. 6.67. Kyme, concrete mole.

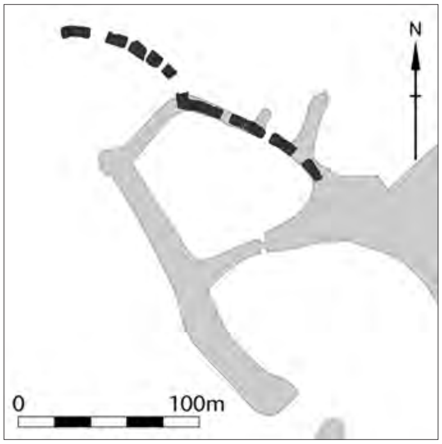


*Fig. 6.68. Side, long concrete mole in four sections.*

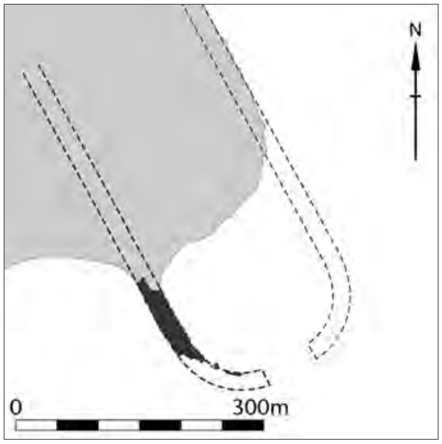


*Fig. 6.69. Pompeiopolis, two concrete moles.*

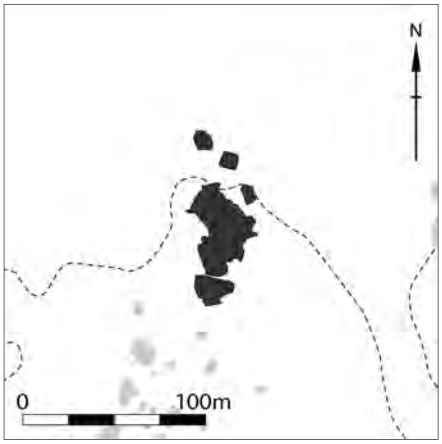


*Fig. 6.70. Sebastos, Area K, row of five concrete blocks and two isolated* pilae.

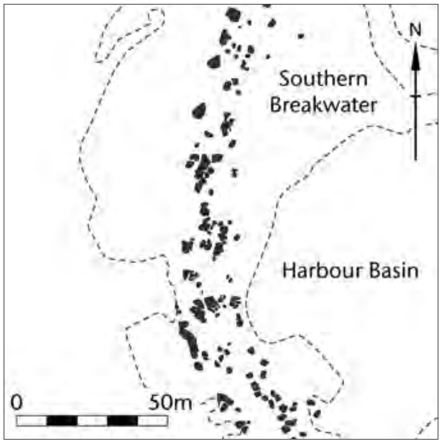


*Fig. 6.71. Sebastos. southwest mole, between Areas K and E/F, large concrete blocks.*

### *6.2.8. Israel*

*Qesaria* (Caesarea Palaestinae), *Sebastos* harbour, *Portus Augusti.* 32° 30’ 19.91” N; 34° 53’ 13.82” E. Archaeological survey and excavation have isolated several areas of particular interest (Figs. 3.2, 4.22–31).

Area K. A row of five concrete blocks and two isolated *pilae* in an area of approximately 70 m × 20 m at the northern end of the main southern mole or breakwater (Fig. 6.70). In 2005 ROMACONS sampled the concrete from K-5; see pp. 73–81. Brandon 1996: 25–40; 1997a: 45–58; 1999: 168–72; Hohlfelder *et al*. 2007: 409–15; Raban 2009: 74–88.

Southwestern mole, between Areas K and E/F. Large concrete blocks arrayed along the line of the southern breakwater, for a distance of approximately 400 m (Fig. 6.71). In 2005 ROMACONS took core samples of the concrete from blocks designated CAHEP SL3 and CO and a block south of Area K; see pp. 73–81. Hohlfelder *et al*. 2007: 409–15.

Area G. A 15 × 11 m concrete block, approximately 2 m tall and another originally of the same size but of which only a fragment now remains (Fig. 6.72). In 2005 ROMACONS sampled the concrete from Area G. Oleson 1989a: 127–30; Hohlfelder *et al*. 2007: 409–15; Raban 2009: 95–100.

Area P. Fragmentary concrete elements set in the rock-cut fish-pond on the promontory that was the site of Herod’s palace. Flinder 1985: 173–78; Oleson 1989b: 160–67.

*Sdot Yam*. 32° 29’ 35.43” N; 34° 53’ 19.93” E. Concrete walls from fish-tanks, 2 km to the south of Caesarea, near the modern harbour at Sdot Yam. A. Raban, pers. comm. 2003.

### 6.2.9. Egypt

*Alexandria*, Eastern Harbour. 31° 12' 18.14" N; 29° 53' 51.63" E. Archaeological survey and excavation have isolated several areas of particular interest (Figs. 3.2, 4.36).

Antirhodos Island. Block of concrete on the southern edge of Antirhodos Island, 15 m long, 8 m wide, *ca.* 1 m thick (Fig. 6.73). Sampled by ROMACONS in 2007; see pp. 85–89. Goddio *et al*. 1998: 32–37; Oleson *et al*. 2011a: 114–15.

Dock. 16 concrete blocks, in a north-south alignment 92 m long, close by Fort Qait Bey (Fig. 6.74). One of the blocks was cored by ROMACONS in 2007; see pp. 85–89. Hohlfelder *et al.* 2011: 118.

Jetty. Concrete jetty extends NNE from peninsula at the southern end of the Royal Harbour (Fig. 6.75). Hohlfelder 2011: 118.

### 6.2.10. Libya

*Labdah* (Leptis Magna). 32° 38' 23.42" N; 14° 17' 54.75" E. (Fig. 3.2). There is concrete behind the ashlar-faced quay on the western flank of the harbour, and there are concrete *pilae* in the sea on both north and east moles. Pompilio (2005) appears to suggest that some mortar samples from the west nymphaeum at Leptis Magna contained pumiceous ash pozzolan possibly from the Campi Flegrei. Pompilio, however, does not present sufficient data to support this attribution. Bartoccini 1958: 27–38; Beltrame 2012: 323–25.

*Sabratah* (Sabratha). 32° 48' 33.94" N; 12° 28' 51.66" E. (Fig. 3.2). 180 m length of concrete on top of a reef running parallel to the shore. Yorke 1966; 8–9; Dallas and Yorke 1968: 23, fig. 3; Yorke 1986: 243–45, fig. 108.

### 6.2.11. Tunisia

*Salakta* (Sullectum). 35° 23' 13.34" N; 11° 02' 30.67" E. (Fig. 3.2). Mole with sections of concrete, 260 m long. Yorke 1966: 13–14.

*Ras Dimasse* (Thapsus). 35° 37' 27.25" N; 11° 02' 56.95" E. Concrete mole 130 m long, now partly buried beneath a modern rubble breakwater (Figs. 3.2, 6.76). Yorke 1966: 7, 13–14; Dallas *et al*. 1968: 25, fig. 4; Lézine 1962: 143–49; Davidson and Yorke 2014.

*Hergia* (Horrea Caelia). 36° 01' 56.86" N; 10° 30' 36.16" E. Two lines of concrete blocks circa 2 × 2 × 2.5 m in the sea off the modern town of Hergia. Yorke 1966: 17.

*Nabeul* (Neapolis). 36° 26' 59.11" N; 10° 46' 38.14" E. Blocks of stone and concrete, 40 m off shore. Yorke 1966: 17–18.

*Kelibia* (Clupea). 36° 50' 07.43" N; 11° 06' 43.64". Remains of a concrete jetty now buried beneath the modern harbour quay. Yorke and Davidson 1969: 21.

*Carthage*. There are several maritime structures around the large harbour that make use of marine concrete (Fig. 3.2).

Quadrilateral of Falbe. 36° 50' 16.96" N; 10° 19' 36.76" E. Concrete walls within the quadrilateral that defined the entrance channel into the inner harbours (Fig. 6.77). They were part of a seawall that is now buried under a modern rubble breakwater and seawall. Yorke and Little 1975: 85–101.

Circular harbour. 36° 50' 45.09" N; 10° 19' 33.11" E. Roman concrete extension to the piers supporting the widened causeway that connected the island in the circular inner harbour to the shore (Fig. 6.78). It appears that these piers have now been cleared away in opening the harbour to the sea on the

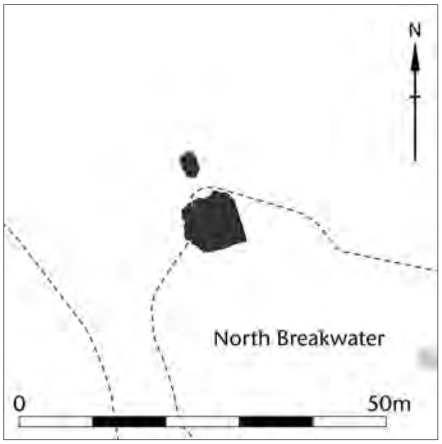


*Fig. 6.72. Sebastos, Area G, large concrete block.*

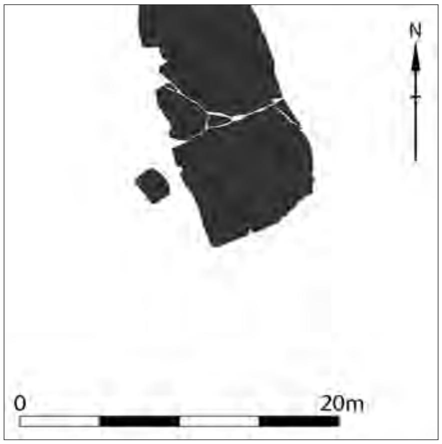


*Fig. 6.73. Alexandria, Antirhodos Island, block of concrete.*

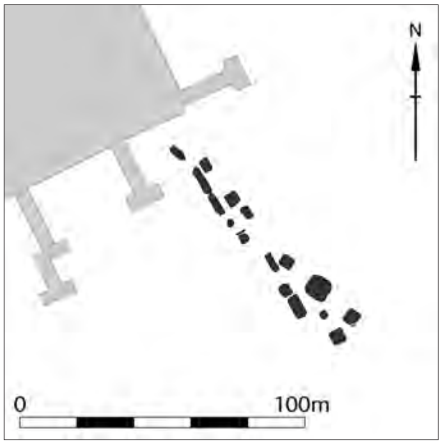


*Fig. 6.74. Alexandria, Dock at "Ball Trap," 16 concrete* pilae.

eastern side. Hurst 1976: 188–90; Yorke 1976: 25; Yorke and Davidson 1985: 157–64.

Neptune block. 36° 50' 59.56" N; 10° 19' 53.06" E. Large concrete block 18 m × 9 m on plan, mostly submerged, but sockets for the tie beams of the formwork are visible (Figs. 6.79–81). Oleson examined the block in 2008, and the concrete appeared to be composed of a greenish marine mortar and tuff aggregate similar to that seen at Santa Liberata. Davis (1981) reports that "pozzolana" was used in cisterns at Carthage; if true, it is to be expected in the harbour structures as well. Yorke and Little 1975: 85–101.

### 6.2.12. Algeria

*Tipasa* (Tipasa). 36° 35' 46.40" N; 2° 27' 35.47" E. Large block of concrete, in the shape of a truncated wedge, approximately 10 m long, 3.7 m high and an average width of 3 m marking the eastern entrance to the ancient harbour (Figs. 3.2, 6.82). On the adjacent northern mole are two smaller blocks of concrete aligned east-west with a gap in-between. Yorke and Davidson 1969: 11–14.

*Cherchel* (Iol Caesarea, Caesarea Mauretaniensis*)*, Cap Tizirine. 36° 36' 50.07" N; 2° 12' 04.35" E. (Fig. 3.2).

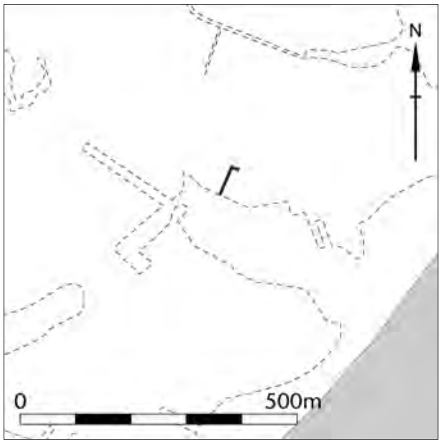


*Fig. 6.75. Alexandria, concrete jetty.*

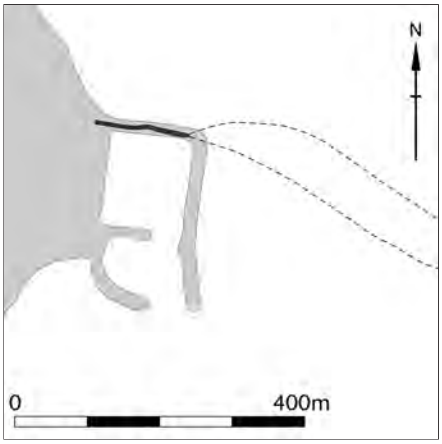


*Fig. 6.76. Thapsus, long concrete mole.*

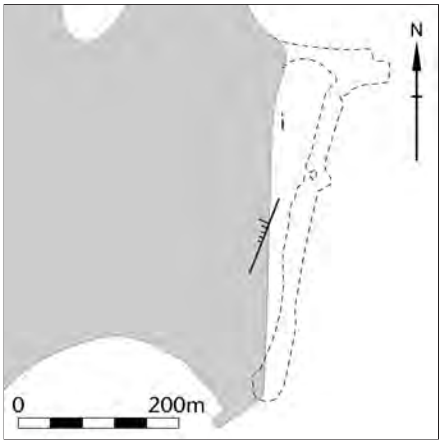


*Fig. 6.77. Carthage, Quadrilateral of Falbe, concrete walls forming the entrance channel to the inner harbours.*

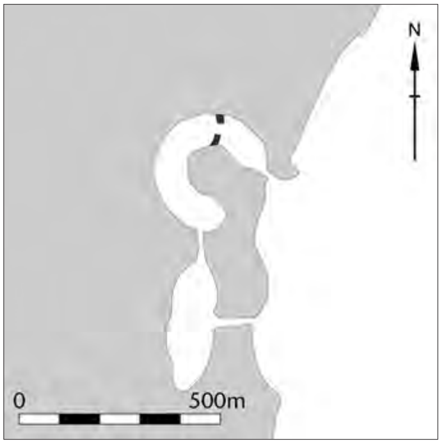


*Fig. 6.78. Carthage, Circular Harbour, Roman concrete extension to the piers supporting the causeway.*

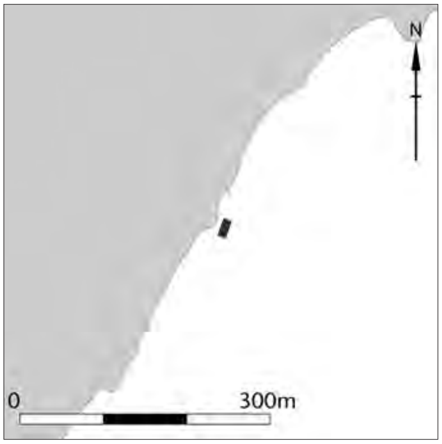


*Fig. 6.79. Carthage, Neptune block, large, isolated concrete block, plan.*

*Fig. 6.80. Carthage, Neptune block, view of holes left by* catenae*.*

*Fig. 6.81. Carthage, Neptune block, detail of concrete.*

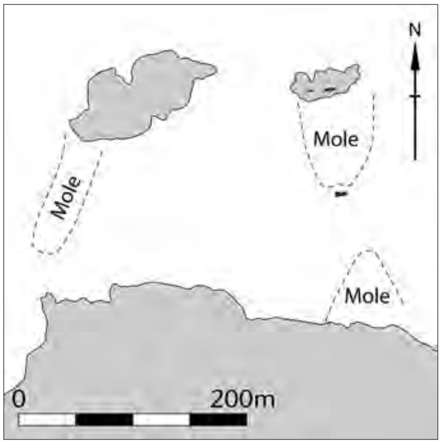


*Fig. 6.82. Tipasa, large block of concrete.*

Concrete and rock-cut fish-pools on the eastern side of Cap Tizirine. Yorke and Davidson 1969: 11–12.

Ecueil du Gd. Hamman to Pte. des Marabouts. 36° 36’ 49” N; 2° 11’ 32.75” E to 36°36’ 36.40” N; 2° 11’ 33.71” E. Concrete structures located between Ecueil du Gd. Hamman and Pte. des Marabouts. The Ecueil has a low concrete arch that lines up with a large bastion of concrete on the shore on the Pointe des Marabouts and scattered lumps of concrete in-between. Yorke and Davidson 1969: 10–11; Leveau 1984: 47–50.

West of Îlot Joinville. 36° 36’ 36.02” N; 2° 11’ 09.30” E. Seven large concrete *pilae* (6 m × 8 m × 5 m) in a line to the west of Îlot Joinville (Fig. 6.83). One of the blocks just breaks the surface of the sea. Yorke and Davidson 1969: 10–11.

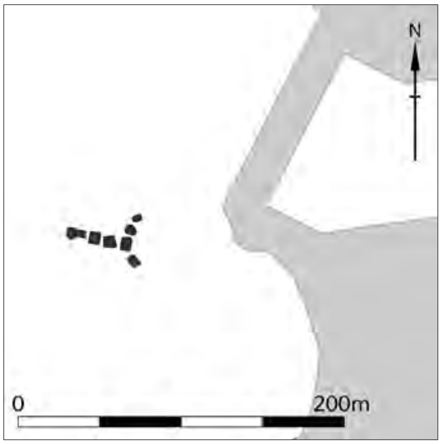


*Fig. 6.83. Cherchel, Seven large concrete* pilae *in a line.*

# Chapter 7

# Sea-Water Concretes and their Material Characteristics

*M. D. Jackson*

*with contributions by G. Vola, E. Gotti, and B. Zanga*

## 7.1. Introduction

Roman maritime concrete structures have remained cohesive and intact for 2000 years. The secrets to their extraordinary endurance in the aggressive sea-water environment, which attacks modern concretes through diverse physical and chemical processes, have long remained a mystery. The fundamental binding substance of all the concretes drilled by ROMACONS is a hydraulic pozzolanic mortar (Fig. 7.1a), a composite material formulated mainly from hydrated lime and pumiceous volcanic ash. This rough, heterogeneous material holds the clues to understanding the overall coherence and longevity of the concrete structures. Its crystalline cementitious hydrates are the nanoscale expression of Roman builders' adept empirical expertise in building exceptionally tenacious concrete structures in the sea (Fig. 7.1b, c, d).

The Roman architect and engineer Vitruvius described the ash that occurs from Cumae to the promontory of Minerva, near Sorrento (Fig. 7.2) as *pulvis,* "dust" or "powder," and he recognized its volcanic origin and importance to maritime concrete construction (*De arch.* 2.6.1; see pp. 17–19, Passage 7). Pyroclastic deposits produced by explosive eruptions of the Campi Flegrei and Somma-Vesuvius volcanic districts form the northern shoreline and landscape of the Gulf of Naples; while the Sorrentine peninsula is mainly composed of Mesozoic carbonate rock deposits. The ancient Roman towns of Baiae (Baia) and Puteoli (Pozzuoli) lie within the active caldera of Campi Flegrei volcano, which has had a complex deformational history produced by tumescence and deflation of the volcanic edifice over the past several millennia (Dvorak and Mastrolorenzo 1991; Orsi *et al*. 1996; Morhange *et al.* 2006). The non-eruptive deflations are manifested by sea level rise and local marine transgressions, and inflations are associated with sea level fall. Near Baia, the volcanic tuffs that are presumed to have been used as *caementa,* or coarse aggregate, in many of the maritime concretes (Fig. 7.1a) are mainly soft, porous, pumiceous pyroclastic rocks on land. Remarkably, the associated the volcanic ash (*pulvis*) seems to gain integrity and cohesion in the sea-water environment, as noted by Seneca (*Q Nat.* 3.20.3) and Pliny (*HN* 35.166–67) (see pp. 26–27, Passages 14, 16). In fact, the natural zeolitic cements that consolidate volcanic ash to form lithified tuff commonly develop in alkaline environments, including sea-water and saline lakes (Hay and Sheppard 2001).

In the ancient maritime concretes, adhesion of tuff *caementa* with the cementitious matrix of the mortar is one of the primary factors influencing the long-term stability of the harbour structures. As compared with Portland cement concretes, the ancient concrete fabric is exceptionally heterogeneous at many scales: there are decimetre-scale coarse rubble *caementa*, composed mainly of glassy volcanic tuff or carbonate rock, and millimetre-scale relicts of hydrated lime and pumiceous clasts in the mortar, which contains micron-scale crystalline and poorly-crystalline cementitious hydrates and relicts of fine pumiceous volcanic ash. The nanoscale bonding environments of calcium, silicon, and aluminium in these cementitious hydrates determine their material characteristics (Fig. 7.1) (Jackson *et al.* 2013a, b).

Deciphering the mineralogical fabric of the ancient mortars has yielded many surprising findings that confirm the chemical and mechanical stability of Roman maritime concrete and its cementitious fabric. Here, new analyses of ancient texts are integrated with principles of modern cement chemistry to provide insights into the geologic materials of the concrete design mix, installation techniques, and initial chemical conditions and pozzolanic processes in the sea-water saturated mass (pp. 145–75). A thermal model for exothermic heat evolved through cementitious processes describes the temperature history of a well-constrained breakwater, Baianus Sinus in the Bay of Pozzuoli, and constrains the principal hardening of the wet mass to about one year or two (pp. 183–84). The development of

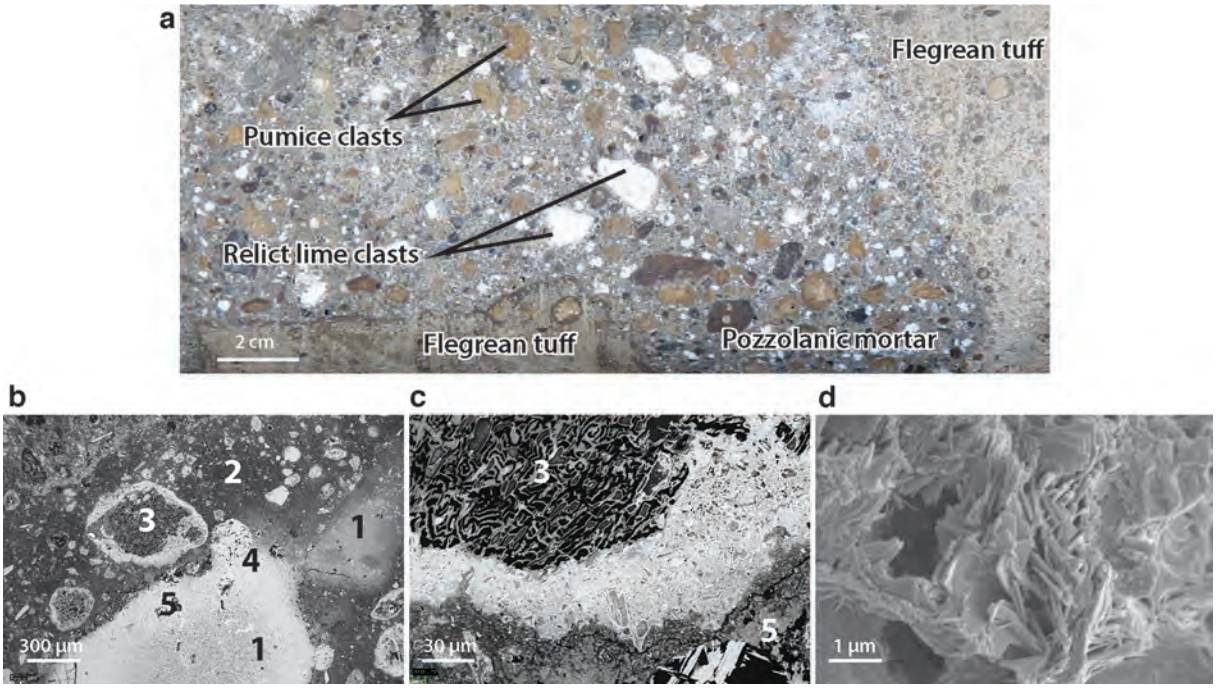


*Fig. 7.1. Characteristic fabric of ancient Roman maritime concrete, shown in the drill core of the Baianus Sinus* pila *(BAI.2006.03). a. Photograph of a core sample showing pumiceous tuff* caementa*, and pumiceous volcanic ash and relict lime clasts in the pozzolanic mortar. b. Partially dissolved relict lime clasts (1), poorly crystalline, calcium-aluminium-silicate-hydrate (C-A-S-H) binder in the cementitious matrix (2), relict pumice clasts with associated cementitious hydrates (3), and chloride and sulphate microstructures (4, 5) (SEM-BSE image). c. Detail of (b) showing the pozzolanic reaction rim around a pumice clast (SEM-BSE image). d. Al-tobermorite crystals in a relict lime clast (SEM-SE image).*

compressive strength in the concrete reproduction installed in Brindisi in 2004 also indicates substantial cohesion between 6 and 24 months hydration (pp.175–83, Chapter 5). Geochemical studies and careful identifications of crystalline assemblages in mortar fabrics reveal remarkably consistent mineralogical and chemical compositions over all the harbour concretes. These reflect only minor variations from the surface of a structure to its interior pp. 166–75). They also suggest a rather standardized hydrated lime-pumiceous volcanic ash mix design. The very long-term cohesion of the concretes appears to be associated with a crystalline cementitious phase, Al-tobermorite, which may improve bonding and mechanical strength relative to poorly crystalline binder (pp. 168–69, 183–84). In addition, the later development of zeolite mineral, possibly over hundreds of years may contribute to porosity reduction in some concretes (pp. 169–70, Fig. 7.4). In many respects, the durability of the ancient maritime concrete can be understood in terms of the diagenetic processes that produce mineral cements in stable rocks of the Earth's crust. These are the chemical and physical changes undergone by the lime and pyroclastic rock after their initial installation in sea-water, which led to early cohesion at relatively low temperatures and pressures and continued to add to cohesion in the sea-water concrete environment over very long periods of time. Roman builders almost certainly suspected that these cementitious phases and processes were responsible for the stability and cohesion of the concretes, and they seem to have maximized their impact with the selection of pumiceous volcanic ash as the principal component of all the maritime mortars.

Recent studies using a variety of advanced microscopic and analytical techniques reveal that the cementitious hydrates of the ancient sea-water mortars show a fascinating range of compositions and microstructures which are astonishingly intricate, and beautiful in their own right (Figs. 7.3, 7.4; see pp. 168–70). The principal poorly-crystalline cementitious component, calcium-aluminium-silicate-hydrate (C-A-S-H) (Vola *et al.* 2013; Stanislao *et al.* 2011; Jackson *et al.* 2012, 2013b), is the focus of studies of environmentally-friendly concretes that incorporate diverse supplemental materials, including volcanic ash and industrial waste products, to replace kiln-fired Portland cement (Massazza 1988; Snellings *et al.* 2012). The principal crystalline cementitious component, Al-tobermorite, is a calcium-aluminium-silicate-hydrate mineral, ($[Ca_4(Si_{5.5}Al_{0.5}O_{17}H_2)]Ca_{0.2}Na_{0.1} \cdot 4H_2O$) (Taylor 1992), with 11Å interlayer spacing, which occurs rarely in hydrothermal geologic environments. The crystals have myriad industrial applications but, at present, can only be produced in small quantities through laboratory syntheses at elevated temperatures (80 to 200°C), substantially higher than those that occur in conventional moist air-cured concretes. Tobermorite, with pure, or ideal, composition ($Ca_5(Si_6O_{18}H_2) \bullet 8H_2O$) and another calcium silicate mineral, jennite ($Ca_9Si_6O_{18}(OH)_6 \bullet 8H_2O$), form the model basis of poorly-crystalline calcium-silicate-hydrate (C-S-H), the "glue" of Portland cement concretes (Taylor 2004: 130, 140–42). Neither tobermorite nor Al-tobermorite has ever been observed in conventional concrete, so it is rather astonishing that the crystals occur in all the concrete harbour structures drilled by ROMACONS. Other crystalline cementitious hydrates, such as hydrocalumite and ettringite, as well as zeolite minerals, developed in the sea-water mortars. They also occur as rock-forming minerals in the Earth's crust.

The most ubiquitous cementitious mineral is Al-tobermorite. It occurs in relict lime clasts, in the cementitious matrix and pumiceous pozzolan, and as fibres in relict voids (Fig. 7.3). The most striking microstructures in the mortar fabric are those formed by sulphate and calcium-chloroaluminate crystals, mainly hydrocalumite ($Ca_2Al(OH)_6[Cl_{1-x}(OH)_x] \bullet 3H_2O$), a chloride-bearing Friedel's salt, and ettringite ($(Ca_6Al_2(SO_4)_3(OH)_{12} \bullet 26(H_2O))$, a sulphate-bearing phase (Fig. 7.3e, f). These sequester the $Cl^-$ and $SO_4^{2-}$ anions that attack modern maritime concretes through the corrosion of steel reinforcements and damaging expansions (Massazza 1985, Mehta 1990). Phillipsite ($((Ca, Na_2, K_2)_3Al_6Si_{10}O_{32} \bullet 12H_2O)$), a zeolite mineral, crystallized in open pores and the cementitious matrix of some of the mortars (Fig. 7.4), probably after the initial high pH cementitious system associated with hydrated lime, or calcium hydroxide, was complete (Vola *et al.* 2011; Jackson *et al.* 2012). The diverse mineralogical assemblages surely developed over long time spans and changing chemical and temperature environments.

In November 2004, the ROMACONS group constructed a historically accurate 7.44 $m^3$ concrete block, or *pila*, at Brindisi harbour (see Chapter 5) using sea-water, the alkali-rich, pumiceous pyroclastic deposit quarried at Bacoli (Fig. 7.2) – the lithified tuff facies is the *caementa* and the poorly consolidated ash facies is the mortar pozzolan – and aged slaked lime with a nearly pure CaO composition (Oleson *et al.* 2006; Gotti *et al.* 2008). Drill cores through the *pila* in March and November 2005, November 2006, May 2008, and November 2009 record chemical processes that occurred during immersion in sea-water from 6 months to 5 years hydration.

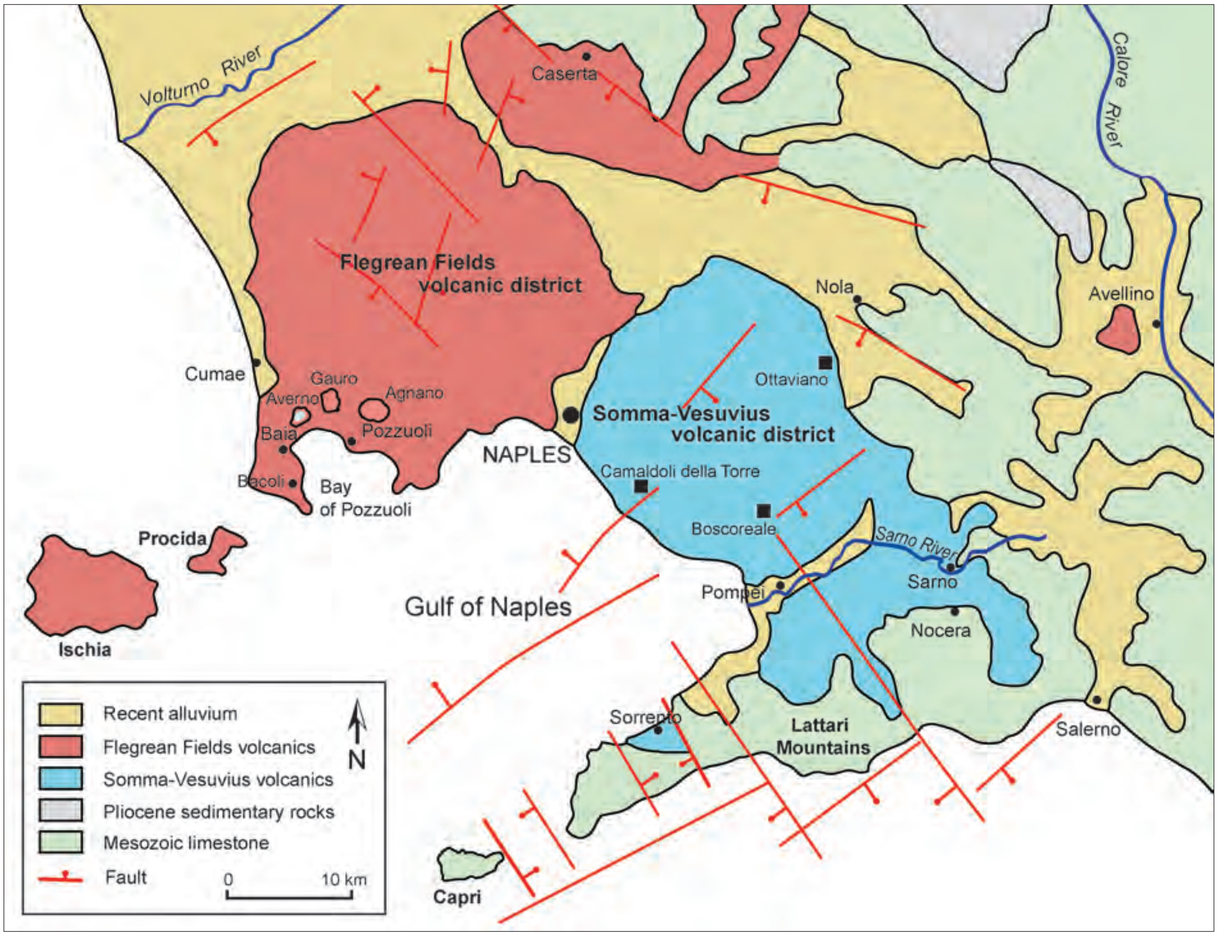


*Fig. 7.2. Geologic sketch map of Bay of Naples showing the Flegrean Fields and Somma-Vesuvius volcanic districts and the limestone bedrock of the Sorrento peninsula (after Orsi* et al. *1996).*

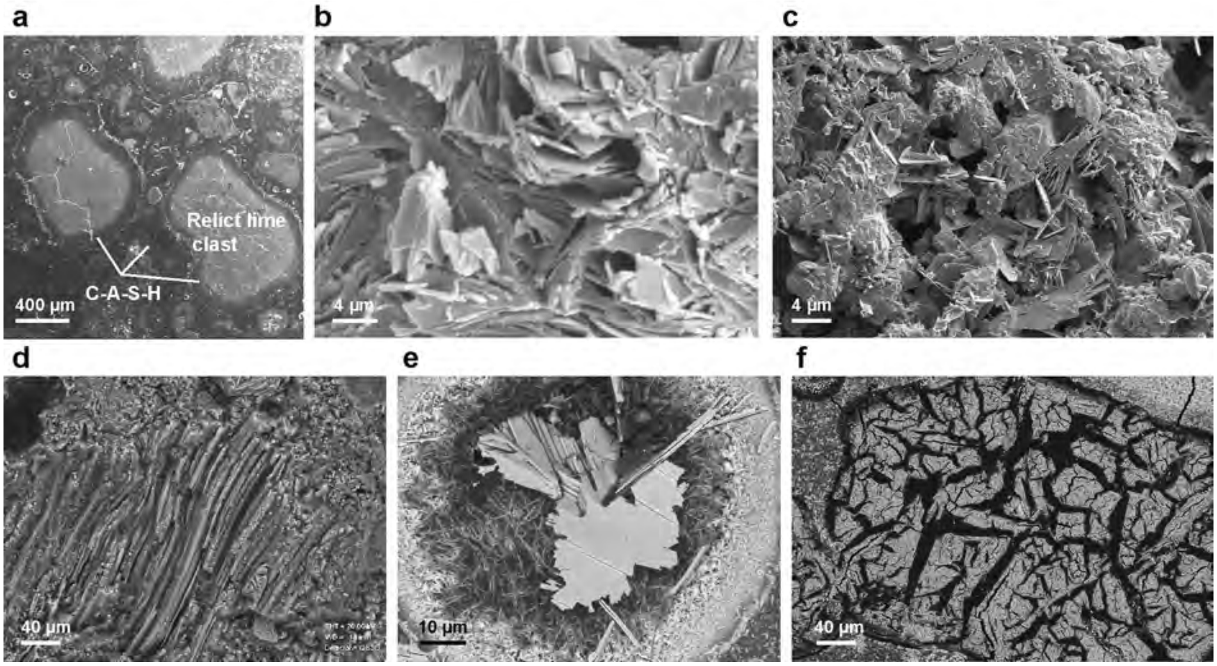


*Fig. 7.3. Cementitious hydrates in the ancient maritime mortars. a. C-A-S-H in the cementitious matrix and the perimeters of relict lime clasts, Baianus Sinus (SEM-BSE image). b. Platy crystals of Al-tobermorite, relict lime clast, Baianus Sinus (SEM-SE image). c. Platy Al-tobermorite crystals and C-A-S-H, cementitious matrix, Baianus Sinus (SEM-SE image). d. Cementitious hydrates in a tubular pumice clast, Caesarea (G.Vola). e. Hydrocalumite crystals in a relict void surrounded by thread-like Al-tobermorite crystals, Baianus Sinus (SEM-BSE image). f. Ettringite, sub-spherical microstructure at the perimeter of a relict lime clast, Baianus Sinus (SEM-BSE image).*

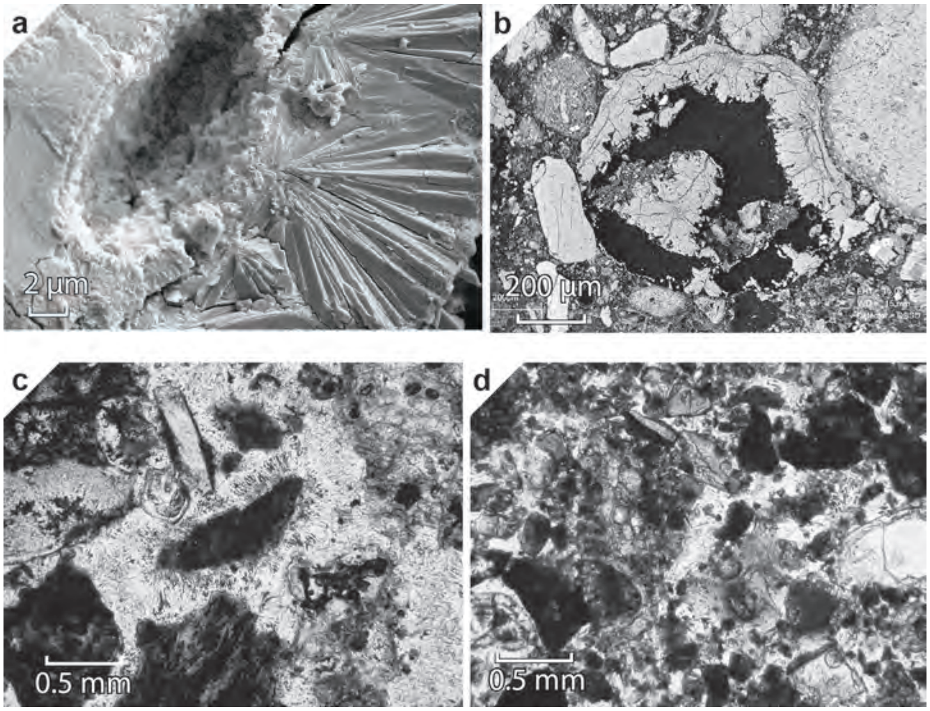


*Fig. 7.4. Zeolite mineral microstructures in components of the ancient maritime concretes. a. Pumice clast with relict geological phillipsite and C-A-S-H in a large vesicle, Baianus Sinus mortar (SEM-SE image). b.* In situ *phillipsite in a pore of the cementitious matrix, Portus Cosanus mortar (SEM-BSE image) (after Jackson* et al. *2013). c. Possible* in situ *phillipsite in Tufo Lionato* caementa*, Portus Traiani concrete (petrographic image, plane polarized light). d. Tufo Lionato from the Salone Quarry, northeast of Rome (petrographic image, plane polarized light) (see Jackson* et al. *2005).*

Comparison of the young concrete with the ancient materials, in terms of cementitious components, mortar fabrics, chemical composition, and physical properties, gives new insights into the processes of hydration of the lime-pyroclastic rock system in the sea-water environment.

This chapter first describes the raw geologic materials of the ancient concretes, their possible provenance, and the diverse cementitious components of the mortar fabrics and their fascinating microstructures. The engineering and material characteristics of the ancient mortars and concretes are then described, and compared to those of the experimental concrete *pila* constructed at Brindisi. Integrating these descriptions with interdisciplinary findings from archaeological science, mineralogy, and geochemistry provides an analytical foundation for gaining insights into the enduring qualities of the maritime structures, the proven expertise of Roman builders, and future applications to modern, environmentally-sustainable concretes formulated with lime and pyroclastic rock.

## 7.2. Geologic raw materials of the concretes

The massive maritime concrete harbour structures that Romans constructed in ports throughout the Mediterranean area are some of the most durable cementitious materials on the planet. To build these extraordinarily long-lived structures, builders used four ingredients: pumiceous volcanic ash, lime calcined from limestone in kilns at about 850 to 900 ºC, sea-water, and rough chunks of rock *caementa*. The volcanic ash pozzolan and tuff *caementa* come from pyroclastic deposits that were ejected from volcanic vents during explosive eruptions. Volcanic ash is composed of sand-sized and smaller particles (less than 2 mm diameter) of variably vesiculated glass (vitrics), as pumice or scoriae, and crystals derived from magma, or molten rock, as well as particles of rock, mainly lavas broken from the underground edifice of the volcano (lithics). Lapilli are particles 2 to 64 mm in diameter; bombs are larger fragments. Tuff is the rock that forms from volcanic ash and lapilli through processes of lithification and the development of mineral cements or, in some cases, the welding of volcanic glass. Here, the term "pumiceous volcanic ash" refers to loosely consolidated pyroclastic ash and lapilli with a predominance of pumice particles. In some harbours far distant from Naples, other local rocks were used as *caementa*, mainly local carbonate rocks or to a lesser extent, other local silicate rock and ceramic fragments.

The macroscale map of a 20 cm segment of the Portus Traiani PTR.2002.01 drill core, 75 cm below the top of the harbour construction at Portus (Fig. 4.1) and now 1.75 underwater, gives an illustration of the strongly heterogeneous fabric of the ancient maritime concrete (Fig. 7.5). The *caementa* are Tufo Lionato, a moderately well-lithified tuff

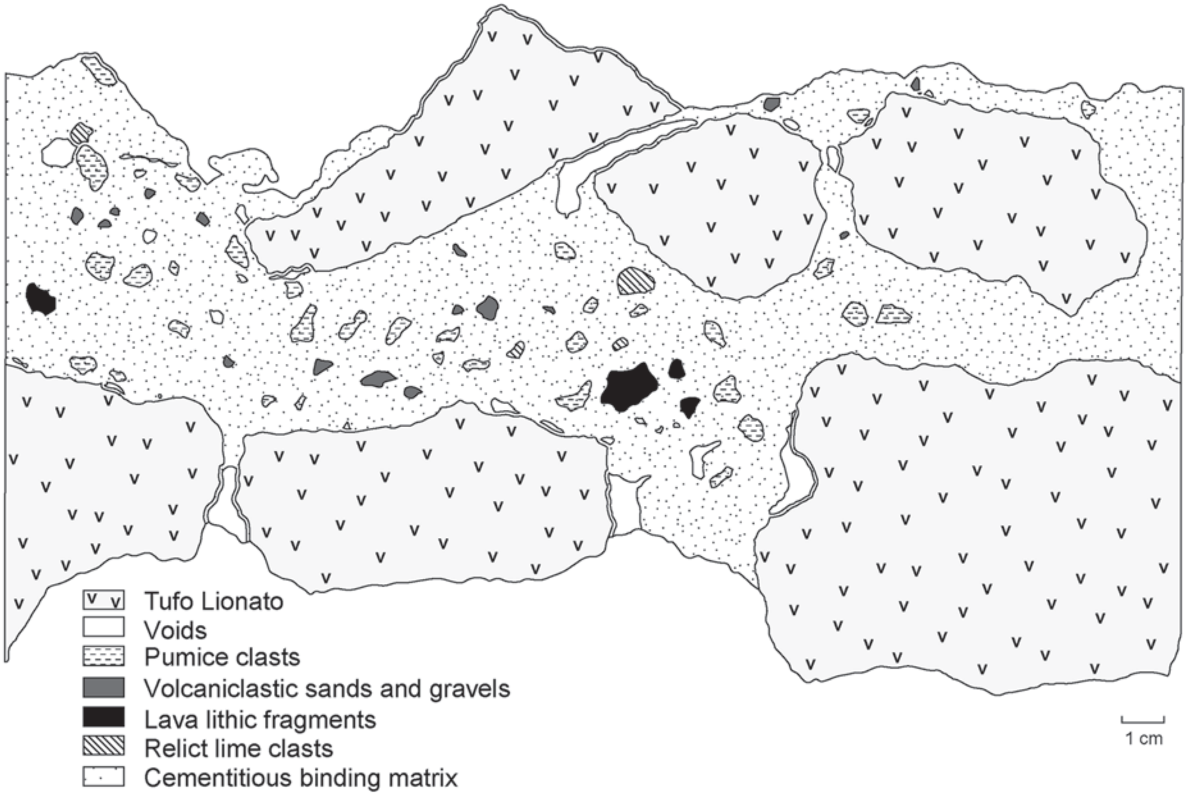


*Fig. 7.5. Macroscale map of a segment of the Portus Traiani concrete, showing the principal components of the ancient Roman maritime concrete fabric.*

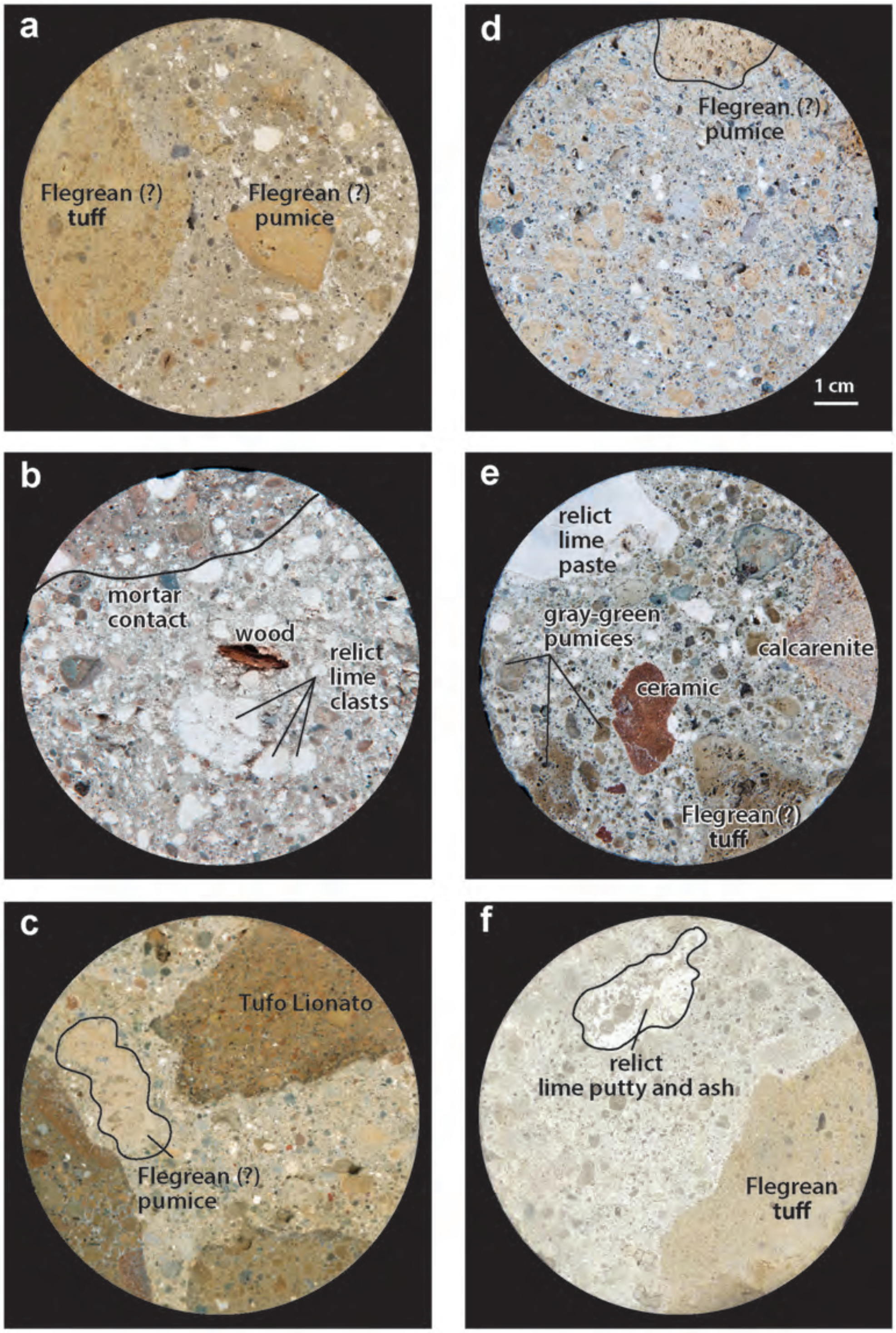


*Fig. 7.6. Slices of drill cores of the ancient maritime concretes and the young Brindisi concrete reproduction, showing macroscale fabrics of the mortars and glassy volcanic tuff* caementa*. All drill cores are 9 cm in diameter. a. Santa Liberata (SLI.2004.01) concrete, possible Flegrean tuff* caementa *(specimen SLI.2004.01.T1) and pumice clast (specimen SLI.04.01.P1). b. Portus Claudius (POR.2002.01) mortar, relict lime fabrics (C. Hagen) (see also Fig. 7.14). c. Portus Traiani (PTR.2002.01) concrete (see also Fig. 7.5), Tufo Lionato* caementa *from Alban Hills volcano (specimen PTR.02.02.T1, see also Fig. 7.4) and possible Flegrean pumice clasts (specimen PTR.02.01.P1). d. Portus Neronis (ANZ.2002.01) mortar, with possible Flegrean pumice and pumiceous ash (C. Hagen). e. Sebastos, Caesarea (CAE.2005.05) concrete, showing diverse mortar components (C. Hagen), with pumiceous tuff* caementa *and pumice clasts (specimen CAE.05.05.P1). f. Brindisi (BRI.2009.01) concrete, Bacoli Tuff (specimens 05.BRI.02.T1, 06.BRI.01.T1) and lime-ash putty (See also Fig. 7.14).*

with natural zeolite cements, whose distinctive tawny-orange colour is derived from a predominance of iron-rich palagonitic volcanic glass. This is a vitric-crystal-lithic erupted from the nearby Alban Hills volcanic district (Fig. 7.7), which was used ubiquitously in ancient Rome as both dimension stone and *caementa* in monumental constructions (Jackson *et al*. 2005, 2009, 2011; Jackson and Marra 2006). The cementitious matrix of the mortar is of particular importance: this is the material composed of cementitious hydrates and relicts of volcanic ash pozzolan, less than 2 mm in size, which binds the concrete. The predominant mortar pozzolan is silt- to fine gravel-sized, pale yellowish-brown volcanic ash with light greyish-orange pumice fragments up to 3 cm in diameter, sanidine crystal fragments, and occasional lava lithic fragments. (Sanidine is a potassium feldspar $((K,Na)(Si,Al)_4O_8)$ that crystallized in the magma at high temperature). Builders augmented the pumiceous ash pozzolan with dark grey and reddened volcaniclastic sand and gravel, about 10 to 15 per cent by volume based on a petrographic point count. There are occasional dull white relicts of lime clasts, but most of the lime reacted to form C-A-S-H in the pumiceous cementitious matrix. Overall, the concrete has a very coherent fabric, in which the Tufo Lionato *caementa* and volcanic ash pozzolans are firmly bonded in a compact, well-consolidated drill core sample.

The nearby Claudian harbour construction at Portus (Fig. 4.1) also contains light yellowish grey and greyish-orange pumiceous ash pozzolan and Tufo Lionato *caementa*, but the mortar has a rough, porous fabric, common partially-calcined limestone clasts, and abundant dull white, centimetre-sized inclusions (Fig. 7.6c). Although the Portus Claudius (about AD 40 to 50) and Portus Traiani (about AD 106 to 113) concretes were constructed of similar raw materials in rather close proximity, they show variations in their mortar fabrics that are likely the result of differences in the care and attention to detail used in the preparation of the mortar and the installation of the concrete structures. The sections that follow describe these variations from multiple analytical perspectives.

***7.2.1. Rocks used as coarse rubble caementa.*** The yellowish-grey volcanic tuff *caementa* of the Portus Cosanus and the Santa Liberata structures in Tuscany, of Portus Neronis at Anzio, and of the Bay of Pozzuoli structures at Portus Baianus, Baianus Sinus and Portus Iulius, closely resemble the glassy Neapolitan Yellow Tuff and Bacoli Tuff of the Campi Flegrei volcanic district (Orsi *et al.* 1996; de' Gennaro *et al.* 1999; Morra *et al.* 2010; Fedele *et al.* 2011), in their macroscopic fabric (Figs. 7.1a, 7.6a, d). Studies of the tuff *caementa* in thin section with the petrographic microscope show that these are composed of an altered fine ash, vitric-crystal matrix with sanidine and clinopyroxene crystal fragments, which surrounds abundant yellowish-grey and greyish-orange lapilli-sized pumice clasts with zeolite mineral in vesicles, and common lava lithic fragments. The exceptions are the concretes of the Imperial age Portus Claudius and Portus Traiani harbour constructions, which contain mainly tawny-orange Tufo Lionato, the most widely used volcanic tuff building stone of late Republican and Imperial age construction in Rome (Figs. 7.5, 7.6b, c) (Jackson and Marra 2006). In addition, two *pila* structures at

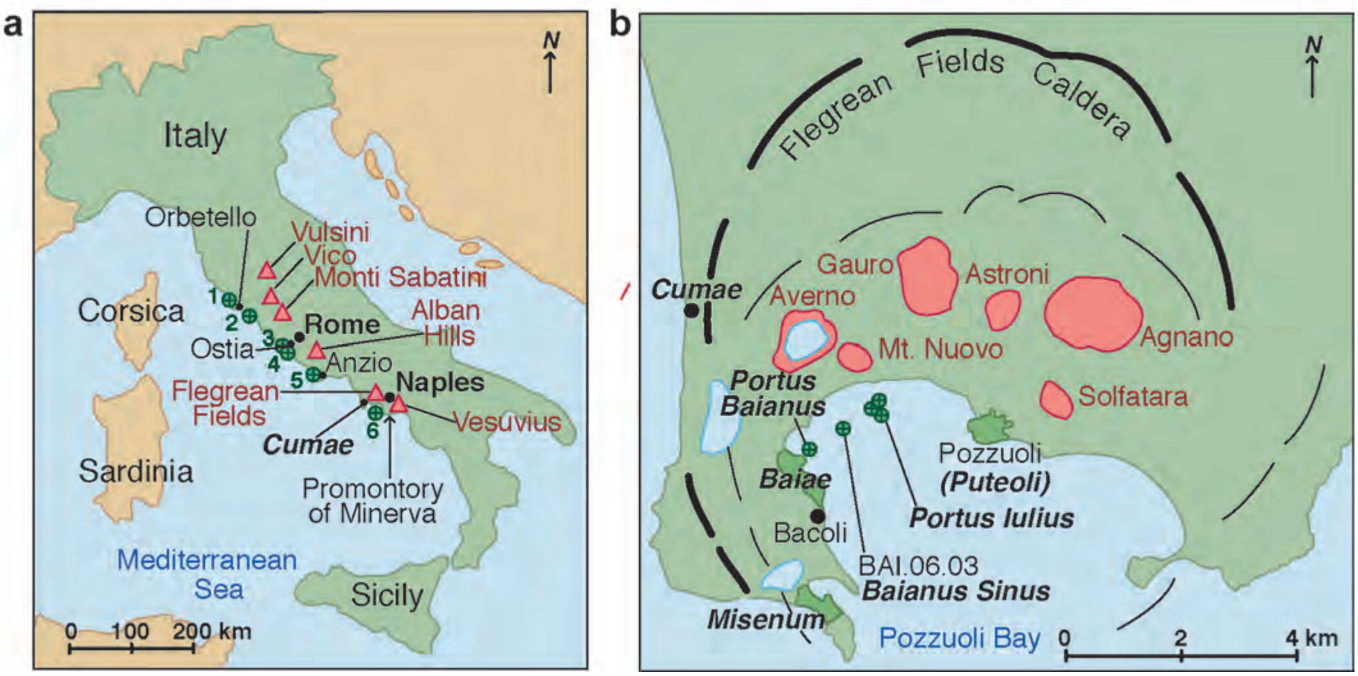


*Fig. 7.7. Maps of the central Italian coast and the Bay of Pozzuoli, showing harbour drill sites and volcanic districts (after Jackson* et al. *2013b).*

Portus Cosanus (cores PCO.2002.02, PCO.2002.05) contain a variety of igneous rocks, mainly lavas, and occasional limestone *caementa*; this the widest lithological variability of *caementa* in any of the ROMACONS cores, with the exception of the Pompeiopolis concretes.

The harbour structures far distant from Naples, at Egnazia, Chersonesos, Pompeiopolis, Caesarea, and Alexandria do contain occasional cobble-sized aggregate of sanidine-bearing yellowish grey pumiceous tuff with relict natural zeolite cements (Figs. 7.8, 7.9). The mineralogical association of phillipsite>chabazite>analcite in the tuff *caementa* at Pompeiopolis, for example, suggests these rocks come from Neapolitan Yellow Tuff deposits of the Campi Flegrei volcanic district (Stanislao *et al.* 2011:485), more than 2,000 km distant by sea from the harbour site.

There is, however, very little decimetre-sized tuff *caementa* in the eastern Mediterranean maritime concretes. Rather, this is generally carbonate rock, which occurs as various local limestones or calcareous sandstone (Fig. 7.8). At Egnazia harbour, constructed in second or first century BC on the Apulian Adriatic coast near modern Brindisi, the coarse aggregate is a porous, fossiliferous limestone, likely from the Pliocene-Pleistocene "Calcarenite di Gravina" formation (Vola *et al.* 2011c), previously reported as "Tufi delle Murge" (Merla and Ercoli 1971). These rocks have been quarried locally since the fourth century BC (Calia *et al.* 2011). Fragments of bioclastic packstone-wackestone *caementa* containing benthonic foraminifera, which lived on the ancient sea floor, likely come from older rocks, such as the "Calcare di Bari" formation (Stanislao 2011). At Chersonesos harbour, constructed in the first century BC or AD on the north coast of Crete, the porous, rather poorly consolidated concretes contain occasional yellow-grey pumiceous tuff fragments but most of the *caementa* are irregularly shaped chunks of fossiliferous wackestone ranging from about 5 to 20 cm in length, probably from local Miocene-Pliocene deposits of the Chersonesos stratigraphic succession (Frydas and Bellas 2009; Vola *et al.* 2011c; Stanislao 2011). Coal fragments in the mortars, 0.5 to 2.0 mm in size, seem to come from local lignite beds in lacustrine and terrestrial deposits around the harbour site (Vidakis and Meulenkamp 1996). At Pompeiopolis, the concrete incorporates decimetre-sized pumiceous tuff, rounded cobbles of stony coral, and amphibolite rocks, likely from local fluvial deposits (Vola *et al*. 2010a; 2010b; Stanislao *et al.* 2011). In addition, fragments of the yellowish-red argillaceous carbonate bedrock, which forms the lower segments of the drill cores, also occur in the concretes.

At Sebastos, the harbour of Caesarea Palaestina constructed in 23 to 15 BC, the *caementa* are mainly from *kurkar* eolianite deposits (Sneh *et al.* 1998). The sediments accumulated in coastal dunes, beaches and other settings, and commonly form ridges and sea cliffs along the coastline of Israel. *Kurkar* is a sandstone composed mainly of quartz grains, and sand-sized particles of corals, shells, other carbonate grains, bits of older limestones and dolomites, and natural calcium-carbonate cement. Pleistocene calcareous grainstone ridges that trend parallel to the coastline are composed of coastal sand dunes with calcite cement. Quaternary calcareous grainstone, sometimes known as 'beach rock', also has quartz and carbonate sand grains, but accumulates in the beach zone and can overlie wind blown deposits (Mart and Peregman 1996: 6). Distinguishing among these different depositional environments is difficult. The presence of common detrital quartz grains, feldspars, frequent foraminifera, rare gastropods and bivalves, and a natural sparry calcite cement in the fossiliferous sandstone *caementa* of the Caesarea concretes suggest that at least some of these rocks were obtained from the beach environment (Vola *et al.* 2011a). At Alexandria, the *caementa* are principally oolithic-bioclastic grainstone, with benthonic foraminifera, algae, and rare gastropods (Vola *et al.* 2011c, Stanislao 2011), whose origin remains unknown. Many different Quaternary deposits crop out near the harbour and the Mallahet Mariut marsh, including duricrusts, sand, gravel, and recent coastal deposits (Klitzsch *et al.* 1986; Harrell 2012), but these sediments seem not to have been used in the maritime concretes.

In sum, the coarse aggregate of nearly all the concrete structures drilled by ROMACONS is composed of two principal rock types: either glassy tuff or carbonate rock. There are also fragments of broken ceramics in some of the concretes. These are the only waste products present; recycled concrete fragments have not been observed. Given the diverse rock assemblages in the Mediterranean region, and at individual harbour sites, it is remarkable that builders adhered to such a narrow selection of rubble aggregate over 150 years of harbour construction. (The two exceptions are Portus Cosanus, one of the earliest harbour constructions, and Pompeiopolis, one of the more distant and obscure harbour sites.) Very large quantities of limestone were quarried for the production of lime, and it is possible that some this carbonate rock was also used as *caementa*. Builders' preferences were surely based on empirical observations of service life of the maritime structures and also, perhaps, on their observations of the natural lithification of these clastic rocks in the marine environment, as shown by exposures of well consolidated limestones along the eastern Mediterranean coastline and pumiceous tuff deposits in the Bay of Pozzuoli. Remarkably, Seneca and Pliny both describe the lithification of glassy tuff deposits that crop out along the Gulf of Naples (see pp. 26–27, Passages 14, 16), and Pliny emphasizes the use of pyroclastic rock, as from Cumae, in the maritime concretes.

***7.2.2. Volcanic provenance of the tuff* caementa.** Vitruvius (*De arch.* 2.6.1, pp. 17–19) described the volcanic origin of *tofus*, or volcanic tuff, "in the vicinity of Baiae and the territory of the municipalities around Mount Vesuvius" that is produced through "the movement of fiercely hot fire and vapour through fissures deep under the mountain and land."

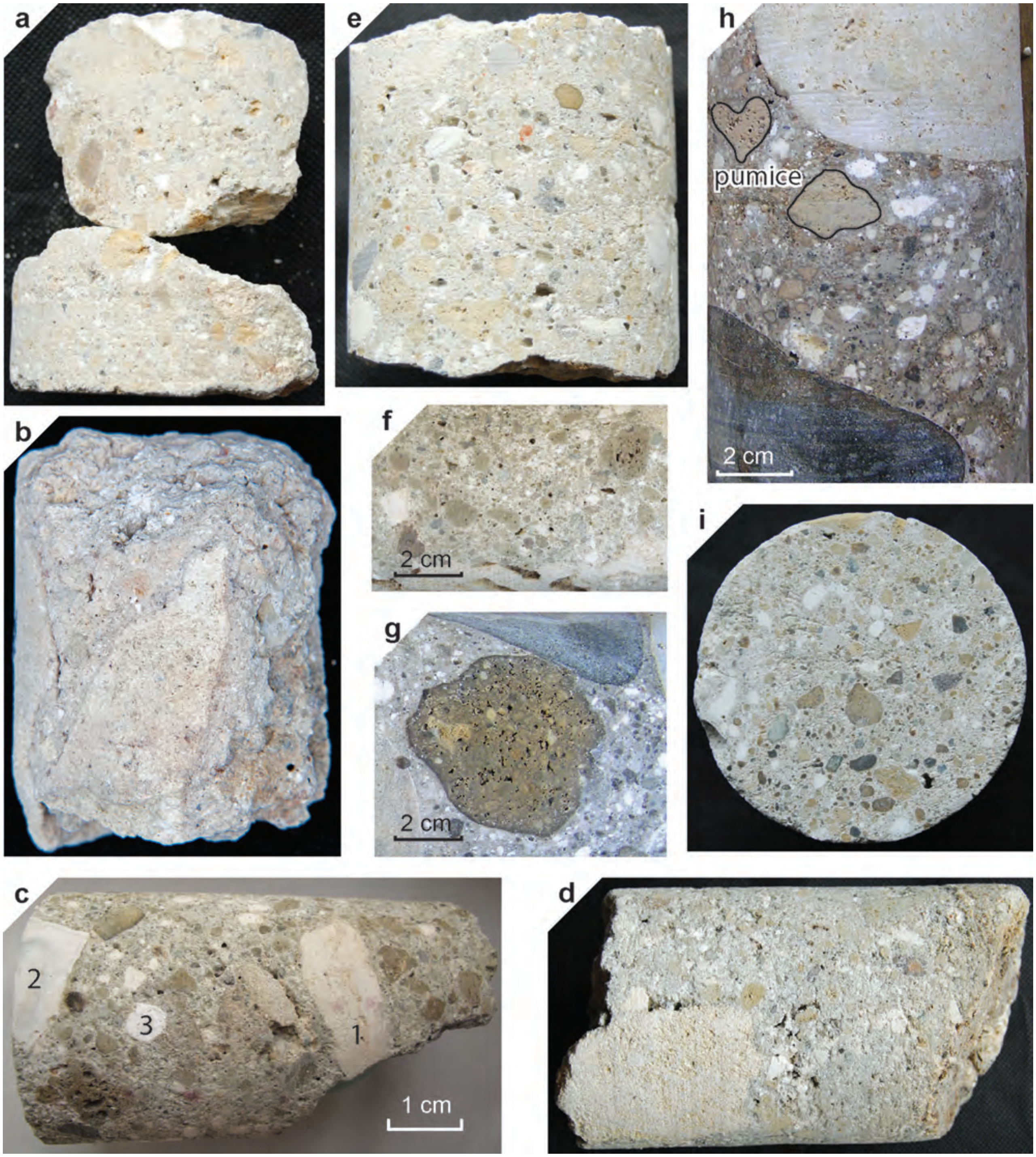


*Fig. 7.8. Photographs of the ancient maritime concretes of Egnazia and Eastern Mediterranean harbour structures. a. Egnazia (EGN.2008.02), mortar with pale orangish-gray pumiceous pozzolan (C. Brandon). b. Chersonesos (CHR.2007.02), concrete with fossiliferous limestone* caementa *and porous mortar with pale yellowish-gray pumice (C. Hagen). c. Caesarea (CAE.2005.05), mortar with various calcareous clasts and grayish-green pumice, and fragments of calcarenite (1), a hardened clot of lime putty (2), and relict lime clasts (3). d. Caesarea (CAE.2005.01), concrete with calcareous sandstone* caementa *and voids at the interface with a mortar that has pale yellowish gray pumice (C. Brandon). e. Caesarea (CAE.2005.02), mortar with pale yellowish-gray pumice (C. Brandon). f. (Caesarea (CAE.2005.05), mortar with greenish-gray pumice. g. Pompeiopolis (POM.2009.02), concrete with pumiceous tuff and rounded river cobble* caementa *(G. Vola). h. Pompeiopolis (POM.2009.02), concrete with river cobble* caementa *and mortar with yellowish-gray pumice (G. Vola). i. Alexandria (ALE.07.03), mortar with pale yellowish-gray pumice (C. Brandon).*

The Neapolitan Yellow Tuff is the product of a voluminous Campi Flegrei eruption about 15,000 years ago that produced a central caldera that is now partially submerged beneath the Bay of Pozzuoli (Orsi *et al.* 1996). The Bacoli Tuff erupted from Bacoli volcano about 8,600 years ago (Fedele *et al.* 2011). This is a volcanic edifice that can be classified as an ash ring near Bacoli and Fondi di Baia (Figs. 7.2, 7.7). Both deposits contain alkali-rich volcanic glass with trachytic compositions, as large lapilli to fine ash-sized frothy pumice particles. The alteration of the volcanic glass on the ground surface of the Campi Flegrei volcanic district produced natural zeolite minerals, and conferred a characteristic pale yellow colour to deposits of both the unconsolidated ash and the lithified tuff. The degree of lithification can vary from loose ash to compact tuff over a scale of tens of metres in some locations (de' Gennaro *et al.* 2000). In these zones, Roman builders could have quarried ash for mortar pozzolan and tuff for decimetre-sized coarse aggregate from the same site. The poorly consolidated Bacoli Tuff and Neapolitan Yellow Tuff have excellent pozzolanic reactivity; the zeolites and volcanic glass react with hydrated lime to form various stable cementitious hydrates with calcium-aluminium-silicate compositions (Sersale and Orsini 1969; Massazza and Costa 1979).

To constrain the volcanic provenance of the tuff components of the ancient maritime concretes the results of trace element and mineralogical analyses of powdered specimens of tuff *caementa* are compared with new and previously published analyses of geological specimens (Fig. 7.10; Tables A4.1, A4.2). The relative abundances of incompatible, immobile trace elements have been employed successfully as geochemical signatures of pyroclastic rocks in numerous archaeological provenance studies. Steinhauser *et al.* (2010), for example, used Europium/Thorium (Eu/Th) and Barium/Tantalum (Ba/Ta) ratios in pumice glass shards to distinguish among eastern Mediterranean pumice deposits in the North Sinai desert. Zirconium/Ytrium (Zr/Y) and Niobium/Ytrium (Nb/Y) ratios have been shown to be accurate indicators of eruptive provenance in the central Italian volcanic districts (Marra *et al.* 2010). Here, Zr/Y, Nb/Y, Eu/Th, Ba/Ta, Ta/Th and Lanthamun/Ytterbium (La/Yb) ratios in powdered tuff specimens are used to describe whole rock *caementa* compositions in the sea-water concretes (Figs. 7.10–7.13). In particular, determinations of the composition of the pumiceous tuff quarried at Bacoli (Fig. 7.7) for the 2004 experimental reproduction of the ancient concrete at Brindisi (see Chapter 5), with primary sanidine, and authigenic analcite, phillipsite and chabazite, provide a useful reference. Specimens BRI.2005.02.T1 and BRI.2006.01.T1 are the coarse aggregate of the experimental concrete block (Figs. A3.45–47), drilled one and two years after installation, respectively. It should be noted that establishing volcanic provenance from trace element ratios in whole rock tuff samples is problematic, since the tuff is composed of variable proportions of extraneous lithic components, such as lavas and limestone, as well as juvenile components of the magmatic portion, represented by pumices and scoriae. The chemical data from the tuff *caementa* are integrated with mineralogical and petrographic studies to provide qualitative information regarding volcanic provenance.

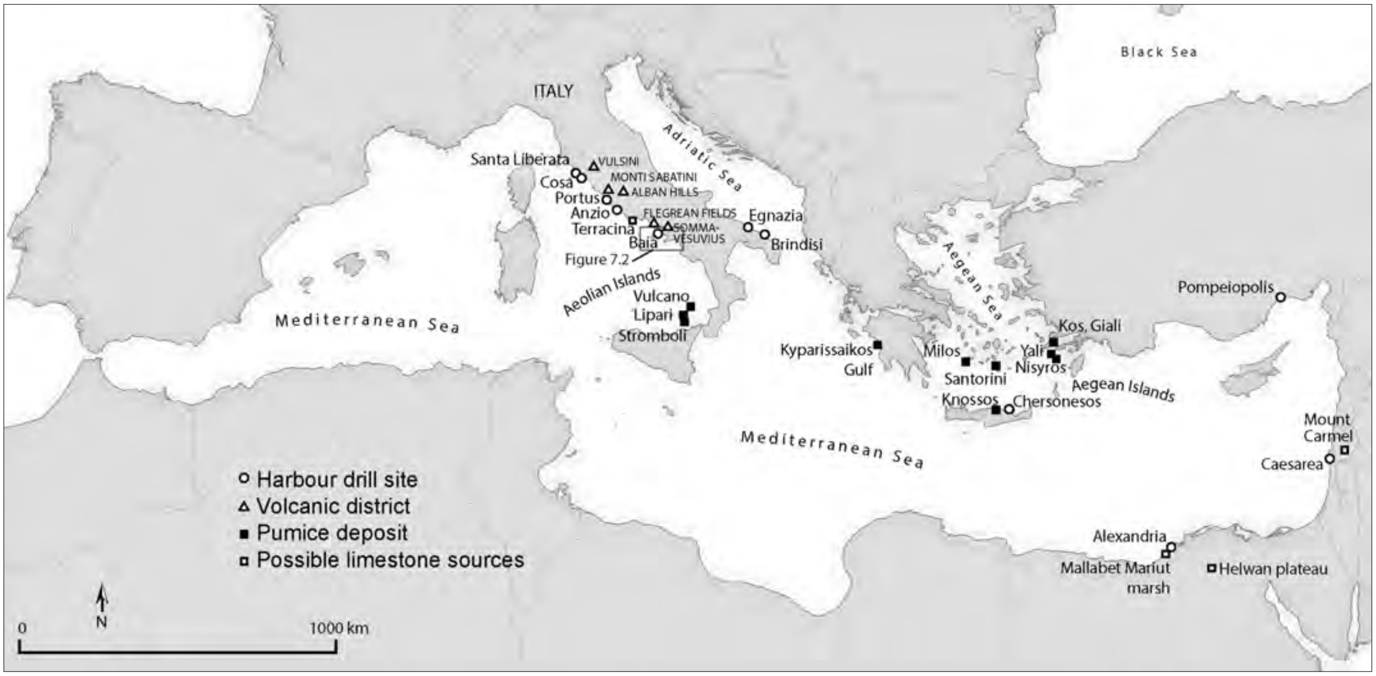


*Fig. 7.9. Map showing locations of Mediterranean volcanic districts, pumice deposits and possible limestone sources described in the text.*

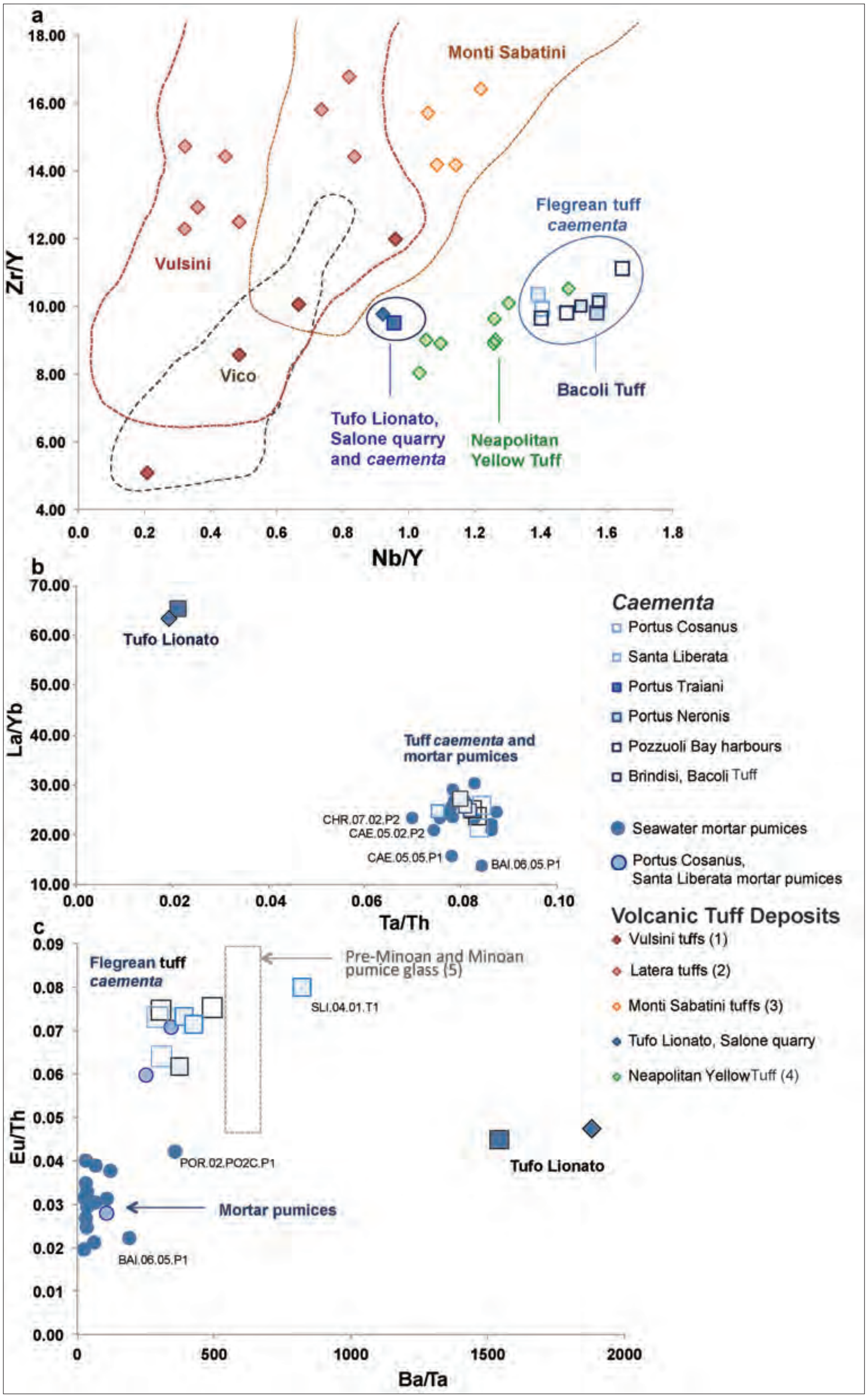


*Fig. 7.10. Trace element studies of volcanic tuff* caementa *in the maritime concretes and the Bacoli Tuff* caementa *in the 2004 Brindisi concrete reproduction (Table A4.2). a. Zr/Y and Nb/Y ratios, compared with glassy tuff deposits of the Vulsini, Vico, and Monti Sabatini volcanic districts (for generalized compositional fields, see Marra* et al. *2013b), Tufo Lionato (this study), and the Neapolitan Yellow Tuff (Orsi* et al. *1992). b. Eu/Th and Ba/Th ratios. c. La/Yb and Ta/Th ratios of all specimens of volcanic tuff* caementa *and pumice clasts. (1) Parker 1989; (2) Turbeville 1993; (3) Lancaster* et al. *2011; (4) Orsi* et al. *1992; (5) Steinhauser* et al. *2010.*

*Portus Cosanus and Santa Liberata harbour structures.* Trigila (1987: 313–14) gives petrographic descriptions of the tuff *caementa* of the Portus Cosanus concrete from Pier 3 and the Spring House platform (Figs. 4.10, 8.29–30): yellow pumice fragments are enclosed in an altered vitric matrix composed of zeolite (mainly phillipsite and chabazite), calcite and clay minerals, and the primary volcanic crystal assemblage is sanidine, plagioclase feldspar (labradorite ((Ca, Na)(Al, $Si)_4O_8$)), magnetite, clinopyroxene, and apatite. It is suggested that the *caementa* may come from pumiceous yellow tuff deposits near Lago Bolsena in the Vulsini volcanic district (1987: 314), about 60 km east-northeast of the harbour site (Fig. 7.7), which have been used as building stone since Etruscan times (Ciccioli *et al.* 2009). These pyroclastic products, including the Pitigliano tuff, contain leucite, a potassic silicate mineral ($KAlSi_2O_6$),which is present in lava and tuff lithic fragments and, also, in pumice fragments (Trigila *et al.* 1971; Parker 1989; Turbeville 1993). Leucite is not present, however, in the Portus Cosanus and Santa Liberata tuff *caementa* examined in this study (Table A4.1).

Yellow grey pumiceous tuffs also occur throughout the Monti Sabatini volcanic district, about 90 km southeast of the Portus Cosanus and Santa Liberata harbour sites. These rocks contain sanidine and clinopyroxene crystals, like the Campi Flegrei tuffs, but also abundant leucite and its sodic replacement, analcite (Nappi *et al.* 1979; Jackson *et al.* 2005). Leucite has not been detected in any of the tuff *caementa* of the maritime concretes, however, with the exception of Tufo Lionato *caementa* from the Alban Hills volcanic district in the Portus Traiani and Portus Claudius concretes (Figs. 7.5, 7.6). The absence of leucite suggests that the tuff *caementa* did not come from the Monti Sabatini volcanic district.

By contrast, the mineral assemblage of sanidine, plagioclase, and zeolite (analcite, phillipsite, and chabasite) in numerous tuff *caementa* specimens from Santa Liberata concretes are quite similar to Flegrean tuffs (de' Gennaro *et al.* 2000) (Table A4.1). Furthermore, Zr/Y and Nb/Y trace element ratios of the Portus Cosanus specimen (PCO.2003.04.T1) from the *Pila* 1.5 structure, the Spring House platform structure (specimen PCO.SH.1), and the Santa Liberata specimen (SLI.2004.01.T1) from the *Pila* 2 structure at Santa Liberata (Fig. 4.17) fall very close to the compositional field of the Bacoli Tuff, quarried at Bacoli for the 2004 Brindisi concrete reproduction (Fig. 7.10a), as do Eu/Th, Ba/Ta, La/Yb, and Ta/Th ratios (Fig. 7.10b, c). Overall, it seems that at least some of the compositions of the tuff *caementa* in the Portus Cosanus and Santa Liberata harbour structures best fit a Flegrean provenance. The source of the mafic igneous rock clasts in some of the *pilae* structures (cores PCO.2002.02, PCO.2002.05), however, are of great interest. Mafic rocks are quite rare in the Campi Flegrei volcanic district, and these *caementa* likely have a different volcanic origin.

*Portus Claudius and Portus Traiani harbour structures.* The *caementa* of the Portus Claudius and Portus Traiani concretes have a very distinctive fabric. Leucite, analcite, and clinopyroxene are the predominant crystal fragments; there is no sanidine (Table A4.1). Moderate to light brown palagonitic glass forms a more coarse grained altered vitric matrix, and there are common lava lithic fragments. The pyroclastic fabric in thin section and the mineralogical composition of a specimen of tuff *caementa* (PTR.2002.02.T1) from the Portus Traiani Severan warehouse structure (Fig. 4.1) is quite similar to Tufo Lionato from the Salone quarry along the Aniene River, about 10 km northeast of Rome (Jackson *et al.* 2005) (Figs. 7.4b, c, 7.10a; Table A4.1). Immobile element ratios of Zr/Y and NbY (Fig. 7.10a), Ba/Ta and Eu/Th (Fig. 7.10b), and Ta/Th and La/Yb (Fig. 7.10c) in both specimens are very different from all the other pyroclastic rock and pumice specimens analyzed from the maritime concretes. Builders in Rome had centuries of experience working with Tufo Lionato (Jackson and Marra 2006); Vitruvius described it as a soft building stone termed *rubrum*, and recorded its use as both dimension stone and as *caementa* in concrete structures on land (*De arch.* 2.7.1–5). Builders evidently considered it satisfactory for the Portus harbour concretes in the first and early second century. Tufo Lionato does not occur in any other of the ROMACONS drill cores.

*Portus Neronis.* The Portus Neronis concrete has few tuff *caementa*, but a greyish-yellow pumiceous tuff specimen (ANZ.2002.01.T1) near the base of the core is composed of altered fine ash, and a vitric-crystal matrix surrounds abundant lapilli-sized pumice clasts with phillipsite. The mineral assemblage is phillipsite, sanidine, albite, illite, and no leucite (Table A4.3). These characteristics suggest Flegrean tuff. The trace element signatures are very close to those measured for the Bacoli Tuff (Fig. 7.10; Table A4.1, A4.2).

*Bay of Pozzuoli structures.* The tuff *caementa* specimens from concrete structures in the Bay of Pozzuoli have an altered vitric matrix of fine ash that surrounds abundant pumice clasts. The greyish-yellow, vitric-crystal tuff *caementa* specimens from the Baianus Sinus (BAI, 2006.03) and Portus Baianus (BAI.2006.02) drill cores in the Bay of Pozzuoli have illite, sanidine, and orthoclase crystals, and authigenic phillipsite, chabazite and analcite. The tuff *caementa* specimen of the Portus Iulius structure (BAI.2006.05) has sanidine and orthoclase (Table A4.1). The trace element compositions of whole rock specimens from the Baianus Sinus *pila* (BAI.2006.03.T1), and hand samples taken in the 1980s from a mole in a harbour structure at Pozzuoli (POZZ.01.T1) and the Roman baths at Baiae (BAI.02.T1), which were analyzed in 2002, cluster near those of the Bacoli Tuff (Figs. 7.10–12; Table A4.2).

*Summary.* The primary volcanic crystal assemblages and mortar fabrics of tuff *caementa* from the harbour concretes of the central Italian coast at Portus Cosanus, Santa Liberata, Portus Neronis, and Bay of Pozzuoli harbour structures resemble those of the Bacoli Tuff, as do qualitative, presumably immobile trace element compositions (Figs. 7.6, 7.7, 7.10). It seems possible that builders could have imported Flegrean tuff about 320 km northwards along the central Italian coast to the Tuscany harbour sites. These were some of the early maritime structures, constructed in mid-first century BC. Perhaps, in their efforts to ensure the permanence of the structures in the sea, builders used a proven formulation that could have been first developed in the Bay of Pozzuoli, based on observations recorded by Vitruvius and Seneca in first century BC (*cf.* pp. 17–19, 20–23, 25, Passages 7, 9, 14). When Pliny the Elder mentioned the importance of *caementa* quarried at Cumae (*HN* 35.166), he was likely referring to the widespread pyroclastic deposits in that area. Nevertheless, he wrote about 100 years after the construction of the Portus Cosanus and Santa Liberata maritime structures. Future analyses of the glass compositions of pumice clasts removed from these tuff *caementa* and those of the eastern Mediterranean harbour concretes should further elucidate their volcanic provenance.

***7.2.3. Pumiceous volcanic ash pozzolan.*** Petrographic, mineralogical and chemical studies of the harbour concrete fabrics in ports constructed over three centuries, from the first century BC through the second century AD, from Pozzuoli to Pompeiopolis, Egnazia to Alexandria, and Cosa to Caesarea (Fig. 7.9) indicate that the common pozzolanic ingredient in all the mortars is a substantial fraction of pumiceous volcanic ash: as pumiceous glass particles, crystal fragments, and bits of lava lithic fragments (Fig. 7.8). The pumice particles range in colour from pale yellowish grey to greyish-orange to greenish-grey (Figs. 7.6, 7.8). They have varying degrees of transformation to cementitious hydrates. Some relict pumices retain little glass and are filled with white accumulations of poorly crystalline and crystalline cementitious phases, while larger clasts, generally greater than 0.5 cm diameter, may retain some unreacted glass and relict natural zeolite, mainly phillipsite (Fig. 7.4).

Although the mortars of the harbour concretes along the central Italian coast contain a predominance of pumiceous volcanic ash pozzolan, they show local variations. The Portus Cosanus mortars, for example, also contain crystalline sands, mainly quartz, various feldspars, and mica (muscovite) which give the mortar a speckled appearance (Oleson *et al.* 2004). These were likely excavated locally from aeolian dune sands along the shoreline of the Ansedonia promontory (Signorini 1967; Pertusati *et al.* 2005). In addition, some of the Portus Cosanus mortars contain traces of leucite and analcite. The origins of these crystals remain unknown: they could be derived from the shoreline sands or from an, as yet, unidentified volcanic ash pozzolan. Certain Santa Liberata mortars contain crushed ceramic fragments, in addition to particles of greyish yellow pumiceous tuff (Vola *et al.* 2011a). The Portus Traiani concretes contain a small proportion of scoriaceous volcanic sands (Figs. 7.5, 7.6c). These have the characteristic textures and mineral assemblage of the Pozzolane Rosse pyroclastic flow (Jackson *et al.* 2010), erupted from nearby Alban Hills volcano (Fig. 7.7, Table A4.1), but they could have been excavated from alluvial deposits near the harbour construction sites. The mortar pozzolan of the Portus Neronis concrete near Anzio, and the Portus Baianus and Baianus Sinus concretes in the Bay of Pozzuoli, is pale yellowish-grey and greyish-orange pumiceous ash. The mortar of the Portus Iulius structure has both pale greyish-orange and greyish-green glassy pumices. Farther from Naples, pumiceous ash predominates (Fig. 7.8), but variations occur, mainly as the addition of ceramic fragments, as in the Egnazia maritime mortars; as particles of dolomitic limestone and *cocciopesto* ceramic in the Chersonesos mortars (Vola *et al.* 2011b); as a small proportion of travertine and *cocciopesto* particles in the Pompeiopolis mortars (Stanislao *et al.* 2011); as calcareous sandstone particles in the Caesarea mortars (Vola *et al.* 2011a); and as limestone particles in the Alexandria mortars. In the mortars of the concrete structures at Pompeiopolis, Stanislao *et al.* (2011) found that compositions of clinopyroxene crystals fall within the range of those from Neapolitan Yellow Tuff deposits in the Campi Flegrei volcanic district.

***7.2.4. Volcanic provenance of the pumices.*** Pumiceous volcanic ash is the predominant component of all the ancient maritime mortars. Vitruvius' comments in first century BC and Pliny's comments in first century AD regarding the geographical origin of *pulvis* as from the volcanic districts of the Gulf of Naples suggest the possibility that the pumiceous ash in harbour concretes constructed in the first and second century AD far distant from Naples might also be derived from this area. Only at Chersonesos harbour, on Crete, do pumice deposits occur nearby, so every other harbour installation, with the exception of those in the Bay of Pozzuoli and the Tiber river at Ostia required the shipment of large volumes of volcanic ash to the construction site.

Passages 5.12.2–3 and 2.6.1 from *De architectura*, provide the most specific information about excavation sites for *pulvis* in first century BC (pp. 17–19, 20–23, Passages 7, 9). Vitruvius first describes this in a broad statement, "Powder (*pulvis*) is to be brought from the region that runs from Cumae to the promontory of Minerva" (5.12.2–3), and he then refines this to "a variety of powder (*pulvis*) … naturally effects an admirable result. It originates in the vicinity of Baiae and the territory of the municipalities around Mount Vesuvius" (2.6.1). Recent analytical investigations have validated Vitruvius' comments on diverse geotechnical topics, using geological and engineering principles and experimental tests (Jackson *et al.* 2005, 2010, 2011; Jackson and Kosso 2013), so it is possible that his statements on the geographic provenance of *pulvis* are correct, as well.

Vitruvius' broad statement (*De arch.* 5.12.2) refers to the entire Gulf of Naples from modern Cumae to the Sorrentine peninsula, and his more specific statement refers to the area that is covered by Pleistocene and Quaternary pyroclastic rocks erupted from both the Campi Flegrei and Somma-Vesuvius volcanic districts (Fig. 7.2; for a summary of volcanism in the Gulf of Naples and the Campanian plain, see De Vivo 2001). South of Mount Vesuvius, a succession of Mesozoic carbonate rocks, calcitic and dolomitic in composition, crops out near Stabia and continues southward along the Sorrentine peninsula (Fusi 1996). Vitruvius thus implies that *pulvis* was quarried from both Campi Flegrei eruptive deposits, "in the vicinity of Baiae," and Somma-Vesuvius eruptive deposits, from "the territory of the municipalities around Mount Vesuvius." Vitruvius also refers to *spongia sive pumex Pompeianus* ("the sponge-like rock called Pompeian pumice"; *De arch.* 2.6.2), which he compares to rocks at Mount Etna in Sicily and in Mysia (probably the Kula cinder cone field in Turkey; *De arch.* 2.6.3). These are dark coloured, mafic vesicular lavas and scoriae that do not occur in any of the maritime concretes drilled by ROMACONS. Recent studies, however, have identified dark scoriae *caementa* in the concrete vaults of monumental structures in Rome as Vesuvian in origin (Lancaster *et al.* 2011, Marra *et al.* 2013b). Some architectural concretes in Rome also contain light coloured pumice in their mortars. Certain bulk pumice specimens, separated from the mortars of the Forum of Caesar (46 to 44 BC), the Basilica Ulpia of the Forum of Trajan (about AD 105), and the Great Hall of the Markets of Trajan (about AD 105) plot in the field of Monti Sabatini compositions (Fig. 7.11) (Lancaster *et al.* 2011, Marra *et al.* 2013). A grey Baths of Diocletian (AD 298 to 306) pumice specimen has been interpreted as Flegrean in origin (Lancaster *et al.* 2010; Marra *et al.* 2013b) (Fig. 7.12). Other specimens, from the Colosseum (AD 70 to 79) and the Forum of Trajan, plot in the field designated as the Post-Campanian Ignimbrite from the Camaldoli della Torre drill core on Mount Vesuvius (Lancaster *et al.* 2011, Marra *et al.* 2013b) (Fig. 7.13).

It seems, therefore, important to clarify whether the pumiceous ash of the first century BC maritime concretes to which Vitruvius presumably refers – that is, structures at Portus Cosanus, Santa Liberata, and the Bay of Pozzuoli – comes from the Gulf of Naples and whether a Campi Flegrei or Somma-Vesuvius source could be identified. If so, did builders continue to use these materials in constructions of the first and second centuries, more than 2,000 kilometres distant from the Gulf of Naples? Or, alternatively, did they employ pozzolanic ash from the numerous pumiceous deposits that exist throughout the Mediterranean region? Romans were surely familiar with these materials, which form both primary volcanic deposits and sedimentary tsunami deposits associated with the pre-historic eruption of Thera, or Santorini, in the Aegean Islands (McCoy and Heiken 2000) (Fig. 7.9).

The crystal assemblages of the pumices (Table A4.1) and concentrations of presumably immobile trace elements in the larger, less-reacted pumice clasts removed from the mortars (Table A4.2) should reflect the mineralogical and chemical signature of their source magma and, thus, provide a qualitative assessment of volcanic provenance, when compared with published analyses of bulk geologic specimens. In Figure 7.11, the results of geochemical analyses of 17 pumice specimens for Zr/Y and Nb/Y (Table A4.2) are compared with analyses of pumices, as powdered specimens of glass and crystals, reported in the volcanological literature for the Campi Flegrei and Somma-Vesuvius volcanic districts, the Monti Sabatini volcanic district north of Rome, and Aeolian and Aegean Island deposits. These are primary eruptive deposits that Romans could have excavated to obtain substantial quantities of pumiceous pozzolan, and not distal airfall deposits of fine glass shards. Overall, the bulk compositions of the pumices extracted from the sea-water mortars cluster around a range of La/Yb=15–33 and Ta/Th=0.07–0.09 (Fig. 7.10b); these values fall in the range of Gulf of Naples pumice compositions (Figs. 7.12–13). The Eu/Th and Ba/Ta glass compositions of the Santorini Minoan and pre-Minoan pumices, and Gialli pumice in north Sinai, Egypt provide a useful reference for eastern Mediterranean pumice sources (Sterba *et al.* 2009; Steinhauser *et al.* 2010). The glass of those pumices have Eu/Th=0.4–0.13, and Ba/Ta=450–725 (Fig. 7.10c) but these cannot be directly compared with the sea-water mortar pumice specimens, which also contain volcanic crystals and authigenic zeolite crystals.

*Overview of pumice trace element compositions.* It is most instructive to begin with a comparison of Zr/Y and Nb/Y ratios of the maritime mortar pumice specimens and pumice from deposits far beyond the Gulf of Naples (Fig. 7.11). Aegean Island pumices mainly have siliceous rhyolitic or dacitic compositions. The pumice erupted by Thera volcano on Santorini Island (Fig. 7.9) in the Lower Pumice 1 and 2, Cape Riva, and Minoan eruptions have plagioclase, orthopyroxene, clinopyroxene, magnetite, and ilmenite phenocrysts, in order of abundance. The bulk compositions of pumice from the Minoan deposits on Santorini have Nb/Y=0.03–0.3 and Zr/Y=3.74–6.53 (Vinci *et al.* 1984; Druitt *et al.* 1999). This mineral assemblage is very different from that of the mortar pumices, which have mainly sanidine phenocrysts and authigenic zeolite textures. The trace element ratios are very low, compared to the lowest value of Nb/Y=1.64 and Zr/Y=11.32, in a Santa Liberata specimen. Somewhat surprisingly, there seem to be no clear Minoan signatures in the pumice specimens extracted from the sea-water mortars. Certain pumices from the Monte Pilato rhyolitic tuff cone on Lipari in the Aeolian Islands (Daví *et al.* 2011) have Zr/Y and Nb/Y that fall near those of two pumice specimens from Egnazia harbour concrete and one specimen from Pompeiopolis harbour concrete. Monte Pilato erupted in AD 776, however, many centuries after the harbours were constructed. The much older Pomiciazzo siliceous pumice from Lipari Island (Giocada *et al.* 2003) contains plagioclase feldspar (oligoclase), potassium feldspar, amphibole, zircon and apatite; neither the crystal assemblage nor the trace element ratios correlate well with the mortar pumices. Pumices from Vulcano in the Aeolian Islands (De Astis *et al.* 1997) have variable latite to rhyolite compositions, a crystal assemblage of plagioclase feldspar, clinopyroxene, potassium feldspar, magnetite, and olivine that does not fit with the mortar pumice mineral assemblage; Nb/Y and Zr/Y ratios are far too low. At Stromboli, vesicular pumices show syneruptive intermingling of magma (Bertagnini *et al.* 2011); they contain diopside and

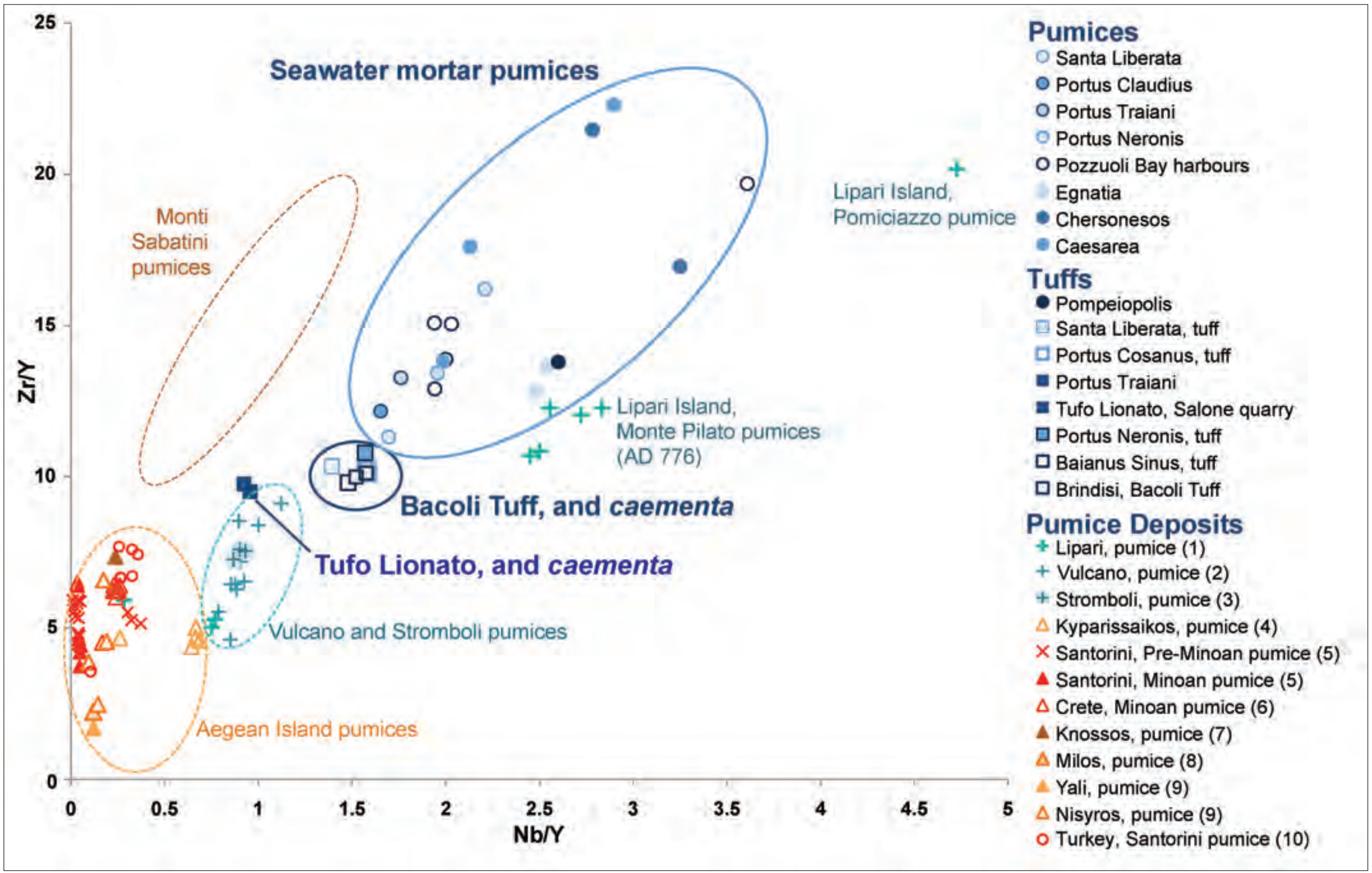


*Fig. 7.11.Trace element studies, Zr/Y and Nb/Y, of pumice clasts from the volcanic ash pozzolan of the ancient maritime mortars compared with Mediterranean pumice deposits beyond the Bay of Naples (Fig. 7.9; Table A4.2).* **Monti Sabatini** *deposits: Lancaster* et al. *2011; Marra* et al. *2013b;* **Aeolian Islands** *deposits: (1) Lipari pumice, Gioncada* et al. *2003 (Pomiciazzo pumice); Daví* et al. *2011 (Monte Pilato pumice); (2) Vulcano pumice, De Astis* et al. *1997; (3) Stromboli pumice, Bertagnini and Landi 1996;* **Aegean Islands** *deposits: (4) Kyparissiakos Gulf pumice, Ionian Sea, Bathrellos* et al. *2009; (5) Santorini, Thera pumice, Pre-Minoan and Minoan eruptions, Druitt* et al. *1999; (6) Minoan pumice, Vinci* et al. *1984; (7) Knossos pumice, Warren and Pulchelt 1990; (8) Milos pumice, Fytikas* et al. *1996; (9) Yali pumice, Margari* et al. *2007 (see also Allen and McPhie 2000); (9) Nisyros pumice, Margari* et al. *2007 (see also Francalanci* et al. *1995); (10) Santorini air fall deposits at Gölhisar Gölü, Turkey, pumice glass, Eastwood* et al. *1999.*

olivine crystals, and Nb/Y and Zr/Y ratios are far lower than those of the pumices in the maritime mortars. Pumices of the Monti Sabatini volcanic district (Fig. 7.7) have Nb/Y ratios that are consistently lower than those in the maritime mortars and, in addition, they contain leucite crystals (Lancaster *et al.* 2011; Marra *et al*. 2011, 2013). No such pumices have been detected in the ancient maritime mortars. In Figures 7.12–13, the Nb/Y, Zr/Y, La/Yb, and Nb/Zr ratios of the maritime mortar pumices are compared with the numerous pumice deposits that occur within the complex interlayered stratigraphy of the Campi Flegrei and Somma-Vesuvius volcanic districts to provide further insights into their possible eruptive sources.

*Comparisons with Campi Flegrei eruptive units.* Figure 7.12a illustrates the Zr/Y and Nb/Y compositions of bulk pumice samples from the very large number of pumice deposits that occur in the Campi Flegrei volcanic district. Recent deposits, erupted over the past 15,000 years, are listed from youngest to oldest in the comprehensive chronostratigraphic framework of Fedele *et al.* (2011). The pumices of the central Italian coast harbour concretes are greyish-orange (10YR5/4 to 8/4), with occasional sanidine crystals and common authigenic zeolite (phillipsite, chabazite, and analcite) and clay mineral (mainly halloysite) (Table A4.1). Their compositions, and that of a greyish-orange Caesarea specimen (CAE-1983.P1), fall within a well-constrained range of Nb/Y=1.6–2.1 and Zr/Y=11–15, with the exception of one Portus Neronis specimen (ANZ.02.01.P1) (Table A4.2). A well-constrained range of La/Yb=20–24 and Nb/Zr=11–15 covers the compositions of all these specimens (Fig. 7.12b): from Portus Cosanus, Santa Liberata, Portus Claudius, Portus Traiani, Portus Neronis, Portus Baianus, Baianus Sinus, one Portus Iulius specimen, and the Caesarea specimen. These compositional ranges fall well within the field of the entire Campi Flegrei volcanic

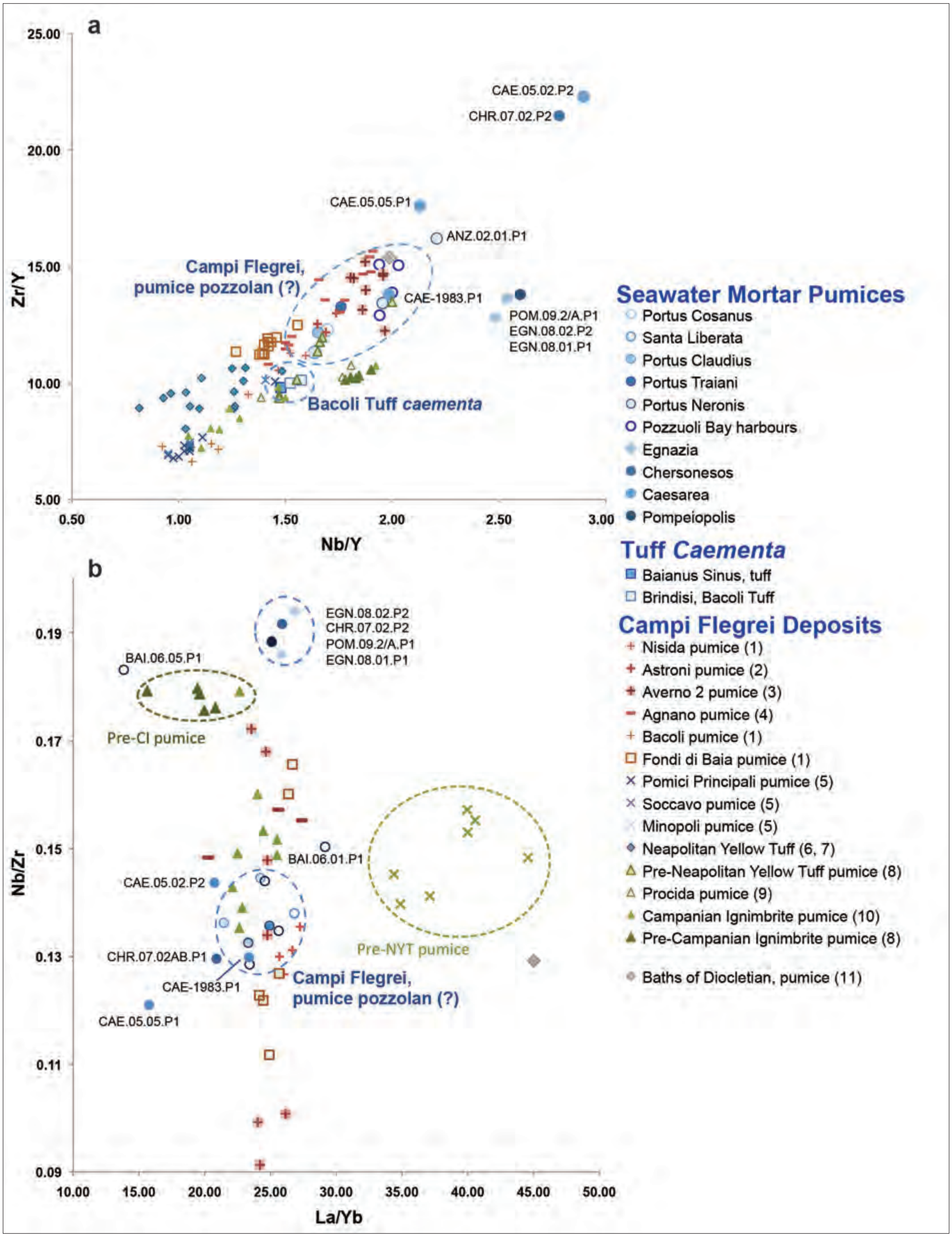


*Fig. 7.12. Trace element studies of pumice clasts from the volcanic ash pozzolan of the ancient maritime mortars compared with Campi Flegrei pumice deposits (Fig. 7.2; Table A4.2). Post Neapolitan Yellow Tuff volcanic chronostratigraphy from Fedele* et al. *2011. a. Zr/Y and Nb/Y. b. Nb/Zr and La/Yb. (1) Fedele* et al. *2011; (2) Tonarini* et al. *2009; (3) Di Vito* et al. *2011; 4) di Vita* et al. *1999; (5) Lustrino* et al. *2002; (6) Orsi* et al. *1992; (7) Scarpati* et al. *1993; (8) Pabst* et al. *2008; (9) De Astis* et al. *2004; (10) Civetta* et al. *1991; (11) Lancaster* et al. *2011; Marra* et al. *2013b.*

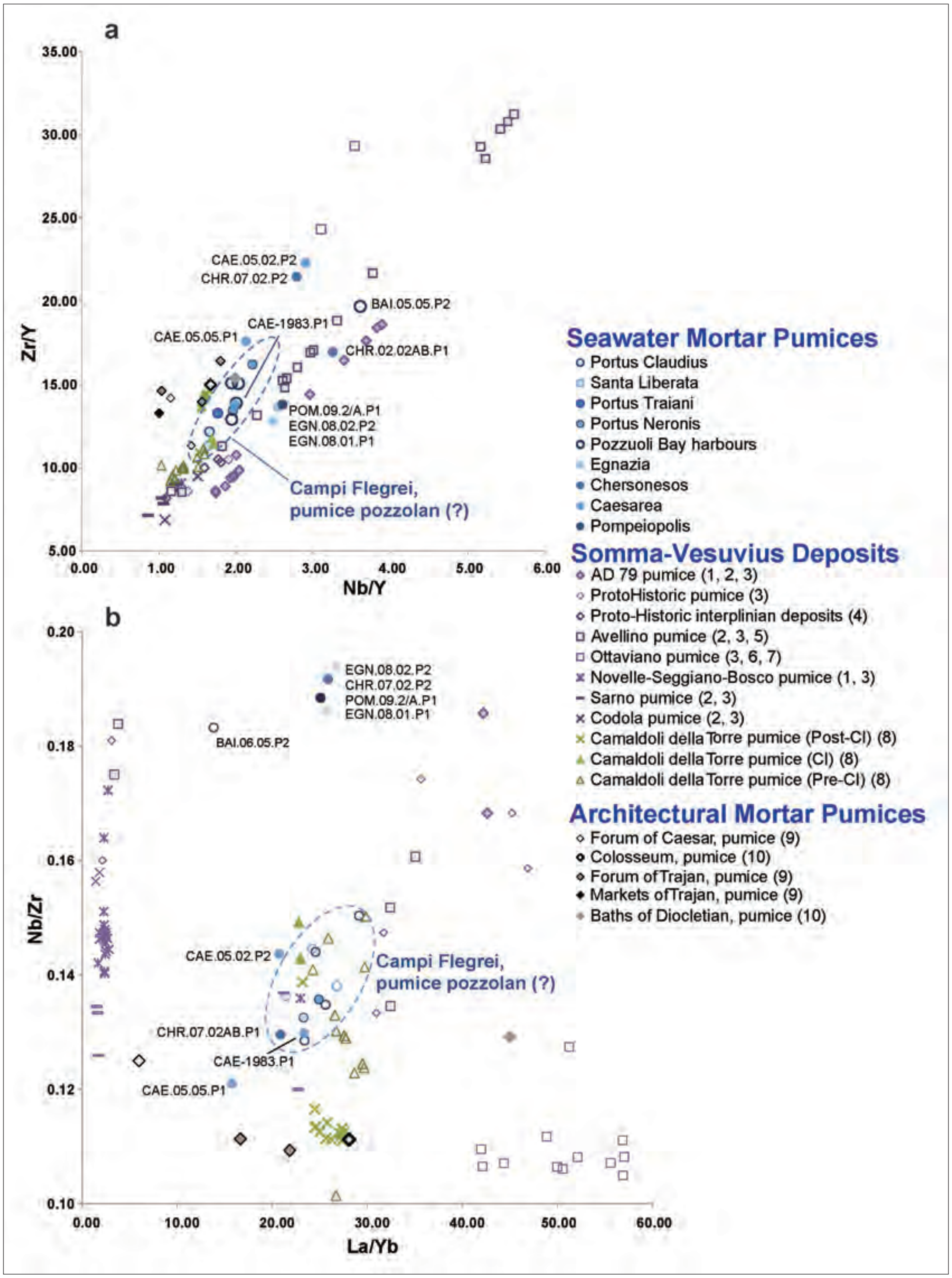


*Fig. 7.13. Trace element studies of pumice clasts from the volcanic ash pozzolan of the ancient maritime mortars compared with Somma-Vesuvius pumice deposits (Fig. 7.2; Table A4.2). Volcanic chronostratigraphy from Di Renzo 2007. a. Zr/Y and Nb/Y. b. Nb/Zr and La/Yb. AD 79 pumice: (1) Cioni* et al. *1995; (2) Ayuso* et al. *1998; (3) Paone* et al. *2006; Piochi* et al. *2006; Protohistoric pumices: (3) Paone* et al. *2006; (4) Somma* et al. *2001; Avellino pumice: (2) Ayuso* et al. *1998; (3) Paone* et al. *2006; (5) Sulpizio* et al. *2010; Ottaviano pumice: (3) Paone* et al. *2006; (6) Piochi* et al. *2006; (7)Aulinas* et al. *2008; Novelle-Seggiano-Bosco pumice: (1) Cioni* et al. *2003; (3) Paone* et al. *2006; Sarno pumice: (2) Ayuso* et al. *1998; (3) Paone* et al. *2006; Codola pumice: (2) Ayuso* et al. *1998; (3) Paone* et al. *2006; Camaldoli della Torre pumice (CI): (8) Di Renzo* et al. *2007; Camaldoli della Torre pumice (Post-CI): (8) Di Renzo* et al. *2007; Camaldoli della Torre pumice (Pre-CI): (8) Di Renzo* et al. *2007; Pumices, Roman architectural mortars: (9) Marra* et al. *2013b; (10) Lancaster* et al. *2011.*

district. This, and the uniform crystal assemblages suggest that these pumices could possibly have been excavated from Campi Flegrei deposits, but the eruptive units are not clear. It is possible that the photograph of the Santa Liberata concrete that shows tuff *caementa* near a large mortar pumice (Fig. 7.6a) may represent both *tofus* and *pulvis* from the vicinity of Baiae, as Vitruvius described.

*Comparisons with Somma-Vesuvius eruptive units.* The volcanic provenance of pumice specimens with Zr/Y>16 and Nb/Y>2 are quite difficult to decipher. These are compared with compositions of Vesuvian pumice deposits, listed here in the chronological succession of Di Renzo *et al.* (2007) (Fig. 7.13). As regards the Sebastos harbour concretes from Caesarea, the CAE.1983.P1 specimen falls in the Campi Flegrei field (Fig. 7.12), while the CAE.2005.02.P2 and CAE.2005.05.P1 specimens are outliers in Zr/Y, Nb/Y, Nb/Zr, and La/Yb. The pale yellowish- to greyish-orange (10YR 7/6) Caesarea CAE.2005.02.P2 specimen (Fig. 7.8e) has sanidine crystals and authigenic calcite, phillipsite, and analcite (Table A4.1), but no clear correlation with Nb/Y and Zr/Y compositions of Vesuvian pumices reported in the volcanological literature (Fig. 7.13a). The La/Yb and Nb/Zr values fall close to the Campi Flegrei compositional field, as well as few high La/Yb values reported for the Vesuvian Sarno and Seggiari-Novelle pumices (Ayuso *et al.* 1998). In contrast, the greenish-grey (5GY 4/1) Caesarea CAE.2005.05.P1 specimen (Fig. 7.8c, f) has Nb/Y and Zr/Y close to the Campi Flegrei compositional field, but La/Yb and Nb/Zr lie between the compositions of Sarno pumices and those pumices designated as post-Campanian Ignimbrite from the Camaldoli della Torre borehole (di Renzo *et al*. 2007). Although these compositions fall in the overall Somma-Vesuvius and Campi Flegrei compositional field (Fig. 7.11), they show no close correlation with any single deposit. They most certainly do not come from the pyroclastic deposits of the Mount Carmel region to the east of the Sebastos harbour site (Fig. 7.9). These are basic rocks, rich in iron and magnesium, that contain xenoliths of garnet-bearing clinopyroxenite, a rare type of ultramafic inclusion associated with alkali basalts, as well as peridotite and olivine gabbro (Segev *et al.* 2003). No such rocks have been observed in the Caesarea concretes.

As regards the Egnazia, Chersonesos, and Pompeioplois harbour concretes in southern Italy, northern Crete, and southeastern Turkey, the pale yellowish-brown (10YR 6/3) EGN.2008.01.P1 Egnazia specimen, the pale orangish-grey (10YR8/4-7/4) EGN.2008.02.P2 Egnazia specimen (Fig. 7.8a), the light olive- or yellowish- grey (5Y6/1-7/1) POM.2009.2A.P1 Pompeiopolis specimen (Fig. 7.8g), and the pale yellowish-orange (10YR6/6-7/6) CHR.2007.02.P2 Chersonesos specimen (Fig. 7.8b) have a similar mineral assemblage (Table A4.1): primary sanidine and illite, with authigenic calcite, phillipsite, chabazite, and nontronite. Their trace element signatures, however, cannot be reconciled with specific Gulf of Naples eruptive units. The pale yellowish-orange (10YR6/6 to 7/6) Chersonesos specimen (CHR.2002.02AB.P1) has Zr/Y and Nb/Y close to certain Avellino and AD 79 pumices (Fig. 7.13b). The Nb/Zr and La/Yb ratios, however, land in the field of Campi Flegrei pumice compositions (Fig. 7.12b). In contrast, a group of two pumice specimens from Egnazia (EGN.2008.01.P1, EGN.2008.02.P1) and one Pompeiopolis specimen (POM.2009.2A.P1) fall within a compositional gap between the Avellino and AD 79 pumices in the Zr/Y, Nb/Y plot; these are joined by a Chersonesos specimen (CHR.2007.02.P2) in an open expanse of the Nb/Zr and La/Yb plot (Fig. 7.13a, b). A Portus Iulius specimen (BAI.2005.05.P2) with high Nb/Zr falls in this same area. The Egnazia harbour structures likely date to first century BC, and only the Chersonesos and Pompeiopolis concretes could possibly include the first century AD pumice deposits. Remarkably, none of these compositions approaches the trace element signatures or crystal compositions of the Aegean Island pumices (pp. 153–59). The pre-Minoan and Minoan pumice deposits from Thera volcano on Santorini have very low Nb/Y=0.02–0.3 and Zr/Y=4.5–6.4 and a mineral assemblage with predominant plagioclase and orthopyroxene (Vinci 1984; Druitt *et al.* 1999). Although air fall tephra from the Minoan eruption of Santorini were deposited on eastern Crete (Vitaliano and Vitaliano 1974), the compositions of the pumices in the concrete at Chersonesos harbour do not correlate well with those of the Thera eruptions, and it is possible that the pumiceous pozzolan may not derive from a local source.

The disparities among the presumably immobile trace element ratios of the bulk pumice specimens removed from the eastern Mediterranean harbour concretes could possibly be resolved through determinations of glass compositions in individual pumice clasts with electron microprobe analyses, similar to the analyses performed by Stanislao *et al.* (2011) on clinopyroxene in the Pompeiopolis mortars. Several Vesuvian pumice deposits have variable trace element ratios (Fig. 7.13; see also Mues-Schumacher (1994) and Kaneko *et al.* (2005) for variations in Nb/Zr in AD 79 pumice deposits at Boscoreale, Ottaviano, and Pompeii). These result, in part, from fine-scale mixing of magma. In the Avellino and AD 79 Plinian fall deposits, for example, there is intermingling of white phonolitic glass and grey tephritic-phonolitic glass with different isotopic compositions in pumice clasts (Civetta *et al.* 1991). Microscopy studies show that most pumice clasts in the maritime mortars now contain little unreacted volcanic glass and their primary petrographic features are obscured by abundant opaque cementitious hydrates (for example, Figs. 7.1c, 7.3d). Differential dissolution during pozzolanic reaction and long-term alteration in sea-water could skew trace element compositions to that of the residual glass and crystals. Since the trace element analyses are derived from 3 to 4 gram specimens comprised of many pumices, they may reflect those skewed compositions. Analyses of glass compositions of individual pumice clasts within the mortars could resolve these variations and, in addition, clarify whether a mortar sample might contain a mix of pumices from different deposits.

*Summary*. When compared with other Mediterranean pumice deposits, the mineral assemblages and trace element signatures of powdered pumice samples removed from the central Italian coast harbour mortars seem to be closest to Campi Flegrei pumice compositions (Fig. 7.11, 7.12). This includes structures constructed prior to or during Vitruvius' lifetime – at Portus Cosanus, Santa Liberata, and the Bay of Pozzuoli harbours – as well as specimens from Portus Claudius, Portus Traiani, Portus Neronis, and one Caesarea specimen. Pumiceous volcanic ash pozzolan with unequivocal Vesuvian trace element signatures has not been detected in the first century BC concretes drilled by ROMACONS, but could possibly have been used as pozzolan in other late Republican age maritime structures, given Vitruvius' accurate comments on other geotechnical topics.

The precise origins of the pumiceous pozzolan in the maritime concretes from Egnazia, Chersonesos, Caesarea, and Pompeiopolis are quite difficult to resolve. The specimens have a consistent mineralogical assemblage and a relatively close grouping of Eu/Th, Ba/Ta, La/Yb, and Th/Ta trace element ratios, overall (Fig. 7.10b, c). These do not correlate well with those of Monti Sabatini, Aegean Island and Aeolian Island pumice deposits (Fig. 7.11). Despite the compositional disparities among the trace element data for the bulk pumice specimens, it seems that their compositions fall in the overall compositional field of the Gulf of Naples volcanic districts. Given the very large quantities of pumiceous pozzolan employed in the large concrete installations, such as Caesarea (pp. 75–76), mixing of ash from different eruptive units by builders at excavation sites, shipyards, large-scale storage areas, and the harbour construction site could have been a common occurrence. If the pumices did originate in the Gulf of Naples, a most intriguing question remains: why would Romans have shipped thousands of metric tons of pumiceous volcanic ash to eastern Mediterranean harbour sites, when numerous pumice deposits exist in this area?

***7.2.5. Sources of lime.*** Some of the white inclusions scattered through the mortars of the harbour concretes are clearly recognizable as white, boxy particles of poorly-calcined limestone with intact macrofossils and calcium carbonate phases – calcite, vaterite, aragonite – identified through X-ray diffraction analyses (Table A4.1). Others, however, are dull white, opaque, inclusions with relatively smooth boundaries. Contrary to first appearances, these millimetre- to centimetre-sized particles are generally not simple bits of lime that have carbonated to form calcite. Instead, they are partially-dissolved relict lime clasts that are now composed of a core of Al-tobermorite crystals, a rare calcium-silicate-hydrate mineral, surrounded by a rim of poorly-crystalline calcium-aluminium-silicate-hydrate, the fundamental binding substance of the concrete (Figs. 7.1, 7.3). In addition to relict lime particles, small particles of limestone and calcareous grainstone are incorporated in the pumiceous ash-hydrated lime mortar mix of certain eastern Mediterranean harbour concretes – as at Chersonesos, Caesarea, and Alexandria.

As regards the limestone nodules in mortars of certain architectural concretes at Pompeii, note that these are not poorly-calcined lime but, rather, lithic fragments in pozzolanic ash produced by Plinian eruptions that ruptured the limestone edifice underlying Mount Vesuvius (Miriello *et al.* 2010). These nodules have not been identified in the maritime mortars. Some of these Pompeii mortars contain trace amounts of tobermorite as a cementitious phase.

***7.2.6. Limestone bedrock near harbour sites.*** The limestone that builders calcined in kilns to produce quicklime (CaO) for the maritime mortars undoubtedly had many sources but, as yet, these have not been carefully investigated. A brief list of possible geological occurrences of limestone near the harbour sites follows.

At Portus Cosanus and Santa Liberata in Tuscany, upper Triassic limestone and dolomitic limestone from outcrops near the harbour sites (Pertusati *et al.* 2005) could have been calcined on site (Oleson *et al.* 2004).

At Portus, near modern Ostia in the active Tiber River delta, there are no limestone occurrences. The Mesozoic-Cenozoic carbonate bedrock of the Monte Soratte and the Apennine foothills near Tivoli, 25 km northeast of Rome, produces a very pure lime, about 94 weight % CaO, as determined through laboratory calcination of specimens (Jackson *et al.* 2007). These indurated limestones (*silice*) have the very compact (*spissis*) and hard (*duriore*) texture that Vitruvius specified was best for mortars (*De arch.* 2.5.1; pp. 16–17, Passage 6). The lime used in the monumental concretes of Rome does seem to have been nearly pure calcium oxide, based on the compositions of relict particles in the ancient mortars and recent reproductions of these materials (Samuelli Ferretti 1997; Jackson *et al.* 2009; Brune *et al.* 2013). It was possibly calcined near the quarry sites, close to historic kilns and modern cement plants, and then transported about 30 km down the Aniene and Tiber Rivers to Rome. Based on examination of ancient texts, however, DeLaine (1995, 2001) suggests that lime calcined in Terracina fed construction demands in Rome from the third century BC to the fourth century AD. The lime would have been transported 125 km north along the coast to the Tiber River delta at Portus, and then upriver to the City. The second or third-century Roman grammarian Pomponius Porphyrio (*Commentum in Horati Sermones* 1.5. *pr.* 1, 26.1) comments that Terracina was given the epithet "white" (*candida*) because the mountain on which it was built "...does not consist of white stone, but of stone particularly suitable for burning lime. Therefore it seems to have been called 'white' from the lime." (...*non candida saxa habet, sed calci coquendae aptissima. Ergo a calce videtur candida dixisse*). The origin(s) of the lime for the Portus Claudius and Portus Traiani concretes thus remains unclear. Even if the limestone source rock is the same for both harbours, then the quality of the calcined lime product in the Portus Traiani mortars is far higher than that in the Portus Claudius mortars (Fig. 7.6): there, relict lime clasts are mainly fine grained and dissolved, while those at Portus Claudius have disparate particle sizes, and are frequently underburned, occurring as relict limestone, or overburned, occurring as bits of pseudocalcite (Jackson *et al.* 2012).

Pliocene-Holocene marine and continental sediments underlie the Anzio area (Mancini *et al.* 2008), and the southern reaches of the Alban Hills volcanic district form the coastal highlands above the harbour; no carbonate bedrock is exposed. Lime was surely imported to the Portus Neronis construction site, but the source remains unknown.

If lime for the Bay of Pozzuoli mortars had a source similar to that of the city of Pompeii, then it likely would have originated from various sites in the Sarno River valley (Lugli 1957: vol.1, pp. 379–85), since there is no limestone bedrock exposed within the Campi Flegrei and Somma-Vesuvius volcanic districts (Fig. 7.2). Lime kilns existed in the Monti Lattari at Nola and Nocera, and within the Sorrentine peninsula, as well as within the city itself (Giuliano 2010). Perhaps the lime for the Bay of Pozzuoli harbour concretes comes from these Mesozoic carbonate rocks (Fusi 1996), as well.

At Egnazia, lime for the mortar preparation was possibly calcined from the nearby Cretaceous carbonate rock succession, composed of limestones and dolomites. These are the "Calcare di Bari" that crop out a few kilometres inland from the ancient harbour site (Calia *et al.* 2011). The *caementa,* however*,* are mainly bioclastic packstone-grainstones, the local Pliocene-Pleistocene "Calcarenite di Gravina" formation, which was used as building stone throughout the city (Cassano 2009; Calia *et al.* 2011).

The rocks that crop out on the Chersonesos peninsula on the northern coast of Crete are middle to late Miocene marly limestone and sandy-and silty-marls, with abundant calcareous nanofossils, and occasional gypsum beds (Frydas and Bellas 2009). There is a general absence of information about calcination of limestone in ancient Crete, but the earthy character of the Chersonesos mortar (Fig. 7.8b) suggests a poorly calcined lime. This may derive from local marly limestone deposits. The mortar also includes nodules of poorly-calcined limestone and lignite particles (Vola *et al.* 2010, 2011c; Stanislao 2011), possibly from these same deposits.

At Sebastos, on the central coast of Israel, mortars of the sea-water concretes contain bits of the local eolianite calcareous sandstone, or *kurkar*, as well as relicts of fossiliferous marine limestone (Fig. 7.8c) (Vola *et al.* 2011a). The lime and poorly-calcined marine limestone fragments may come from Mid-Cretaceous limestone deposits that crop out about 3 km northeast of the harbour, near the source of the high aqueducts leading to Caesarea (Mart and Peregman 1996: 19). Here, a sequence of hard, massive to well-bedded, Mid-Cretaceous limestones and dolomites crop out in the Mount Carmel area, east of a series of Upper Cretaceous olivine basalt lava flows and deposits that are strongly offset by faults (Segev *et al.* 2003; 2009).

The Alexandria mortars contain particles of oolitic grainstone as aggregate, whose provenance remains unclear. The closest sources of marine limestone, however, are middle Eocene deposits exposed on the Mokattam and Helwan plateaus on the eastern bank of the Nile River valley, near Cairo, about 180 km south of the Alexandria harbour (Klitzsch *et al.* 1987), and the Alkoraymat area (Solan *et al.* 2010), about 300 km south of the harbour. It is not known whether lime was calcined at these sites, or at other Mediterranean sites, and then transported to the construction site, possibly as matured slaked lime.

This brief outline of limestone occurrences near the harbour sites is only a cursory overview of potential lime sources. Comprehensive petrographic, geochemical and mineralogical investigations are needed to clarify lime compositions and fabrics, and their possible geologic sources. Examination of the relict lime particles with petrographic and scanning electron microscopy suggests, however, that these are mainly relatively pure CaO, or "fat" limes, rather than argillaceous or siliceous "hydraulic" limes (Elsen *et al.* 2012), with the possible exception of the Chersonesos harbour mortars. Reaction of the hydrated lime with the pumiceous ash pozzolan present in all the mortars produced exceptionally durable aluminous cementitious hydrates, mainly Al-tobermorite and C-A-S-H (Fig. 7.3). The influence of residual MgO in lime derived from more or less dolomitic sources may have produced complex hydration reactions and magnesium bearing hydrates – as brucite, hydrotalcite, and gypsum – in association with relict lime clasts. Further research is needed to clarify these processes.

## 7.3. Concrete mix design and preparation

The ratios of lime and *pulvis* pozzolan that Vitruvius (*De arch.* 5.1.2–3) and Pliny (*HN* 36.174–76) recommended for maritime mortars were presumably recorded as volumetric proportions (pp. 20–23, 28, Passages 9, 18), and these have been cited extensively in the archaeological literature. Little is known, however, about the volumetric proportions of mortar and *caementa* in the maritime concretes. Here, their relative proportions exposed on the surfaces of the drill cores have been systematically recorded and translated to estimated volumetric ratios (pp. 160–61), Table 7.1). The volumetric proportions of raw materials in a typical maritime concrete, that of the Baianus Sinus drill core (BAI.06.03) from the Bay of Pozzuoli, are then translated to proportions by mass of *caementa*, pumiceous ash pozzolan, and lime (*calx*) in the original dry concrete mix (pp. 160–63, Table 7.2). Mass proportions, described in terms of the unit weights of the constituent concrete materials, provide new information for archaeological models evaluating shipping and trade in the ancient world, and for analytical models evaluating physical processes. Descriptions of the fine scale relict lime microstructures in the mortar fabrics provide clues to builders' procedures for preparing the quicklime, mixing the mortars, and hydrating the mortar mix in sea-water (pp. 163–66).

***7.3.1. Mortar to caementa ratios.*** Measurements of the ratio of mortar to *caementa* on the surfaces of twenty-six cores suggest that the ancient concretes have estimated volumetric ratios that fall between 36 to 83 volume % mortar to 17 to 64 volume % *caementa* (Table 7.1, Fig. 7.18a). Most of the measurements fall in a 60 to 40 mortar to *caementa* volumetric ratio, but this underestimates the coarse aggregate to some extent: 55 to 60 volume % mortar and 40 to 45 volume % *caementa* may be more accurate (pp. 161–63). The compositions of the central Italian coast harbour concretes mainly fall within this range, suggesting practised and consistent concrete installations with tuff *caementa*. The Alexandria concretes also show rather uniform compositions, 51 to 57 volume % mortar and 43 to 49 *caementa*, mainly oolitic limestone. The Caesarea concretes, by contrast, show very heterogeneous compositions, 17 to 41 volume % mortar and 59 to 83 volume % *caementa*, mainly calcareous sandstone. This may be related to difficulties of installing the concrete mix in the open sea (pp. 275–79). Overall, the cores record very little gravitational settling of *caementa* within the uncured mix; the fragments are enclosed by mortar to a greater-or-lesser degree, and there is no apparent stratification produced by sinking of *caementa* within the forms. Builders evidently compacted the concretes to remove large interfacial void spaces, but their methods for doing so remain unclear.

***7.3.2. Lime to pozzolan ratios.*** The empirical observations of the preparation of the sea-water concretes recorded by Vitruvius (*De arch.* 5.12.2–3, 2.6.4) provide essential information about mortar mix design and installation practices. Vitruvius recommended a 1:2 lime to *pulvis* volcanic ash ratio, presumably by volume, for sea-water harbour mortars (*De arch.* 5.12.2; see pp. 23, 108–10).

> Those concrete structures that are to be in the water must be made in this fashion. Pumiceous volcanic pozzolan (*pulvis*; lit. "dust" or "powder") is to be brought from the region that runs from Cumae to the promontory of Minerva and mixed in the trough in the proportions of two parts to one of lime.

The proportions by mass of dry quicklime and *pulvis* in Vitruvius' ideal sea-water mortar can be computed using the 1:2 volumetric ratio, and bulk mass density of 880 $kg/m^3$ for the dry lump quicklime, CaO, calcined at about 900°C (Krukowsky 2010), and a unit weight of 1000 to 1200 $kg/m^3$

| **Drill Core** | **Mortar** | ***Caementa*** | **Binder/Aggregate ratio**[3] |
|---|---|---|---|
| **Portus Cosanus**[1] | | | |
| PCO.2003.01 | 69 | 31 | |
| PCO.2003.02 | 57 | 43 | |
| PCO.2003.03 | 77 | 23 | |
| PCO.2003.04 | 58 | 42 | |
| PCO.2003.05, poor core recovery | | | |
| **Santa Liberata**[1] | | | |
| SLI.03.01 | 73 | 27 | |
| SLI.04.01 | 55 | 45 | |
| **Portus Claudius**[1] | | | |
| POR.2002.01, 8% core recovery | | | |
| POR.2002.02 | 67 | 33 | |
| POR.2002.03, 23% core recovery | | | |
| **Portus Traiani**[1] | | | |
| PTR.02.02 | 65 | 35 | 0.9[5] |
| **Portus Neronis**[1] | | | |
| ANZ.02.01 | 68 | 32 | |
| **Bay of Pozzuoli**[1] | | | |
| BAI.06.01 | 72 | 28 | 2.4 |
| BAI.06.02 | 67 | 33 | 1.4 |
| BAI.06.03 | 64 | 36 | 3.0, 3.15 |
| BAI.06.04 | 61 | 39 | |
| BAI.06.05 | 60 | 40 | 3.5 |
| Egnazia | | | |
| EGN.08.01 | 55 | 45 | 1.7, 1.7 |
| **Chersonessos** | | | |
| CHR.05.01, poor core recovery | | | |
| CHR.07.02 | 74 | 26 | 3.4, 3.4 |
| **Pompeiopolis** | | | |
| POM.09.01 | 36 | 64 | 4.0[4] |
| POM.09.02 | 46 | 54 | 2.2, 4.9, 1.5[4] |
| **Caesarea** | | | |
| CAE.05.01 | 59 | 41 | |
| CAE.05.02 | 75 | 25 | |
| CAE.05.03, poor core recovery | | | |
| CAE.05.04 | 83 | 17 | |
| CAE.05.05 | 67 | 33 | |
| **Alexandria** | | | |
| ALE.07.01 | 56 | 44 | 3.3 |
| ALE.07.02 | 57 | 43 | 2.2 |
| ALE.07.03 | 54 | 46 | 2.3 |
| ALE.07.04 | 51 | 49 | |
| **Brindisi Reproduction**[2] | | | |
| BRI.05.01 | 67 | 33 | |
| BRI.05.02 | 76 | 24 | |
| BRI.06.01 | 72 | 28 | |
| BRI.08.01 | 72 | 28 | |

*Table 7.1. Volumetric proportions of mortar and* caementa *measured along longitudinal transects of the maritime concrete drill cores, and binder to aggregate ratios (pp. 186–87, 7.7), measured through point counts of thin sections of the maritime mortars (Stanislao* et al. *2011).*

[1]Oleson *et al.* 2004, [2]Oleson *et al.* 2006, [3]Based on point counts of mortar thin sections, Vola *et al.* 2010a, [4]Stanislao *et al.* 2011, [5]This study.

*Table 7.2. Proportions of geologic materials in the original mix of the sea-water concrete, inferred from ancient sources and measured unit weights of constituents in the Baianus Sinus core sample (after Jackson* et al. *2013b).*

| **Raw materials of Roman sea-water concrete (*De architectura* 2.6.1, 5.12.2–3)** | **Unit weight (Kg/m$^3$)** |
|---|---|
| *calx*<br>dry lump quicklime | 880 * |
| *pulvis*<br>Neapolitan Yellow Tuff, poorly consolidated, volcanic ash pozzolan | ~1000–1200 ** |
| *tofus* or Flegrean Tuff<br>Neapolitan Yellow Tuff, lithified tuff, decimeter-sized aggregate | ~1200–1400 **, † |
| BAI.06.03 concrete, from drill core | 1494 † |

*Krukowsky 2010, Brune 2011. **Papakonstantinou *et al.* 2012. †CTG Italcementi Laboratories.

| **Lime: *pulvis* ratio in dry sea-water mortar mix** | | **Weight % dry mortar mix ‡** | | **Weight % dry concrete mix §** | | **Unit weight dry concrete mix (Kg/m$^3$)** |
|---|---|---|---|---|---|---|
| by volume | by weight ‡ | Lime | Ash | Lime | Ash | |
| 1: 2 ǁ | 0.37–0.44 | 27–31 | 69–73 | 11–15 | 34–45 | 1080–1220 |
| 1: 2.7 # | 0.27–0.33 | 21–25 | 75–79 | 8–11 | 37–44 | 1085–1230 |

‡ See explanation in text. §Mortar forms about 55–60 volume %, and tuff coarse aggregate about 40–45 volume % in the typical concrete mix (Table 7.1). ǁ *De architectura* 5.12.2–3, Oleson *et al.* 2004. # Oleson *et al.* 2006.

for the poorly consolidated facies of the Neapolitan Yellow Tuff (Papakonstantinou *et al.* 2012). The ratio by weight of ash pozzolan in the mortar ranges from 0.37 to 0.44 (1 × 880:2 × 1200 = 0.37 to 1 × 880:2 × 1000 = 0.44). The quicklime would form about 27 to 31 weight % of the mortar mix (880 kg/(2400+880) kg = 27 weight % to 880 kg /(2000+880) kg = 31 weight %), and pumiceous ash would form about 69 to 73 weight % (Table 7.2). With these ratios, one cubic metre of the dry mortar mix would have been composed of about 238 to 273 kg dry quicklime, and 690 to 876 kg ash pozzolan, depending on variations in the unit weights of these materials (Brune *et al.* 2013; Jackson *et al.* 2013b).

Computation of the overall weight of dry quicklime and pyroclastic rock in a cubic metre of the maritime concrete begins with measurements of the relative amounts of mortar and coarse *caementa* fragments exposed on the surfaces of the drill cores (Table 7.1; p. 187). The median of all the ancient concretes based on these measurements is about 62% mortar and 38% *caementa* (Fig. 7.18a). Small tuff and carbonate rock fragments are present throughout the concretes but were not included in the surveys, so adding about 5 volume percent *caementa* to the visual estimates gives a range of 55 to 60 volume % mortar and 40 to 45 volume % *caementa*. For a concrete with Flegrean tuff *caementa* and ash this would correspond to about 480 to 630 kg lithified tuff with 1200 to 1400 kg/m$^3$ unit weight, equivalent to the lithified Neapolitan Yellow Tuff (Papakonstantinou *et al.* 2012), 131 to 162 kg dry quicklime, and 418 to 482 kg ash pozzolan with 1100 kg/m$^3$ unit weight, an average value for the poorly lithified Neapolitan Yellow Tuff (Papakonstantinou *et al.* 2012), in the dry concrete mix before submersion in sea-water. The total dry unit weight would be about 1080 to 1220 kg/m$^3$. The quicklime would have formed about 11 to 15 weight % of the total mix (Table 7.2). The 2004 reproduction of the maritime concrete in Brindisi suggests, however, that builders may have used a 1:2.7 lime: *pulvis* mix (Oleson *et al.* 2006), about the same volumetric ratio that Vitruvius recommended for concrete mortars on land (*De arch.* 2.5.1; pp. 16–17, Passage 6). If so, dry quicklime would have formed about 21 to 25 weight % of the mortar. Using the volumetric ratios of 55 to 60 volume % mortar and 40 to 45 volume % *caementa,* and the 1200 to 1400 kg/m$^3$ unit weight of the lithified Neapolitan Yellow Tuff for the tuff *caementa*, this corresponds to: 780 to 910 kg tuff aggregate, 102 to 132 kg dry quicklime, and 521 to 454 kg ash pozzolan for a unit weight of about 1085 to 1230 kg/m$^3$ for the dry concrete mix before submersion in sea-water. The quicklime would have formed about 8 to 11 weight % of the concrete (Table 7.2).

The 25% volume loss associated with the hydration of quicklime in the architectural mortars of Rome, suggested by Delaine (1997:123), may not directly apply to the maritime mortars. In the architectural mortars, an apparent volume decrease occurs through consolidation during mixing of the lime putty and evaporation of water in the slaking process. By contrast, the hydration of pebble lime in the maritime mortars (pp. 163–66) seems to have occurred in an infinite aqueous environment and there is a pervasive macroscale porosity at the millimetre-scale. However, when builders compacted the wet mass of concrete submerged in sea-water, they probably reduced its volume by about 5 to 10% (Brune *et al.* 2013). The unit weights of tuff, lime, and pozzolanic ash listed above for the ideal dry mix formulated with pumiceous tuff *caementa* are therefore low, and could be increased slightly.

These estimates suggest that the Roman sea-water concrete formulation formulated with tuff *caementa* required about 10 to 15 weight % quicklime. Lime could have been calcined *in situ* or transported to the harbour site, perhaps as matured slaked lime (pp.163–64).). The concrete mix formulated with lightweight tuff *caementa* did, however, require a substantial relative proportion of volcanic ash pozzolan, about 34 to 45 weight % (Table 7.2). In comparison, for a concrete formulated with 40 to 45 volume percent limestone or calcareous sandstone *caementa*, with a typical unit weight of about 2100 kg/m$^3$, the ideal dry mix would have had unit weight of about 1420 to 1560 kg/m$^3$. Lime would have formed about 8 to 11 weight % of the total concrete mix, and the volcanic ash pozzolan about 27 to 34 weight %.

Roman builders likely used volumetric proportions of lime and volcanic ash to mix mortar at the harbour construction sites (Oleson *et al.* 2004). They may have used calculations by weight, however, to estimate the transport of the pumiceous ash as seafaring cargo or ballast to eastern Mediterranean ports. They surely recognized that the ash pozzolan formed a smaller proportion of the overall mix by weight in the concretes formulated with carbonate rock *caementa*. This could have helped justify the potential large-scale shipment of pumiceous ash to sites such as Caesarea, where tuff *caementa* were mainly replaced by calcareous sandstone (pp. 275–79). There, about 35,000 m$^3$ of concrete form the harbour structure (pp. 25–26). One cubic metre of the dry mix contained about 383 to 530 kg ash pozzolan, and with the addition of 10 wt% ash for the volumetrically consolidated concrete, the computation by mass suggests that the Caesarea harbour required about 14,730 to 20,400 metric tons of pumiceous ash. The "admirable" and "marvellous" qualities of *pulvis* volcanic ash described by Vitruvius and Pliny (*De arch.* 2.6.1; *HN* 35.166) suggest that Roman builders could have considered shipment of pumiceous ash to the harbour installations, even to the far distant ports of Pompeiopolis, Caesarea, and Alexandria, to be a wise and practical effort that would ensure the consolidation and longevity of the maritime concrete structures. The trace element signatures of pumice specimens from the eastern Mediterranean concretes and compositions of clinopyroxene from Pompeiopolis mortars (Stanislao *et al.* 2011) tentatively suggest an origin from the Gulf of Naples (Figs. 7.10–7.13). Further corroboration of these results would confirm that builders went to great effort to transport *pulvis* ash to the eastern Mediterranean harbour sites.

***7.3.3. Preparation of limes.*** The production of quicklime, CaO, occurs through calcination of limestone. The decomposition of calcium carbonate ($CaCO_3$) forms calcium oxide (CaO) through the evacuation of carbon dioxide gas ($CO_2$) at temperatures generally greater than 882 ºC, at atmospheric pressures. Slow, steady burning in an arched or domed kiln, like the one described by Cato (pp.12–14 *Agr.*18), would minimize draughts into the chamber and produce, in principle, a highly reactive lime product with a minimum of underburned articles, present as crystalline limestone relicts, and overburned particles, present as dead-burned lime or pseudo-calcite. The cycle of loading, firing, cooling, and extraction would likely have taken two weeks to complete (Williams 2004). At forested sites, such as Portus Cosanus or Santa Liberata, wood fuel could have been harvested on site and limestone bedrock calcined *in situ*. At Portus, however, lime had to be brought from a distance, possibly from quarries in the Monti Sabini in the Apennine foothills northeast of Rome or from Terracina (pp. 159). Limestone was possibly calcined at the quarry site, and the lime transported to the building sites in the Tiber River delta by boat. At Caesarea, for example, the limestone could have been calcined near Mt. Carmel quarries, and the lime transported to the harbour construction site by cart. The burnt lime would have been excavated from the top of the kiln, to avoid contamination with wood ash. Mortars with high proportion of underburned or underburned particles, relicts of wood ash, or a wide range of clast sizes, such as those in the Portus Claudius and Caesarea harbour concretes indicate less well-prepared lime, relative to those with fine grained, highly dissolved particles, such as that at Portus Traiani. These features are visible at the macroscopic scale, and observations at the microscopic scale provide more detail about dissolution and reaction with the pumiceous ash pozzolan, as discussed below.

Modern Italian methods for lime production and hydration are based on millennia of experience. The reaction of quicklime with water to form calcium hydroxide, or *calce spenta* in Italian, produces a strong exothermic reaction and volume expansion. Nowadays, quicklime is hydrated with stoichiometric water in an exact proportion to form powdered calcium hydroxide, c*alce idrata in polvere* in Italian, or with an excess of water to form lime putty, *grassello di calce* in Italian. Lime suspensions have excellent pozzolanic reactivity with volcanic ash from Bacoli, as shown by classic experiments by Sersale and Orsini (1969) and Massazza and Costa (1979). In ancient times hydrated, or slaked, lime products were buried or sealed in containers or under water to preserve them as portlandite ($Ca(OH)_2$) away from contact with carbon dioxide, which would carbonate the calcium hydroxide to form crystalline calcium carbonate, or calcite, and destroy its reactive potential (Stanislao *et al.* 2011). The historical tradition of mortar production in Europe has frequently relied on aged slaked lime (Cazalla *et al.* 2000), and this is also recorded in ancient texts, where three years of aging of quicklime away from atmospheric carbon dioxide is suggested by Pliny (*HN* 36.176) to develop sufficiently refined material characteristics (p. 28). Aging of quicklime improves the workability, or plasticity, of lime putty (Atzeni *et al.* 2004), which is essentially a macroscopically homogeneous dispersion of calcium hydroxide crystals particles in water. Aged lime putty, kept under water for 14 years, produces changes in the crystal size and morphology of portlandite crystals, compared to commercial non-aged hydrated lime. With maturation the crystal morphology changes from prismatic to platy; the proportion of small, submicrometre-sized platy crystals and nanometre-sized spherical aggregates increases; and the surface area increases to nearly five times that of recently hydrated quicklime (Cazalla *et al.* 2000). The aged portlandite dissolves faster in $CO_3^{2-}$ saturated solution and shows a higher rate and degree of carbonation to calcite binder than non-aged hydrated lime putty. This calcite binder is not directly applicable to the Roman sea-water mortars, however, where the lime hydrated in a pozzolanic system. Even so, the experimental work suggests that aged portlandite could have increased pozzolanic reactivity in the ancient sea-water concrete system, and minimized expansive reactions associated with quicklime hydration (pp. 164–66). If Roman builders required aged slaked lime – even in the form of pebble lime – for the pozzolanic mortars of the harbour concretes, then preparation would have begun several years before the actual installation of the structures. It is not clear whether the first slaking would have been achieved with fresh water or sea-water.

***7.3.4. Mixing the mortars.*** Roman builders' methods for mixing the lime-volcanic ash mortars, as well as for slaking the quicklime and hydrating the wet mortar mix remain unclear. The mortars of the conglomeratic concrete structures of the Imperial age monuments of Rome likely began with a lime putty to which granular volcanic ash, or *harena fossicia*, was incorporated. Vitruvius (*De arch.* 7.3) refers to this mortar as *materies ex calce et harena mixta* ("mortar prepared with lime and sand"). During the Republican period, both Cato (*Agr.* 18.7; pp. 12–14, Passage 3) and the Puteoli building contract (*CIL* 10.1781; p. 35, Passage 31) refer to the mix for plaster or for mortared rubble as *calx harenatus* (or *harenata*, "lime with sand"). The stiffly viscous wet mortar mix was packed into forms with vitric tuff and brick *caementa* to form a conglomeratic concrete. Precise reproductions of the mortar of the conglomeratic concrete walls of the Markets of Trajan were produced at Cornell University in 2010, using about a 1:10 weight % ratio of dry quicklime to scoriaceous Pozzolane Rosse volcanic ash (Jackson *et al.* 2009; Brune 2011). The engineering properties and resistance to fracture of the young mortar were measured with innovative experimental tests (Brune *et al.* 2013), and investigations of these and the ancient materials continue.

The mortar of the 2004 reproduction of maritime concrete at Brindisi was prepared in a similar fashion (see Chapter 5): aged slaked lime putty was laboriously mixed with pumiceous volcanic ash from a Bacoli quarry and a small amount of sea water; the wet mix was packed into baskets and lowered into a wooden form that was partially filled with sea-water; the *caementa* were tossed in, and the wet mass compacted (Oleson *et al.* 2006). This was repeated, level by level, until the form was full. The macroscopic scale features of the Brindisi mortar reproduction, however, do not entirely resemble the ancient material. Although there are common sand- and gravel-sized pumiceous clasts, there is a general absence of white inclusions, and the fine-scale fabric has a more homogeneous, well-mixed character. Petrographic studies of the young Brindisi mortar also reveal microscale fabrics that differ from the ancient materials in some respects. The cementitious matrix of the mortar reproduction is composed of irregular zones of pumice shards and volcanic crystals, and tiny relict plates of portlandite (Fig. 7.14a). These are small clots of lime putty mixed with relicts of pumice and crystals; they have narrow curvilinear selvages composed of fine vitric ash shards, which become progressively more opaque over time (Fig. 7.14b). The selvages form a whirl pattern at the millimetre scale, and suggest unconsolidated fine ash on the surfaces of clumps of lime-volcanic ash putty.

In comparison, the ancient mortars have a complex cementitious matrix composed of optically isotropic C-A-S-H (Fig. 7.1b, c) or dull opaque C-A-S-H and Al-tobermorite (Fig. 7.3c), which encloses discrete opaque pumice and relict lime clasts. There is a general absence of curvilinear zones of fine vitric ash shards and opaque amalgams of lime and ash at the millimetre scale. However, Portus Claudius mortar from a retaining wall at the edge of the harbour, does show occasional selvages (Fig. 7.14c). The mortar to the right of the selvage has numerous partially dissolved relict lime clasts, with densely opaque centres and peripheral rims of C-A-S-H, while the mortar to the left has numerous nearly wholly dissolved relict lime clasts, composed mainly of C-A-S-H. Although the origins of these microstructural variations are not clear, it does seem possible that the selvage represents a contact between two different clumps of lime and ash, partially hydrated with sea-water in the mortar trough. A macroscale contact between two different mortar mixes occurs nearby (Fig. 7.7b).

The nearly ubiquitous presence of discrete relict lime clasts in the ancient sea-water mortars and the heterogeneous particulate nature of the mortar fabrics suggest that, in some cases, Roman builders could have mixed pebble lime and pumiceous volcanic ash in the mortar trough with or without a small quantity of sea-water, and then allowed the mixture to fully hydrate in sea-water after installation in the form (pp. 165–66). Some fractured relict lime clasts (Fig. 7.15a), suggest sudden, expansive hydration of pebble quicklime in sea-water. Subsequent dissolution and pozzolanic reaction *in situ* produced C-A-S-H in the periphery and Al-tobermorite in the centre. Most relict lime clasts have continuous, intact fabrics (Figs. 7.3a, 7.15b), however, and suggest particles of aged slaked pebble lime that did not expand substantially in

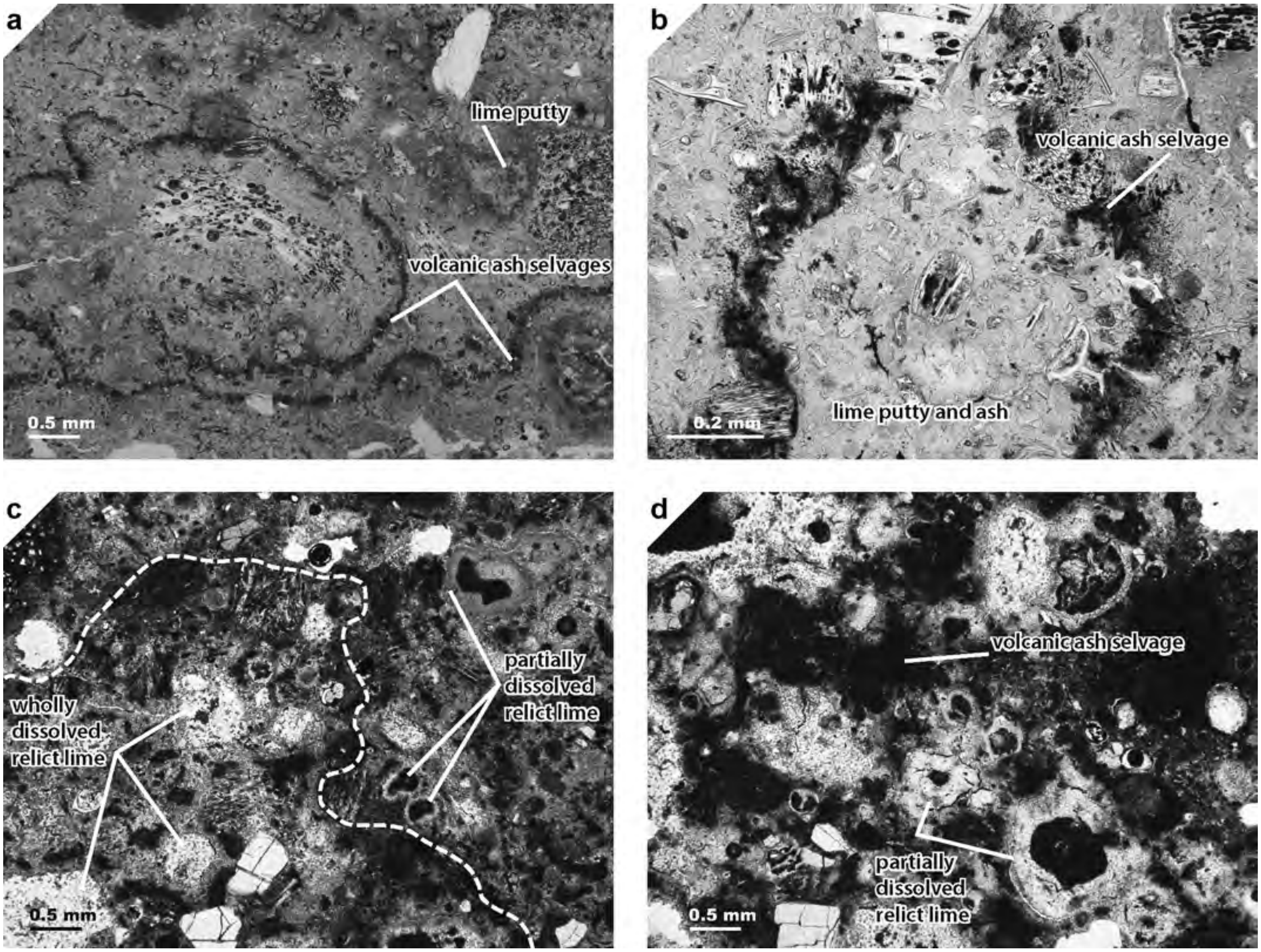


*Fig. 7.14. Petrographic photomicrographs of the lime putty mortar fabric of the Brindisi concrete reproduction and the complex Portus Claudius mortar. Optical micrographs, plane polarized light. a. Brindisi mortar (BRI.2005), 12 months hydration. b. Brindisi mortar (BRI.2006), 24 months hydration. c, d. Portus Claudius mortar (POR.2002.02C). The opaque selvages seem to follow the relict surfaces of partially hydrated lime-volcanic ash clumps.*

sea-water. These also dissolved *in situ* to produce C-A-S-H in a symmetrical rim around a central core of Al-tobermorite. Most of the relict lime clasts are surrounded by a narrow perimetral zone composed mainly of delicate microstructures of hydrocalumite and ettringite. If these had developed prior to installation in the concrete form they would have been deformed or destroyed. It therefore seems possible that builders preferred aged slaked lime, commonly as millimetre- to centimetre-sized pebbles, which re-hydrated *in situ* in the sea-water concrete system. Even so, certain mortars contain macroscale clots of relicts of hydrated lime paste, as shown in the Caesarea (CAE.2005.05) drill core (Figs. 7.6f, 7.8c). Further analytical and experimental investigations are needed to clearly understand variations in the Roman methods for preparing hydrated lime mixtures in the maritime mortars.

***7.3.5. Hydration in sea-water***. Microstructural investigations with petrographic and scanning electron microscopy suggest that hydration of sand-to fine gravel-sized particles of pebble lime occurred mainly in the sea-water environment (Figs. 7.1, 7.3a). Smaller lime clasts were fully dissolved and are composed of optically isotropic C-A-S-H. Larger lime clasts only partially dissolved, and are composed of a perimetral rim of translucent C-A-S-H, and an opaque core of crystalline Al-tobermorite with 11 Å interlayer spacing (Fig. 7.15c). This is the rare, layered hydrothermal mineral that forms the model basis for modern C-A-S-H cementitious hydrates, but does not occur in conventional concretes. In the Baianus Sinus mortar, the compositions of both materials are nearly identical, with a cation atomic ratio of Ca/(Al+Si) about 0.8 (Fig. 7.15d). A narrow border or fine subspherical microstructures of calcium-chloroaluminate and sulfo-aluminate crystals commonly surround the relict lime clasts; calcite is a secondary alteration phase (Vola *et al.* 2011a). Chloride in calcium-chloroaluminate crystals (mainly hydrocalumite) and sulphate in sulfo-aluminate crystals (mainly ettringite) could have been derived from the sea-water that hydrated the lime clast; the anions possibly migrated to the lime clast perimeter, and then crystallized *in situ* (Jackson *et al.* 2012).

It is conceivable that builders could have incorporated pumiceous ash pozzolan and matured pebble lime (or quicklime) in a mortar trough, and then lowered this as a dry mix or as sea-water moistened clumps into forms to produce a mortar that fully hydrated *in situ*. The broken volcanic tuff or limestone *caementa* would then have been tossed in, and the mixture compacted. This would be somewhat analogous to a process of "dry-mixing" that is documented in recent investigations of historic mortars (Forster 2004; Elsen 2006; Válek and Matas 2012). Vitruvius' description of the submersion of the lime-pyroclastic rock mixture in sea-water provides some clues (*De arch.* 2.6.4):

> Therefore, when dissimilar and incompatible materials [lime (*calx*), ash (*pulvis*), and tuff (*tofus*)] are taken and mixed in a moist environment, the urgent need of moisture suddenly satiated by [sea-] water seethes with the heat hidden in the mingled substances and with a strong reaction effects a vehement union and quickly achieves the desired goal of solidity.

Here, Vitruvius explains the cohesion of lime (*calx*), powdery volcanic ash (*pulvis*) and volcanic tuff (*tofus*) in sea-water as a process of hydration, albeit through the rather tenuous Emplecton theory of the four elements (Jackson and Kosso 2013). With sudden saturation in sea-water, the lime and volcanic rock mixture rapidly assembled and solidified underwater during an exothermic reaction that "seethes with the heat hidden (*latenti calore*) in the mingled substances." The hydrated mixture took back (*recepto*) the Liquid element (2.6.1), which had been removed from the lime in the kiln by the intense heat of the Fire (*ignis vehementia*, 2.6.3), and from the tuff and ash by the "the fire and vapour of the flame within, spreading and burning through the fissures" (*penitus ignis et flammae vapor per intervenia permanans et ardens,* 2.6.1) of the volcanic environments of Baia and Vesuvius. Modern scientific investigations validate these empirical observations. Hydration of quicklime to produce portlandite through the reaction $CaO + H_2O \rightarrow Ca(OH)_2$ releases about 273 cal/gram almost instantaneously. However, it is the evolution of heat produced through the formation of C-A-S-H in the cementitious matrix of the mortar that is responsible for elevated temperatures over the first 90 days of hydration, as the mix "gathers into a strong, solid mass" (*De arch*. 2.6.4) (Massazza 2002; Jackson *et al.* 2013b).

The partially dissolved relict lime clast in the Portus Cosanus mortar that is traversed by cracks with opening displacements that extend 50 to 150 μm into the cementitious matrix (Fig. 7.15a) suggests a quicklime particle that hydrated to portlandite, expanded, and fractured *in situ* (Leslie and Hughes 2002; Forster 2004; Elsen 2006), and then dissolved. By contrast, the partially dissolved relict lime clast from the Portus Neronis mortar that has an intact opaque core surrounded by progressively less opaque perimetral rims (Fig. 7.15b), suggests an aged slaked lime particle that hydrated *in situ* with little expansion and gradually reacted to form C-A-S-H. This is the more common microstructure in the maritime mortars (Figs. 7.1b, 7.3a). The aged lime product of the ancient sea-water mortars may have been granular, possibly hydrated with stoichiometric water, similar to c*alce idrata in polvere* but as coarser particles.

Further investigations of microstructures within relict lime clasts and their hydration mechanism are needed to fully clarify builders' methods for the maritime mortar preparations. Perhaps, when Vitruvius and Pliny described the slaking of lime (as *intinctus in aqua*, *De arch.* 2.5.3; and *intrita, HN* 36.176.), they referred to the mortars of concrete structures on land. Pliny's remarks are made with reference to buildings in Rome, and Vitruvius' remarks regarding slaking (*extincta*) of lime and mixing with sand (*harena fossicia*), also are made in reference to methods of building on land (*De arch.* 2.5.1–3). By contrast, Vitruvius' remarks regarding the hydration of the collection of unlike and unequal things (*calix*, *pulvis,* and *tofus)* through sudden saturation with [sea-] water occur in the context of building in the sea (*De arch.* 2.6.1–6, as described above. It is not clear how a more-or-less dry mixed mortar would settle in a form wholly or partially submerged in sea-water, or how local variations in the degree of saturation in sea-water would influence hydration processes and products. In addition, certain mortars contain clots of relict lime paste (Fig. 7.6e). Many questions remain about mortar preparation and installation that the 2004 Brindisi concrete reproduction (Chapter 5) has not fully resolved. It is hoped these will be clarified with further experimental and analytical research.

## 7.4. Pozzolanic cementitious processes in the sea-water mortars

The products of pozzolanic hydration reactions that developed in the sea-water environment as a result of the reaction of lime, sea-water, and pumiceous ash in the ancient concretes are quite different from the cementitious products of conventional cement concretes (pp. 167–68). In concrete made with Portland cement, the "glue" that binds the aggregate components is a poorly crystalline calcium-silicate-hydrate, C-S-H. In Roman sea-water concrete, the C-A-S-H binder is also a poorly crystalline compound, but it contains additional aluminium and less silicon, and is extremely stable. Environmentally-friendly concretes that substitute volcanic ash or fly ash for Portland cement also produce C-A-S-H binder. The Roman C-A-S-H thus provides an important reference for the long-term performance of modern C-A-S-H in these blended cement concretes. In addition, the ancient concrete contains important crystalline cementitious phases (pp. 169–70). A comparison of the bulk chemical compositions of the young Brindisi mortars from 6 months to 60 months hydration provides insights into the early chemical trends in the ancient concretes, and suggests a chemical system that is somewhat open to sea-water (pp. 170-75).

***7.4.1. Comparisons with conventional Portland cement concretes***. Conventional concretes begin with Portland cement, produced by sintering raw materials composed of pure limestone (70 weight %) and other aluminosilicate materials, generally clay minerals (30 weight %) at 1450 ºC, pulverizing the resultant clinker and, finally, adding an aliquot of gypsum (5 weight %). About ~0.815 metric tons of $CO_2$ are emitted per ton of cement, which forms about 10 to 25 weight % of the concrete. Mixing the dry cement with water and relatively inert sand and gravel produces an exothermic heat evolution cycle, as the crystalline compounds in the cement react to form stable low-energy cementitious hydrates. One of these, C-S-H(I), a poorly crystalline form of tobermorite with a larger basal spacing, ~12 Å, and analogous Ca-O layers with silicate tetrahedra chains, is the predominant binding substance of Portland cement based concrete (Taylor 2004: 132–33). The layered, ideal tobermorite ($Ca_5(Si_6O_{18}H_2)\bullet 8H_2O$) structure provides the model basis of the strength mechanism of C-S-H, but crystalline tobermorite is produced hydrothermally, generally at temperatures greater than 120 °C, and has never been observed in conventional concretes (Taylor 2004: 129–31, 344–46).

Conventional concrete is most vulnerable to sea-water attack in spray, splash or intertidal zones, where fractures and spalling result from repeated wet-dry cycles. Microcracking and chemical attacks can eventually cause disintegration through erosion and abrasion by sand and gravel during wave action. When fully submerged in sea-water, however, the concrete is mainly exposed to chemical attack (Mehta 1990). Sea-water generally has concentrations of $Na^+$ at 11 grams/litre, $Cl^-$ at 20 grams/litre, $Mg^{2+}$ at 14 grams/litre and $SO_4^{2-}$ at 27 grams/litre, so processes of alkali silica reaction and chloride, magnesium, and sulphate attack frequently produce deleterious reactions in modern maritime concretes (Mehta and Monteiro 2006:154–62, 180–82). Sulphate attack can produce expansions and microcracking through the formation of secondary ettringite; magnesium ion attack can produce decalcification of C-S-H to eventually form magnesium silicate hydrate and loss of cementitious cohesion; and chloride anions attack the coherent oxide passivity layer of steel reinforcements – that are not present in ancient Roman concrete – causing serious damage and cracking. $CO_2$ attack can lead to decomposition of cementitious products, producing secondary hydrocalumite, thaumasite ($(Ca_3Si(CO_3)(SO_4)(OH)_6\bullet 12(H_2O))$), and aragonite, mainly on exposed surfaces. In dense concretes, however, a thin, protective layer of brucite and aragonite develops on the surfaces of the structure by interaction with $Mg^{2+}$ and $HCO^{3-}$. This can effectively remove the concrete from sea-water attack (see also Massazza 1985; Mehta 1990; Taylor 2004: 370–71, 382–83) and, indeed, many of the ancient Roman sea-water structures have these carbonate surface layers.

Complex, interwoven chemical and physical processes cause deterioration in conventional maritime concretes, but in warm climates permeability is the most important factor influencing magnesium ion attack, $CO_2$ attack, and the leaching of calcium through attack of uncombined calcium hydroxide, or portlandite (Mehta 1990). Natural and artificial pozzolans, such as basaltic ash and granular blast furnace slag, reduce the volume of kiln-fired cement in the concrete mix and produce high ultimate strengths and resistance to decay, even in aggressive sea-water environments (Massazza 1985, 2004; Taylor 2004: 382; Thomas *et al.* 2011). Because little uncombined calcium hydroxide remains in a pozzolanic system after initial hydration, the formation of secondary gypsum and ettringite and related expansion and cracking is much reduced, and there is little leaching of calcium and related porosity increase.

The pozzolans of modern concretes are siliceous and/or aluminous materials, named after Pozzuoli (Fig. 7.2) and its exceptional volcanic ash, which react with hydrated lime, or portlandite, at ordinary temperatures to form compounds with cementitious properties (Massazza 1988). The pyroclastic rock deposits of the Campi Flegrei volcanic district, near Pozzuoli, have two principal pozzolanic components. These are pale yellow volcanic glass, mainly trachytic in composition, and natural zeolite mineral surface coatings and cements that consolidate the pumiceous ash and lithified tuff (de' Gennaro *et al.* 2000). The natural zeolite cements form through hydration of volcanic glass with water vapour immediately after eruption (de' Gennaro *et al.* 2000), or through dissolution-precipitation processes produced through interaction of glass with surface and ground waters (Hay and Iijima 1968). Zeolites are framework silicate minerals that have an open structure with cavities that contain cations and water molecules, with the general formula $M_{x/z}\ [Al_x\bullet\ Si_{1-x}\bullet\ O_2]\ \bullet\ y\ H_2O$, where M is a cation, z its valence state, and x, the number of molecules of that cation. $Al^{+3}$ cations can substitute for $Si^{4+}$ in variable proportions, and alkaline cation exchange compensates for the resulting negative charge balance associated with this substitution. As a result, zeolites with low Si/Al combine readily with $Ca(OH)_2$ to form poorly-crystalline C-A-S-H, but the reactive process remains poorly understood (Massazza 1988). Dissolution of glass and zeolite, and precipitation of cementitious phases may be important in the earliest stages of pozzolanic reaction, but after a short time the reaction is likely controlled by diffusion, where the permeability of the rim of cementitious hydrates surrounding the pozzolanic components determines the progress of ongoing reaction (Mertens *et al.* 2009). The classic experiments by Sersale and Orsini (1969) and Massazza and Costa (1979) show the strong pozzolanic reactivity of Flegrean volcanic glass and its constituent natural zeolite cements, mainly phillipsite and chabazite, or hershelite, which generally have sodium, potassium and/or calcium as cations.

Pozzolans are extremely important to the modern cement industry worldwide: they are used as supplemental cementitious components to replace Portland cement in environmentally-friendly concretes and, also, to extend the durability and service life of high performance concrete structures. When finely ground natural pozzolans or industrial wastes, such as fly ash and blast furnace slag, replace Portland cement in these concretes, they reduce $CO_2$ emissions associated with the fuel consumed to burn rock in kilns to produce clinker and the calcination of carbonate rock components. High volume substitution of finely ground basaltic cinder and limestone for Portland cement clinker, at 30% and 15% by mass, respectively, enhances strength development and durability in self-compacting concrete, while reducing $CO_2$ emissions by nearly 50% compared with 100% Portland cement controls (Celik *et al.* 2014). Preparation of the ancient maritime structures likely produced somewhat lower $CO_2$ emissions than conventional Portland cement concretes: Romans burned limestone at ~ 900 ºC to obtain quicklime, and lime formed about 10 to 15 weight % of the dry concrete mix, depending on whether the *caementa* was lightweight tuff or heavier limestone (Table 7.2).

The overall fabric of conventional concrete can be thought of as a bimodal system: largely non-reactive aggregates, mainly quartz sand and gravel-sized rock materials are enclosed by an extremely fine grained hydrated cement paste. Ordinary Portland cement is generally ground from clinker to a grain size of about 1 to 90 µm, and measurements of the specific surface area and particle size distribution help to determine the reactivity of a given product (Taylor 2004: 90–93). Particles greater than about 0.1 mm are, in principle, inert sand- and gravel-sized aggregates, surrounded by cement paste composed mainly of calcium-silicate-hydrate (C-S-H). The finest ash fraction of the Neapolitan Yellow Tuff falls in the same size range as Portland cement; particles about 25 µm and smaller compose about 50 volume percent of the deposit (de' Gennaro *et al.* 1999). However, in ancient Roman maritime concrete, there is no cement paste. Instead, a cementitious matrix composed of relicts of fine ash, poorly crystalline C-A-S-H, and crystalline cementitious components is intimately intergrown with and inseparable from sand- and gravel-sized ash particles and their relict zeolitic surface coatings, which have, themselves, developed interpenetrating pozzolanic cementitious components. The mortars of the monuments of Rome developed a similarly complex binding matrix (Jackson *et al.* 2009, 2011, 2012). The interpenetrating cementitious fabric and the relicts of pumiceous ash seem to have important influences on the pore structure of the ancient concretes, and its chemical durability (pp. 180-83).

***7.4.2. Cementitious microstructures in the ancient maritime mortars.*** Roman builders did not use a kiln-fired cement to produce the sea-water concretes or metal bars to reinforce them. Rather, they relied on the natural pozzolanic reactivity of hydrated lime with silt-, sand-, and gravel-sized pumiceous volcanic ash to produce binding cementitious hydrates in a pozzolanic mortar. The mortar binds the decimetre-sized chunks of volcanic tuff or limestone *caementa* that form the rock framework of the massive maritime structures. Examples of the diverse microstructures that record pozzolanic cementitious processes and hold the secrets to the long-term consolidation and cohesiveness of the ancient concretes are described in the sections that follow. These materials are the subject of ongoing mineralogical investigations.

*Relict lime clasts.* The relicts of certain pebble lime particles are composed of perimetral rim of poorly-crystalline C-A-S-H that surrounds an internal core of crystalline Al-tobermorite (Fig. 7.3a) that is usually has a dull brown opacity in plane polarized light (Vola *et al.* 2011a); both have Ca/(Al+Si) = 0.8 (Fig. 7.15d). Smaller relict lime particles may be wholly dissolved and transformed to poorly-crystalline C-A-S-H (Jackson *et al.* 2012). Larger relict lime clasts are composed mainly of Al-tobermorite with a diffuse irregular rim of C-A-S-H (Fig. 7.1a). The Al-tobermorite occurs mainly as fine platy crystals in dense ring-like clusters (Figs. 7.1d, 7.3b) Investigations of the bonding environments of silicon and aluminium in the Al-tobermorite of Baianus Sinus relict lime clasts indicate that $Al^{3+}$ substitutes for $Si^{4+}$ in tetrahedral sites of a double chain silicate structure. $Na^+$ and $K^+$ interlayer cations balance the charge induced by pervasive $Al^{3+}$ substitution. By contrast, $Al^{3+}$ in the surrounding C-A-S-H has heterogeneous bonding environments, and is both tetrahedrally and octahedrally-coordinated with oxygen (Jackson *et al.* 2013b).

*Cementitious binding matrix.* The principal cementitious binder of the sea-water mortars is poorly-crystalline aluminous calcium-silicate-hydrate (C-A-S-H), which is translucent in plane polarized light and optically isotropic in crossed polarized light, and may be altered to sparry calcite (Vola *et al.* 2010a, 2011; Stanislao *et al.* 2011; Jackson *et al.* 2012). In the cementitious matrix of the mortars, C-A-S-H grows through relicts of partially- to wholly-altered volcanic ash that are often densely opaque in plane polarized light (Figs. 7.1b, c, 7.3a). Al-tobermorite also occurs within the cementitious matrix, as described for Pompeiopolis mortars (Stanislao *et al.* 2011). The crystals form thin plates that join clots of poorly-crystalline C-A-S-H in the Baianus Sinus mortar (Fig. 7.3c). Point counts of thin sections suggest C-A-S-H binder: aggregate ratios ranging from about 2 to 4 (Vola *et al.* 2011c; Stanislao *et al.* 2011); these are qualitative estimates, however, that depend on the relative abundance of large pumiceous clasts in a given thin section.

*Chloride and sulphate microstructures.* Hydrocalumite and ettringite are the predominant mineral species that concentrate chloride and sulphate in the ancient sea-water mortars. These commonly occur in subspherical microstructures along the perimeters of relict lime clasts (Figs. 7.1b, c, 7.3a, d, e) that may be the result of migration of $Cl^-$ and $SO_4^{2-}$ anions from the sea-water saturated portlandite to aluminium-rich sites along the perimeters of the relict lime clasts. Hydrocalumite occurs in coarse plates, several tens of micrometers in length, and has bright second order interference colours in crossed polarized light. Ettringite has low first order birefringence, and occurs as dull, partially opaque patches with what appear to be shrinkage cracks; there are also crystals with acicular morphology. The crystals can occur alone, together, and/or in association with Al-tobermorite in certain sub-spherical microstructures, or in relict voids of the cementitious matrix. The example in Figure 7.3d shows hydrocalumite plates that crystallized in association with acicular Al-tobermorite. Hydrocalumite and ettringite are generally unstable at temperatures greater than 80 °C and Al-tobermorite generally crystallizes at temperatures greater than 120 °C. If these minerals crystallized contemporaneously, then new perspectives are needed to define their stability fields and, perhaps, inform the sequestration of chloride and sulphate in modern pozzolanic analogues of the ancient maritime concretes.

*Relict pumice clasts.* Particles of pumice and trachytic glass fragments commonly have a perimetral rim composed mainly of C-A-S-H that surrounds relict glass and phenocrysts, and is densely opaque in plane polarized light (Figs. 7.1b, c). This rim preserves the record of pozzolanic processes that bind volcanic glass within the cementitious matrix. C-A-S-H penetrates the vesicular structure of the pumice (Fig. 7.3d),

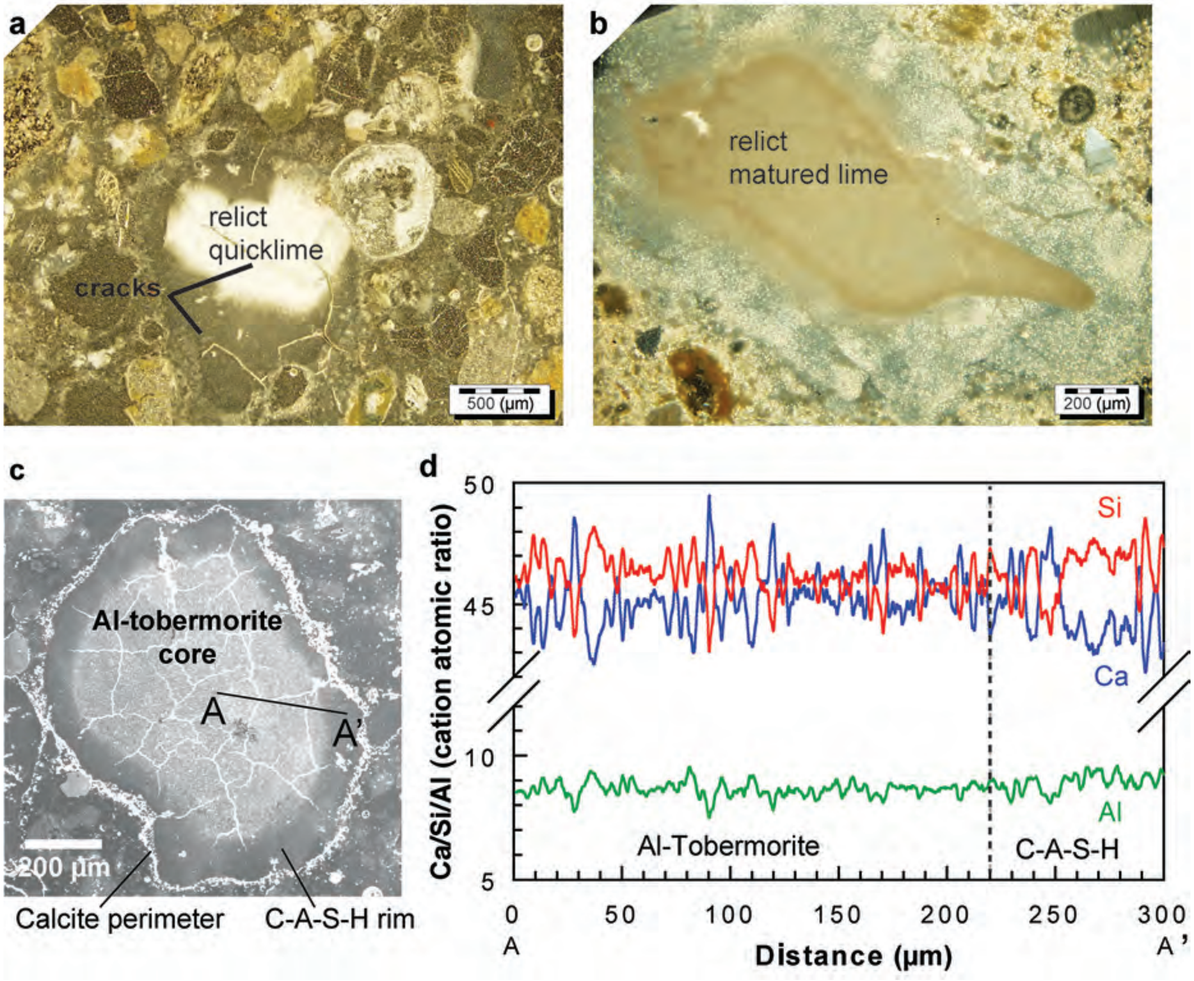


*Fig. 7.15. Petrographic photomicrographs of relict lime clast microstructures, and the composition of C-A-S-H and Al-tobermorite in the Baianus Sinus mortar. Optical micrographs, plane polarized light. a. Portus Cosanus mortar, possible relict quicklime clast, with cracks perhaps produced by in* situ *hydration of quicklime in sea-water, followed by dissolution during pozzolanic reaction. b. Portus Neronis mortar, possible matured slaked lime clast, showing gradual dissolution during pozzolanic reaction. c, d. Typical, partially dissolved, relict lime clast in the* Baianus Sinus *mortar, and compositions as Ca/Si/Al=100 cation atomic ratios from SEM-EDS analyses. The dotted line shows the approximate gradational boundary between Al-tobermorite crystal clusters in the core and poorly crystalline C-A-S-H phase in the perimetral rim (after Jackson* et al. *2013b).*

and Al-tobermorite crystals may occur here, as well. Some of these cementitious reactions involved not only volcanic glass, but also authigenic zeolitic vesicle surface coatings.

*Zeolite microstructures.* Zeolite mineral, mainly phillipsite, occurs as relict coarse grained textures in pumice vesicles (Fig. 7.4a); these are crystals with rosette-like morphology that formed in the geological environment (de' Gennaro *et al.* 2000), but did not fully react in the pozzolanic cementitious system. In addition, zeolite also occurs locally within the mortar fabrics, mainly as phillipsite that crystallized *in situ* within relict voids in the cementitious matrix (Fig. 7.4b) (Vola *et al.* 2011a). These crystals also occur as rosettes, but with smaller grain sizes, and they also seem to have potassic compositions. In the ancient mortar system buffered by portlandite at pH>12 silica, aluminium, calcium, sodium, and potassium were highly mobile (Massazza 1988). Volcanic glass and zeolite dissolved during pozzolanic reaction with lime hydrated in sea-water, and major element species were incorporated in cementitious phases such as C-A-S-H, Al-tobermorite, hydrocalumite, and ettringite. Later, after all portlandite was consumed, it is possible that residual volcanic glass continued to alter in the sea-water environment, and eventually produced local zeolitic microstructures in the mortar and *caementa* fabrics of some concretes (Fig. 7.4). Phillipsite forms in volcanic ash submerged in sea-water (with pH about 8) when alteration of glass to smectite clay mineral raises pH, silica activity, $(Na^++K^+)/H^+$ in a relatively closed hydrologic system (Hay and Guldman 1987). The processes of phillipsite crystallization in the ancient concretes are currently under investigation.

*Summary.* Precise mineral identifications determined from X-ray diffraction analyses, principally by Bruno Zanga at CTG Italcementi Laboratories, reveal that Al-tobermorite occurs in nearly all the mortars of the harbour concretes drilled by ROMACONS (Table A4.1), but that variations occur in the compositions of the mineral assemblages associated with lime clast hydration. Although hydrocalumite and ettringite are common throughout, some lime clasts evidently hydrated in more aluminium-rich conditions, and produced strätlingite ($Ca_2Al[(OH)_6AlSiO_{2\text{-}3}(OH)_{4\text{-}3}]\bullet 2.5(H_2O)$), or gehlenite hydrate ($C_2ASH_8$ in cement notation), for example, at Portus Cosanus. Magnesium-rich phases, brucite ($Mg(OH)_2$), hydrotalcite ($[Mg_{0.75}Al_{0.25}(OH)_2](CO_3)_{0.125}(H_2O)_{0.5}$), and magnesium sulphate ($CaMgSO_4$) also occur. Various crystalline forms of calcium carbonate ($CaCO_3$) occur throughout, as calcite, vaterite, and aragonite; these are common alteration products of the C-A-S-H cementitious binder in both subaerial and submarine environments. Zeolites, mainly phillipsite and chabazite ($((Ca,Na_2,K_2)_3Al_6Si_{10}O_{32}\bullet 12H_2O)$) are also associated with some relict lime clasts. The similarity, overall, of the mineral assemblages associated with Al-tobermorite in all the concretes suggests a consistent volcanic ash composition and cementitious hydration processes that occurred, most likely, far from atmospheric $CO_2$.

***7.4.3. Chemical trends in the sea-water mortars.*** The chemical compositions of the maritime mortars, measured in bulk specimens as weight % oxides mainly through X-ray fluorescence analyses (Figs. 7.16–17; Tables A4.2, A4.3; pp. 186–87), provide insights into chemical processes involving calcium, silica, aluminium and alkali cations in the pozzolanic sea-water system over very long periods of time, particularly when compared to young mortars of the Brindisi concrete reproduction (see Chapter 5). These are bulk mortar specimens that contain variable abundances of pumiceous ash pozzolan and relict lime clasts, and other components, as well, such as quartz-rich beach sands in the Portus Cosanus mortars, and argillaceous and dolomitic limestone particles in the Chersonesos mortars. The bulk compositions can be influenced by numerous factors, so they do not provide quantitative assessments of the cementitious binder of the mortar, but rather a qualitative illustration of possible chemical trends at the macroscale of the highly heterogeneous mortar fabric. In the future, modal ratios determined through petrographic point counts may provide further insights. These too can be problematic because the mortar shows great heterogeneity at the scale of a thin section and, in addition, the scale of resolution of the optical microscope cannot resolve the fine compositional details of the cementitious matrix.

*Inferences regarding magnesium (dolomitic) lime sources*. The mortars of the harbour constructions drilled by ROMACONS mainly contain 10 to 25 weight % CaO+MgO (Fig. 7.16a). This is somewhat less than the estimated 21 to 31 weight % lime estimated in the dry mortar mix (Table 7.2, pp. 161–63) and could be due, in part, to the highly porous fabric of the mortar, which contains 40 to 50 volume % void space (Fig. 7.18d). The Chersonesos mortars show a wide scatter of compositions; this may be the result of variable amounts of limestone clasts in the mortar mix. The Alexandria mortars also show a wide compositional range, despite fairly uniform unit weights and porosity measurements; this is, perhaps, due to the addition of oolitic grainstone particles to the mortar fabric (Vola *et al.* 2011c). The Portus Traiani analyses (blue circles, Fig. 7.16a) show the difference between the bulk mortar composition, which has about 25 weight % CaO+MgO, and the less than 2 mm fraction of the cementitious matrix, which has about 16 weight % CaO+MgO (Table A4.2). In the matrix, Ca/(Al+Si) =0.5 is very low, and $Na_2O+K_2O$=3.72 weight % is quite high relative to Portland cement pastes; alkali cations may be incorporated in the complex C-A-S-H binder and possibly contribute to balancing $Al^{3+}$ substitution for $Si^{4+}$ (Jackson *et al.* 2013b).

To assess whether the lime could have been calcined from limestone containing dolomite ($CaMg(CO_3)_2$), a magnesium-rich carbonate mineral, the concentration of MgO relative to CaO+MgO is shown for a wide variety of centimetre-sized mortar specimens (Fig. 7.16b; Tables A4.2, A4.3). Low magnesium concentrations could suggest lime calcined from nearly pure limestone sources with little dolomite. Elevated

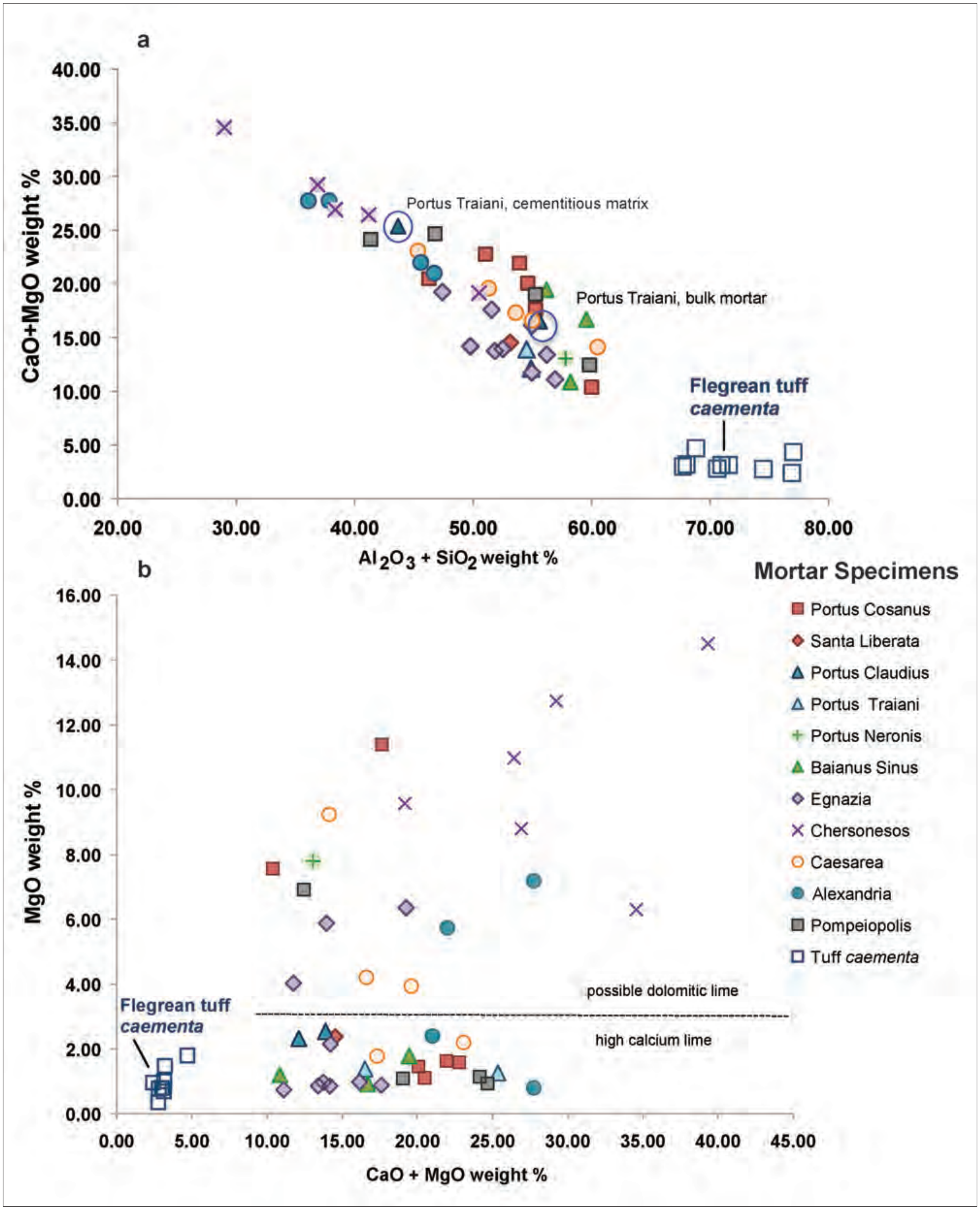


*Fig. 7.16. Results of bulk chemical analyses of the ancient maritime mortars, as weight % oxides, determined from powdered specimens (Tables A4.2, A4.3). a. $CaO$-$Al_2O_3$-$SiO_2$.b. MgO vs CaO+MgO, compositions below the dashed line may represent mortar specimens with high calcium lime, and little dolomitic (magnesium) component. The wide range of values for mortars of specific harbour concretes is due, in part, to heterogeneous proportions of volcanic ash (or limestone particles) in the centimetre-sized specimens.*

MgO could suggest a more or less dolomitic limestone source, and/or, an abundance of another magnesium-rich component, such as ceramic or lava lithic fragments. This hypothesis is complicated by the fact that Flegrean and Vesuvian whole rock pumiceous ash analyses show variable MgO, generally less than 2 weight % but in some deposits up to 8 weight % (for example, Orsi *et al.* 1992; Ayuso *et al*. 1998; Cioni *et al.* 2003; Paone *et al*. 2006; Piochi *et al.* 2006; Pabst *et al.* 2008; Tonarini *et al.* 2009). Minoan and pre-Minoan pumiceous ash generally contains less than 3 to 4 weight % MgO (Druitt *et al.* 1999).

The mortars of the central Italian coast concretes generally have low MgO (< 3 weight %). The exceptions are two Portus Cosanus specimens, one of which (core PCO.2003.05.M1) has an unusual porous fabric, occasional bits of ceramic, and a light olive grey colour, and a Portus Neronis specimen collected in 1969, about which little is known. The mortars of the harbour concretes drilled by ROMACONS far distant from Naples generally have higher MgO contents. In the Egnazia specimens, MgO ranges from lower (< 2 weight %) to higher concentrations (4 to 6 weight %), perhaps the result of dolomitic lime or ceramic fragments. In the poorly consolidated specimens from Chersonesos, MgO ranges from 6 to15 weight % and dolomite occurs in nearly all the mineralogical analyses of the mortars (Table A4.1). This suggests that the Neogene deposits of dolomite or argillaceous limestone with occasional gypsum beds that occur near the harbour site could indeed have been used in the preparation of the earthy mortar. MgO concentrations are low in the Pompeiopolis mortars, with one exception. Lime in these mortars appears to have been calcined from travertine in quarries several kilometres inland from the harbour site (Stanislao *et al.* 2011). The Caesarea and Alexandria mortars show a wide range of MgO concentrations (1 to 9 weight %). This could reflect variable compositions of limestone calcined for lime, as well as the relative abundances of limestone particles incorporated as fine aggregate. The source of both the lime and the oolitic limestone particles in the Alexandria mortars remain unknown.

*Inferences regarding the pumiceous ash mortar mix.* Silica and aluminium in the bulk compositions of the ancient mortars are derived predominantly from the pumiceous ash pozzolan, and occur as about 28 to 48 weight % $SiO_2$ and 8 to 13 weight % $Al_2O_3$ (Fig. 7.16a). Concentrations of $SiO_2$+$Al_2O_3$ in the mortars of the Brindisi concrete reproduction vary from about 45 to 60 weight % (Fig. 7.17a), but the compositions of the 48 month and 60 month specimens are outliers, perhaps associated with an influx of sea-water during the many drilling episodes of the small *pila*. The compositions of the mortar at 6, 12, and 24 months hydration are nearly identical to mortars of the central Italian harbour concretes that were formulated with Flegrean pumice pozzolan (Figs. 7.12, 7.17a). This suggests that the amount of lime in those ancient mortar mixes, either as pure CaO or with a dolomitic component, may be similar to the young Brindisi mortar reproduction with about 12 to 21 weight % CaO (Table A4.3), whose formulation is well known (Oleson *et al.* 2006), and follows the volumetric proportions recorded in ancient texts (Chapter 5).

*Inferences regarding an open hydrologic system in the concretes*. Comparisons of concentrations of alkali cations in the ancient mortars with those of the young Brindisi mortar provide insights into the possible ingress of sodium and the mobility of potassium in the sea-water concrete system. The concentrations of $Na_2O$+$K_2O$ in the Brindisi mortar reproduction are quite high, about 7 to 11 weight % (Tables A4.2, A4.3). In comparison, $Na_2O$+$K_2O$ in the ancient maritime mortars is somewhat lower, and ranges from 4 to 8 weight %. Two Chersonesos specimens have very low values, possibly the result of a low proportion of pumiceous ash in the mortar mix. Even so, these are highly alkaline compositions compared with conventional Portland cement concretes, whose alkali contents are deliberately kept very low to avoid deleterious expansions, cracking, and disaggregation associated with expansive gels produced through alkali-silica reactions (Broekmans 2012). Such reactions seem not to have taken place in the ancient pozzolanic concretes.

The sodium content in specimens from almost every harbour site except Chersonesos, Pompeiopolis and Alexandria coincide with the young Brindisi mortar compositions, with about 2.25 to 3.75 weight % $Na_2O$ (Fig. 7.17b). Lower $Na_2O$ correlates with samples with relatively less pumiceous pozzolan, as for the Portus Cosanus mortars with beach sand, and some of the eastern Mediterranean mortars. Higher values generally correlate with detection of halite, or NaCl salt, in X-ray diffraction analyses (Table A4.1). This suggests sea-water ingress and incorporation of sodium into mortars mainly from Egnazia, Chersonesos, Alexandria, possibly as a result of their porous mortar fabrics and/or proximity to the periphery of the concrete structures. In comparison, the ancient mortars have less $K_2O$ than the young Brindisi mortars, overall (Fig. 7.17c). This includes the mortars of the central Italian coast harbours, which appear to have been produced mainly with Flegrean ash pozzolan (Fig. 7.12). Potassium depletion could be the result of leaching of potassium from the relict glass of the pumiceous ash pozzolan, a common occurrence in hydrolytically altered volcanic ash soils (Jackson *et al.* 2010, and references therein). It is not clear whether this could occur as movement to another component of the concrete fabric, such as the glassy tuff *caementa* (Fig. 7.4d, c), or whether potassium could have left the concrete system entirely. Conversely, the addition of other elements into the sea-water mortar system, such as sodium chloride, could produce a relative depletion in potassium content. In either case, the low $K_2O$ values suggest some degree of fluid mobility in the concrete fabric. The specimens come from widely dispersed locations within the concrete structures so, overall, this may suggest a cementitious system open to sea-water, to at least some degree.

Many of the submerged maritime structures have a thick carbonaceous skin, millimetres to centimetres thick, which likely developed gradually over time and may now protect

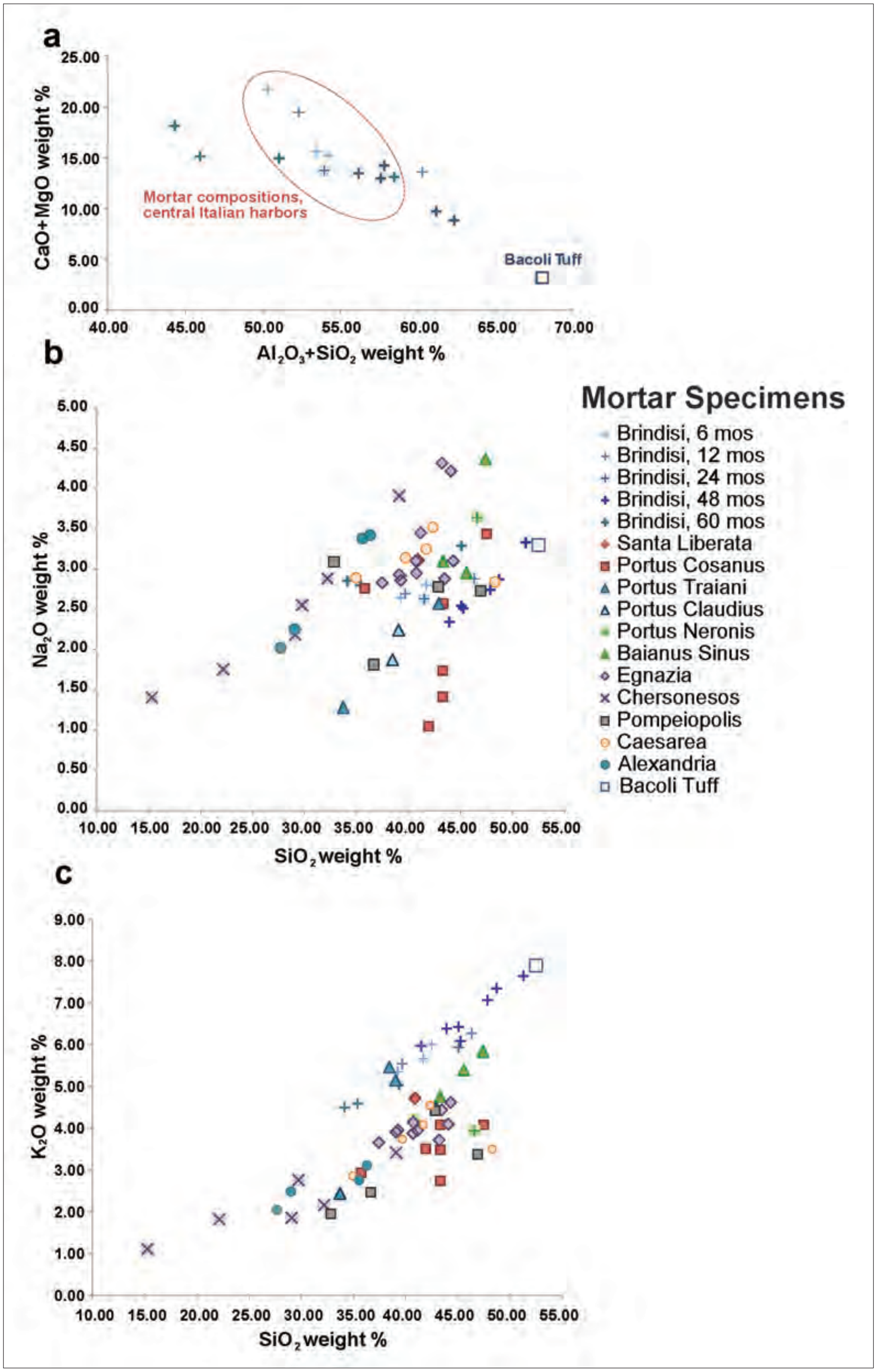


*Fig. 7.17. Results of bulk chemical analyses, as weight % oxides, of powdered bulk mortar specimens from centimetre-sized samples of the Brindisi mortar reproduction and the ancient maritime mortars (see Fig. 7.16; Tables A4.2, A4.3). a. CaO+MgO and $Al_2O_3$ + $SiO_2$ b. $Na_2O$ and $SiO_2$ c. $K_2O$ and $SiO_2$ of the mortars. The outlying compositions of specimens from the 48- and 60-month core samples may reflect the influence of influxes of sea-water during repeated drilling episodes.*

*Table 7.3. Material properties of the maritime concretes measured through engineering testing experiments: unit weight, compressive strength, and Young's (elastic) modulus (pp. 186–87; Fig 7.18).*

| **Experimental Test Specimen** | **Unit Weight (Kg/m$^3$)** | **Uniaxial Compressive Strength (MPa)** | **Young's Modulus (MPa)** |
|---|---|---|---|
| **Portus Cosanus**[1] | | | |
| PCO.03.1B | 1624 | 7.4 | 7200 |
| PCO.03.2B | 2163 | 9.4 | 18800 |
| PCO.03.3B-a | 1652 | 8.0 | 7050 |
| PCO.03.3B-b | 1587 | 7.9 | 8750 |
| PCO.03.3B-a | 1589 | 5.5 | 6500 |
| PCO.03.4B-b | 1557 | 6.4 | 5750 |
| PCO.03.4B-c | 1635 | 5.1 | 4850 |
| **Santa Liberata**[1] | | | |
| SLI.04.1A | 1550 | 8.5 | 6900 |
| SLI.01.1B | 1523 | 8.1 | 6280 |
| SLI.04.1C | 1526 | 7.5 | 6040 |
| **Portus Claudius**[1] | | | |
| POR.02.2 | 1583 | 7.8 | 5560 |
| **Portus Traiani**[1] | | | |
| PTR.02.2C | 1665 | 4.9 | 7570 |
| **Portus Neronis**[1] | | | |
| ANZ.02.A1D | 1549 | 6.3 | 6440 |
| **Baianus Sinus**[1] | | | |
| BAI.06.03 | 1494 | 7.4 | 5098 |
| **Egnazia** | | | |
| EGN.08.01 top (#1) | 1348 | 2.7 | n.d. |
| EGN.08.01 top (#2) | 1263 | 2.4 | n.d. |
| EGN.08.02 middle | 1497 | 7.1 | n.d. |
| **Chersonesos** | | | |
| CHR.07.02 top | 1688 | 3.3 | 5599 |
| CHR.07.02 middle | 1957 | 6.8 | 4178 |
| CHR.07.02 bottom | 2025 | 11.9 | 31476 |
| **Caesarea** | | | |
| CAE.05.01 | 1720 | 3.2 | 6130 |
| CAE.05.02 | 1570 | 6.4 | 6010 |
| CAE.05.04 | 1560 | 5.7 | 4870 |
| CAE.05.05 | 1520 | 3.0 | 2430 |
| **Alexandria** | | | |
| ALE.08.03.1 | 1607 | 2.5 | 3077 |
| ALE.08.03.2 | 1624 | 2.7 | 3077 |
| ALE.08.02 | 1723 | 5.0 | 6053 |
| **Brindisi Reproduction** | | | |
| Six Months[2] | | | |
| BRI.05.01top.6mos | 1530 | 7.0 | 5740 |
| BRI.05.01middle.6mos | 1390 | 3.9 | 3730 |

| Experimental Test Specimen | Unit Weight (Kg/m$^3$) | Uniaxial Compressive Strength (MPa) | Young's Modulus (MPa) |
|---|---|---|---|
| BRI.05.01base.6mos | 1415 | 3.5 | 3880 |
| One Year[1] | | | |
| BRI.05.02top.12mos | 1369 | 4.5 | 4230 |
| BRI.05.02base.12mos | 1398 | 5.6 | 5160 |
| Two Years[2] | | | |
| BRI.06.03.24mos | 1343 | 6.2 | 3648 |
| Four Years | | | |
| BRI.08.01 middle.4yrs | 1059 | 3.3 | n.d. |
| BRI.08.01 bottom.4yrs | 1026 | 3.2 | n.d. |
| BRI.08.02 top (#1).4yrs | 1001 | 2.3 | n.d. |
| BRI.08.02 top (#2).4yrs | 1068 | 4.0 | n.d. |
| BRI.08.02 bottom.4yrs | 1059 | 3.9 | n.d. |
| Five years | | | |
| BRI.2009.01middle1 | 1377 | 6.8 | n.d |
| BRI.2009.01middle2 | 1314 | 4.0 | n.d |
| BRI.2009.01base | 1347 | 4.8 | n.d |

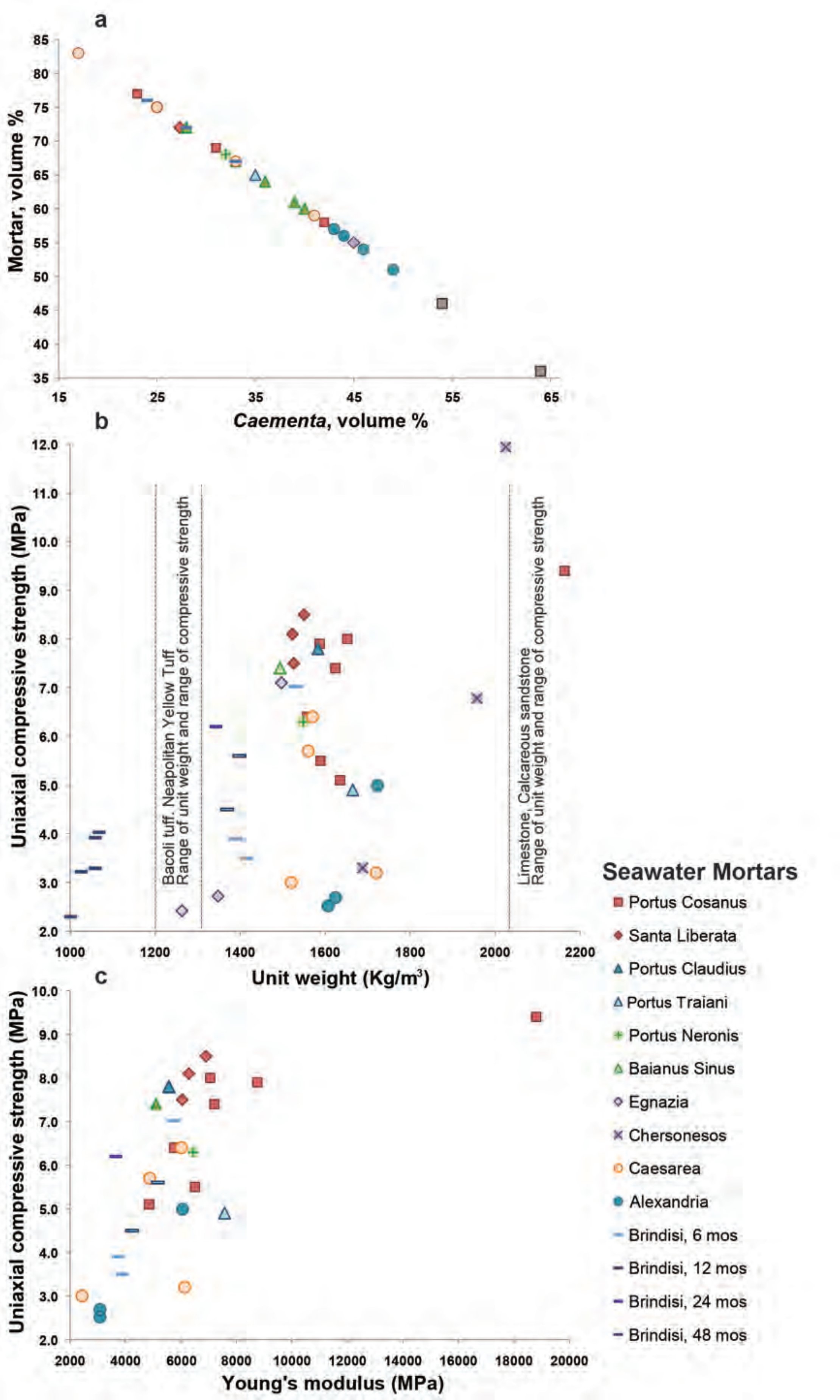
[1]Oleson *et al*. 2004. [2] Oleson *et al.* 2006; Gotti *et al.* 2008

the porous concrete fabric from direct saturation with sea-water. Even so, the major element analyses suggest that the ancient structures may not be closed chemical systems but, rather, that sea-water has penetrated into the concretes over the centuries: along openings created by the decay of wooden tie bars; along fractures, as at Santa Liberata or Caesarea; and through permeable mortar pores and interfacial voids in porous concretes, as at Egnazia and Chersonesos. Compositional maps of the fine scale distribution of elemental sodium, sulphur, chloride, and potassium in the Portus Claudius mortar, for example, indicate that these species are sequestered in discrete crystalline microstructures composed of chloride- and sulphate bearing minerals, commonly in proximity to relict lime clasts (Fig. 7.1) (Jackson *et al.* 2012). In conventional Portland cement concretes, $SO_4^{2-}$ and $Cl^-$ penetration from sea-water have the potential to cause damaging expansive reactions and corrosion of steel reinforcements, so it is remarkable that in at least some of the ancient concretes, these species are immobilized in crystalline microstructures (Fig. 7.3e, f).

## 7.5. Material properties of the maritime concretes

Measurements of the physical properties of the maritime concrete drill cores through testing experiments under ambient conditions in the laboratory provide a useful reference to qualitatively assess the coherence and consolidation of the harbour structures after very long-term exposure to the sea-water environment (Fig. 7.18). The ancient harbour constructions were not generally required to bear large compressive loads. Rather, it seems that their fundamental structural requirement was to remain securely established on the seafloor, while performing as rigid breakwaters, well-consolidated piers to moor large seagoing vessels, and firm foundations for modest subaerial harbour constructions (Vitruvius *De arch.* 2.6.1). This required a strong resistance to abrasion, disaggregation and erosion during wave action, to sea-water chemical attack and decay, and to displacement and fracture as a response to the force of impact of large storm waves. The unit weight, compressive strength, and elastic modulus measured in the drill core specimens of the ancient concrete, and the overall porosity and size distribution of pores measured in the mortars is quite different from those of conventional Portland or blended cement concretes. These physical properties are discussed in terms of the influences of the geological components of the concretes – lime, pumiceous volcanic ash, volcanic tuff, and carbonate rock – and compared with the young Brindisi pila reproduction (pp. 178-80).

***7.5.1. Unit weights of the concretes.*** Measurements of twenty-seven segments of drill cores of the ancient concretes under ambient laboratory conditions (Fig. 7.18b, Table 7.3) indicates that these materials have well-constrained dry unit weight, generally between about 1500 and 1700 kg/m$^3$. This suggests that the subcores of the concrete, which range from about 85 to 215 cm in length, give reasonable representations of the density of the concrete fabrics, overall. The cores of the central Italian



a
Mortar, volume %
85
80
75
70
65
60
55
50
45
40
35
15
25
35
45
55
65
*Caementa*, volume %
b
Uniaxial compressive strength (MPa)
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
Bacoli tuff, Neapolitan Yellow Tuff
Range of unit weight and range of compressive strength
Limestone, Calcareous sandstone
Range of unit weight and range of compressive strength
1000
1200
1400
1600
1800
2000
2200
Unit weight (Kg/m³)
c
Uniaxial compressive strength (MPa)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Young's modulus (MPa)
Seawater Mortars
Portus Cosanus
Santa Liberata
Portus Claudius
Portus Traiani
Portus Neronis
Baianus Sinus
Egnazia
Chersonesos
Caesarea
Alexandria
Brindisi, 6 mos
Brindisi, 12 mos
Brindisi, 24 mos
Brindisi, 48 mos

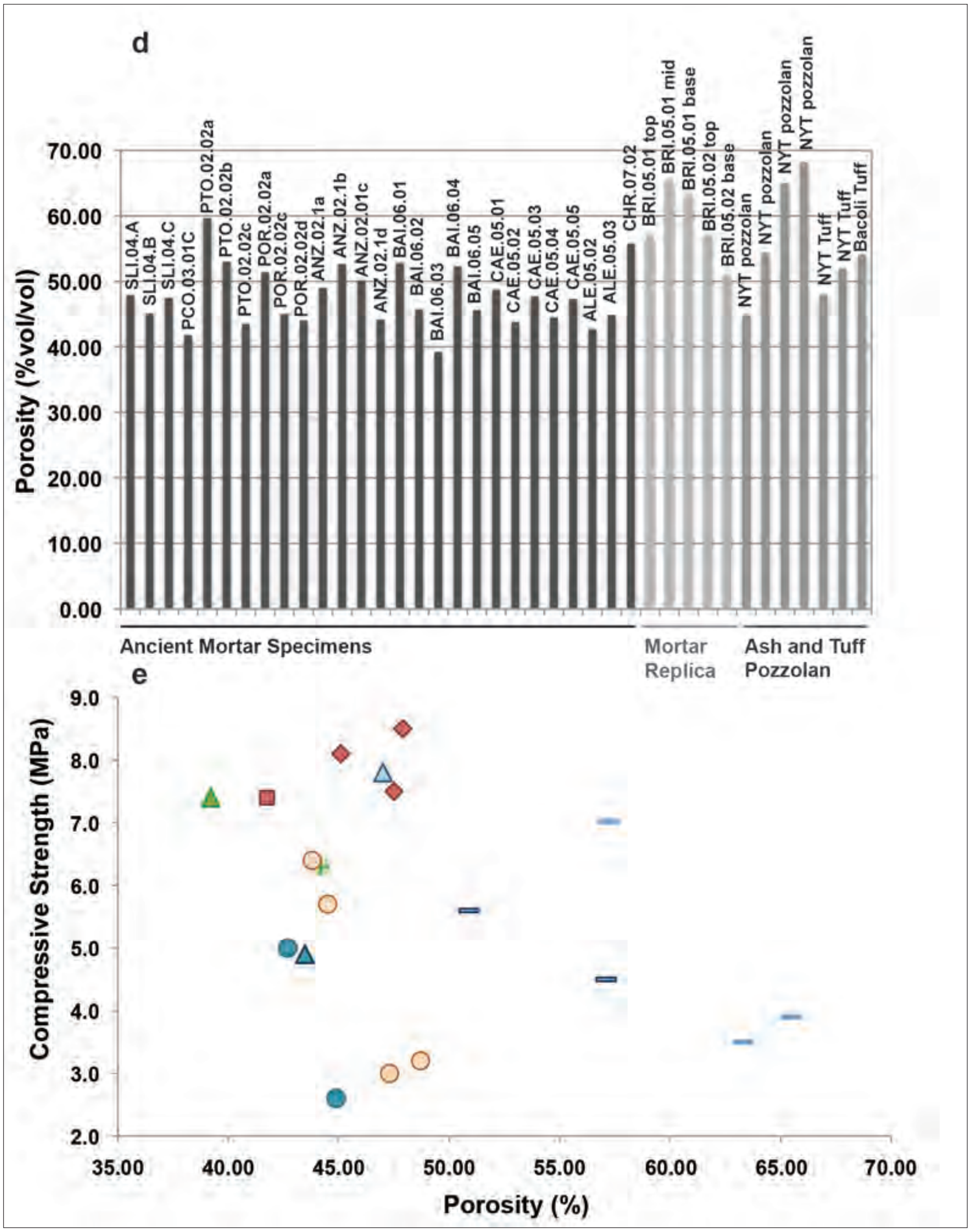


*Fig. 7.18. Determinations of the material characteristics of the ancient concretes and pozzolanic mortars, measured in drill core specimens. a. Measurements of the relative proportions of mortar and decimeter-sized* caementa *(Table 7.1). b. Unit weight and uniaxial compressive strength of drill core segments of the ancient maritime concretes and the young Brindisi concrete reproduction (Table 7.3). Bacoli Tuff unit weight is about 1300 kg/m*$^3$ *(this study); Neapolitan Yellow Tuff unit weight is 1200 to 1400 kg/m*$^3$*, compressive strength is 0.7 to 12 MPa (Colella* et al. *2001); calcareous sandstone (calcarenite) unit weight is about 2020 kg/m*$^3$ *(Scicchitano* et al. *2007), compressive strength is 2 to18 MPa, and limestones are similar (Marcari* et al. *2010); Tufo Lionato from the Salone quarry has unit weight about 1520 kg/m*$^3$ *and compressive strength about 26 MPa (Jackson* et al. *2005). c. Young's modulus (elastic modulus) and uniaxial compressive strength of drill core segments of the ancient maritime concretes and the young Brindisi concrete reproduction (Table 7.3). d. Porosity, as volume %/total volume, of mortars of the ancient maritime concretes (dark gray bars) and young Brindisi reproduction (light gray bars), and of the Neapolitan Yellow Tuff and the Bacoli Tuff (medium gray bars) (Pellegrino 1967 (in Ottaviano 1988)). Each bar represents a single sample measurement (see Table 7.4); Alexandria mortar determinations by Rispoli (2011). e. Mortar porosity and uniaxial compressive strength of drill core segments of the ancient maritime concretes, the young Brindisi concrete reproduction, the Bacoli Tuff, and the Neapolitan Yellow Tuff.*

coast harbour concretes with Flegrean tuff *caementa*, range from 1494 kg/m$^3$ for the Baianus Sinus core (core BAI.2006.03) to 1635 kg/m$^3$ for the Portus Cosanus core segment from Pier 2 (core PCO.2003.02). There is a single outlier from the same Portus Cosanus core with 2163 kg/m$^3$, likely because this segment (core PCO.2002.02B) contains dense, compact lava as *caementa*. The determination of 1550 kg/m$^3$ for an Anzio subcore (core ANZ.2002.A1D) gives an approximation of the unit weight of the mortar at Portus Neronis, since there is a general absence of decimetre-sized *caementa*. The unit weight of a Santa Liberata mortar specimen (SLI.2004.01) is about 1210 kg/m$^3$. Conventional Portland cement mortars have unit weight about 1950 to 2160 kg/m$^3$.

The unit weight of the Neapolitan Yellow Tuff generally ranges from about 1200 to 1400 kg/m$^3$ (Bolondi *et al.* 2007; Papakonstantinou *et al.* 2012), and the very pumiceous Bacoli Tuff used in the 2004 Brindisi concrete reproduction has unit weight, 1205 kg/m$^3$. These glassy, porous rocks have very high water sorption. When saturated with water the Neapolitan Yellow Tuff absorbs between 38 and 52 weight % of its dry weight (Bolondi *et al.* 2007). This suggests that if the tuff or similar poorly lithified pumiceous ash were saturated with sea-water during transport to harbour construction sites, their weight as ballast would increase accordingly. In comparison, the well lithified Tufo Lionato at Portus Claudius and Portus Traiani has unit weight about 1570 kg/m$^3$ and 20 to 30 weight % water absorption (Jackson *et al.* 2005). Unit weights for Tufo Lionato can vary from about 1250 to 1850 kg/m$^3$ through the Roman region (De Casa *et al.* 1999).

The concretes from harbours far distant from Naples show a greater range of unit weights: as low as 1263 kg/m$^3$ for the Egnazia core with rather porous, poorly consolidated mortar; to 1520 to 1570 kg/m$^3$ for Caesarea cores, with one outlier at 1720 kg/m$^3$ that represents a larger proportion of calcarenite sandstone *caementa*; to fairly regular values, 1607 to 1723 kg/m$^3$ for the Alexandria cores, with a more compact and consolidated mortar and carbonate rock *caementa*. The range of unit weights determined for the Chersonesos cores, 1688 to 2925 kg/m$^3$, also depends on the relative proportion of the fossiliferous wackestone *caementa*. Calcarenite grainstone has unit weight of about 2013 to 2590 kg/m$^3$ (Scicchitano *et al.* 2007), and limestone typically has unit weight of about 2450 kg/m$^3$. These values are substantially higher than those of the pumiceous mortar, and thus increase the unit weight of the concrete. The unit weights of the Pompeiopolis cores were not measured.

In comparison with the ancient maritime concretes, the unit weights of the concrete *pila* reproduction at Brindisi are quite low. At six months hydration, the unit weights of the top, middle, and base of the BRI.2005.01 core fall in the range 1390 to 1530 kg/m$^3$. The top and base of the core taken at 12 months hydration shows slightly lower values, 1369 and 1398 kg/m$^3$, and at 24 months, even lower values were measured, 1343 kg/m$^3$. Unit weights drop precipitously in the core taken at 48 months hydration, to 1001 to 1068 kg/m$^3$; this material has a darkly opaque cementitious matrix and occasional *in situ* crystallization of zeolite. They are somewhat higher, however, in the core taken at five years hydration, 1293 to 1377 kg/m$^3$. These variations may reflect the early consolidation of the concrete through formation of C-A-S-H, followed by disturbances to cementitious fabrics and increasing porosity as subsequent drill cores introduced new fluids and atmospheric gases to the 2 m$^3$ curing environment. The low unit weight overall may reflect the higher relative proportion of lightweight Bacoli Tuff used in the reconstruction, compared with the mortar to *caementa* ratios of the ancient concretes and relatively less compaction, as well (Oleson *et al.* 2006).

***7.5.2. Compressive strengths of the concretes.*** Measurement of the uniaxial compressive strength of twenty-seven segments of the drill cores of the ancient concretes, which vary from about 85 to 250 cm in height, indicate that these materials have a wide-ranging response to compressive loading in the laboratory (Fig. 7.18b, Table 7.3). There does not appear, however, to be a clear correlation between the length of the core segments and increased strength. The core segments of the central Italian coast harbour concretes with Flegrean tuff *caementa*, show ultimate strengths in the range of about 5 to 8 MPa under ambient laboratory conditions. The variability of results for the Portus Cosanus subcores (PCO.2002.02) likely results from the variety of rocks used as *caementa*: pumiceous tuff, dense lava, and other igneous rocks. The 6.3 MPa compressive strength measured in the Portus Neronis core segment (ANZ.2002.01), may give an approximation of the mortar strength, since the core segment contains no tuff *caementa*. The 7.4 MPa compressive strength of the Baianus Sinus (BAI.2006.03) core segment can be considered a representative value of the well-consolidated concrete.

The widely scattered compressive strengths of cores from harbour concretes far distant from Naples that contain predominantly wackestone, packstone, and grainstone *caementa* indicate quite unpredictable behaviour, at least in the laboratory setting. For the Egnazia tests, low unit weight correlates with very low compressive strength, 2.4 to 2.7 MPa. This is likely the result of a porous, rather poorly consolidated mortar and poorly bonded wackestone-packstone *caementa.* The Chersonesos tests show dispersed strengths, 11.9 and 6.8 MPa, that seem to correlate with the strength of the fossiliferous wackestone *caementa,* and a very low value, 3.3 MPa, that seems to correspond to disbonding of the porous pumiceous mortar or its debonding with the *caementa*. The three Alexandria tests show moderate strength, 5.0 MPa, to very low strength, 2.5 to 2.7 MPa, likely the result of debonding of the stiff, oolitic grainstone *caementa* along interfacial zones with the pumiceous mortar. The Caesarea tests show a similar result: moderate strength in two cores, 5.7 to 6.4 MPa, and very low strength, 3.0 and 3.2 MPa, in two others. The compressive strengths of the Pompeiopolis cores were not determined, since the very large contrast in material properties between the relatively soft pumiceous mortar and the indurated amphibolite and stony corals of smooth, rounded river cobbles would not have produced a meaningful laboratory measure of mechanical behaviour. Determinations of Young's modulus, a measurement of the ability of the concrete to deform elastically when a compressive force is applied, roughly follow a increasing linear trend with increasing compressive strength. The elastic modulus is generally higher in the core segments of the central Italian coast concretes, 4850 to 8750 MPa, than in those of the harbours far distant from Naples (Fig. 7.18c). Values in the Chersonesos, Caesarea and Alexandria core segments range from 2430 to 6053 MPa, and show great variability among the specimens at each harbour site, similar to the compressive strength results.

The very heterogeneous fabric and mechanical properties of the ancient maritime concretes at the decimetre length scale, especially for those with limestone *caementa*, suggests that the results of laboratory tests on the 9 cm diameter core segments do not provide a rigorous assessment of compressive strength in the maritime environment. The true resistance of the concrete blocks to compressive loads could be higher, even when submerged in sea-water, because the loads are distributed over a broad area.

*Tuff vs. carbonate rock* caementa. The differences in mechanical behaviour among the concrete test specimens may be explained, in part, by the material characteristics of the glassy tuff *caementa*, as compared with the limestone *caementa* of the eastern Mediterranean harbours. Flegrean tuff has low unit weight and elastic modulus, about 1300 kg/m$^3$ and 2760 MPa, and Tufo Lionato has slightly higher weight and elastic modulus, about 1520 kg/m$^3$ and 3967 MPa. The ragged surfaces of the glassy tuffs form coherent bonds with the well-consolidated cementitious matrix of the mortars (Fig. 7.6). Calcarenite grainstone has higher average compressive strength, with an average of 7.36 MPa for specimens sampled in Puglia, and wide ranging Young's Modulus, 4300 to 12000 MPa (Marcari *et al.* 2010), but its bond with the pumiceous maritime mortars seems less cohesive. For example, experimental concrete masonry panels with rectangular calcarenite "bricks" show high elastic stiffness and a rapid strength decrease in their post-peak stress response, indicating quite brittle behaviour overall. In contrast, panels formulated with Neapolitan Yellow Tuff "bricks" show lower compressive strengths, about 3 to 4.5 MPa, but a softer, more controlled post-peak response, indicating more ductile behaviour (Marcari *et al.* 2010).

The wide scatter in compressive strength and elastic response of the core specimens of the eastern Mediterranean harbour concretes may be the result, in part, of the high stiffness of limestone relative to the pumiceous mortar, and interfacial bonds that are weakly cohesive, with little interpenetration of pozzolanic cements. Rupture of the core segments seems to occur mainly along these surfaces. The more predictable capacity of the core segments of the central Italian coast concretes to resist deformation may be the result of more cohesive interfacial bonding between the pumiceous mortar and the pumiceous tuff, and the possibility that a similar stress response may govern the behaviour of both materials as the mortar gains cohesion through long-term hydration. The measured compressive strengths and elastic modulus of the drill core specimens are similar to those of imperial era conglomeratic concretes in the monuments of Rome, about 6 MPa and 2560 MPa, measured in one m$^3$ reproductions of the ancient material with brick *caementa* (Samuelli Ferretti 1997). In comparison, the unit weight and compressive strength of ordinary Portland cement concrete is about 2300 kg/m3 and 30 MPa, and the elastic modulus of the hardened paste may be in the order of 10 to 30 GPa (Mehta and Monteiro 2006).

*Resistance to wave forces.* The force of impact of strong waves on the sides of the ancient concrete structures, generated by typhoons, hurricanes, winter storms, and earthquakes over the centuries, could be close to tens of thousands of metric tons per square metre in large events (Mehta 1991: 25). Such strong wave action affects concrete structures mainly in the supratidal zone, or splash zone, the area above the level of high spring tides. Here, the concrete is also subject to erosion from sand and gravel suspended in sea water. In recent history, many modern breakwaters composed of unreinforced concrete failed and were displaced from their foundations in large storm events throughout the Mediterranean area (Mehta 1991: 24–25). Maritime concretes are now systematically reinforced with steel, but steel is subject to corrosion in salt water, and many reinforced structures suffer salt weathering, disaggregation, and spalling (Mehta 1991: 64–69).

It is remarkable that nearly all the Roman maritime concrete structures studied here show little evidence for substantial translational displacement along their foundations or along fractures. The exception is the Sebastos harbour at Caesarea, which is open to the sea, and may have been subject to exceptionally strong wave forces associated with distant earthquakes in the first century and sixth century, as well as long term subsidence (Reinhardt *et al.* 2006; Dey and Goodman-Tchernov 2010). It may be that the ancient concretes rely on a clast supported framework of *caementa* – mainly glassy volcanic tuff or local carbonate rock – to resist forces at the structural scale. The conglomeratic fabric of the concrete, composed of about 35 to 45 volume % *caementa* (Fig. 7.18a, Table 7.1), may reinforce the concrete structures, and the bonding of *caementa* along interfacial zones with the pumiceous mortar and the massive size and weight of the structures may be responsible, in part, for the long-term strength and stability of the harbour installations. Each of the relatively small *pilae* in the Bay of Pozzuoli near Secca Fumosa (Fig. 7.7), for example, has a volume of about 600 m$^3$ and weighs about 900 metric tons, based on the approximately 1500 kg/m$^3$ unit weight measured in the laboratory for the Baianus Sinus concrete (BAI.2006.03) (Table 7.3).

The resistance to fracture, or toughness, of the ancient maritime concretes may be higher than modern concretes, as a result of the highly heterogeneous particle size distribution of their ash pozzolan and rock *caementa*. Toughness is related to ductility, and describes how much energy a material can absorb before it cracks. Recent fracture testing experiments on a reproduction of the hydrated lime–scoriaceous volcanic ash mortar of the Markets of Trajan wall concrete (Brune *et al.* 2013) supports the hypothesis that the ancient Roman concrete monuments survive by impeding the connectivity and propagation of microcracks. This may be true of the Roman maritime concrete structures, as well.

*Strength development in the Brindisi concrete reproduction.* The unit weights and compressive strengths measured in the Brindisi concrete reproduction are generally lower than the ancient concretes, except for certain Egnazia, Chersonesos, Caesarea, and Alexandria specimens. At 6 months hydration, compressive strength ranges from 3.5 and 3.7 MPa, in the base and middle sections of the core, to 7.0 MPa at the top. The results of tests at 12 months hydration, 4.5 MPa and 5.6 MPa, and at 24 months hydration, 6.2 MPa, fall in this same range. Six months after installation, the concrete seems to have achieved at least 70% of its strength at one year hydration. This suggests that harbour structures installed in the spring could possibly withstand winter storm surges later in the year. The young concrete seems to show a response to compressive loading that is more similar to the tuff, but has yet to acquire the unified strength of the mature concrete composite at 24 months hydration. It is not clear why the results of tests at 48 months hydration show very low strengths, 2.3 to 4.6 MPa. Strengths measured at 60 months hydration, 4.6 to 6.8 MPa, seem similar to those at one to two years hydration – about the point at which C-A-S-H development may have been complete, based on a thermal model of the Baianus Sinus *pila* in the Bay of Pozzuoli (pp. 183–84).

**7.5.3. Porosity of the sea-water mortars.** The relative size distribution and cumulative volume of pores in the ancient mortars has the potential to strongly influence the chemical and mechanical durability of the maritime concrete structures, especially in beach and intertidal environments where there is a continuous cycling of subaerial drying and moisture, and repetitive penetration of sea-water salts into the concrete fabric (Massazza 1985; Mehta 1990). The volume and connectivity of pores in modern cementitious materials have important influences on the transport of fluids through the mortar and/or concrete, so comparisons of pore characteristics of the ancient materials with those of their pyroclastic rock pozzolans and conventional mortars should provide insights into the exceptional resistance to decay of the maritime concretes.

The histogram of Figure 7.18d compares the cumulative porosity, as percent pore volume per total volume of material (% vol/vol), in the ancient mortars, the Brindisi mortar reproduction, the Neapolitan Yellow Tuff, and the Bacoli Tuff, measured through mercury intrusion porosity measurements.

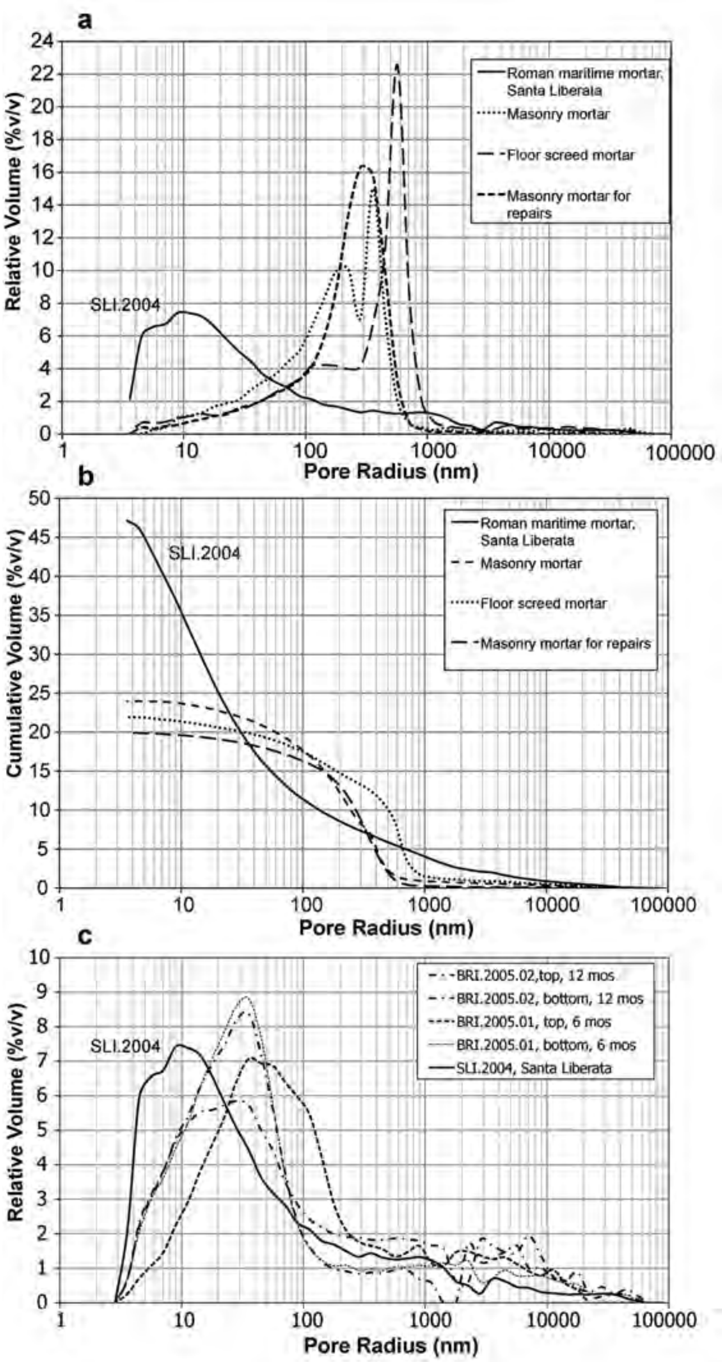


*Fig. 7.19. Determination of the pore structures of the young and ancient sea-water mortars through mercury intrusion porosity experiments (after Gotti* et al. *2008). a. Relative pore size distribution in a typical maritime mortar specimen with Flegrean pumiceous ash pozzolan from Santa Liberata (SLI.2004.01A), compared with modern Portland cement mortars. b. Cumulative porosity of the Santa Liberata (SLI.2004.01A) mortar specimen compared with modern Portland cement mortars. c. Pore size distribution of the Santa Liberata (SLI.2004.01A) mortar specimen compared with the Brindisi mortar reproduction at 6 months hydration (BRI.2005.01) and at 12 months hydration (BRI.2005.02).*

*Table 7.4. Porosity of the maritime mortars and constituent volcanic ash/tuff pozzolan, measured through mercury intrusion porosity tests (p. 187; Fig. 7.18d, e).*

| Specimen | Porosity (%Vol/Vol) | Cumulative Volume ($cm^3$/Vol) |
|---|---|---|
| **Flegrean Pyroclastic Rock** | | |
| NYT pozzolan[1] | 54.4 | n.d. |
| NYT pozzolan[1] | 68.2 | n.d. |
| NYT pozzolan[2] | 45.0 | n.d. |
| NYT pozzolan[2] | 65.0 | n.d. |
| NYT tuff[3] | 48.0 | n.d. |
| NYT tuff[3] | 52.0 | n.d. |
| Bacoli Tuff | 54.1 | 0.45 |
| **Maritime mortars** | | |
| **Portus Cosanus[4]** | | |
| PCO.03.1A | 42.3 | 0.34 |
| PCO.03.1C | 43.6 | 0.36 |
| PCO.03.2A | 35.1 | 0.33 |
| PCO.03.2C | 37.1 | 0.42 |
| PCO.03.3A | 44.7 | 0.23 |
| PCO.03.3C | 45.8 | 0.33 |
| PCO.03.4A | 48.4 | 0.38 |
| PCO.03.5A | 51.3 | 0.44 |
| **Santa Liberata** | | |
| SLI.03.01[5] | 46.5 | 0.42 |
| SLI.04.1A[5] | 47.9 | 0.39 |
| SLI.04.1B[5] | 45.1 | 0.38 |
| SLI.04.1C[4] | 47.5 | 0.39 |
| **Portus Claudius** | | |
| POR.02.2-a | 45.7 | 0.53 |
| POR.02.2-b | 52.3 | 0.36 |
| POR.02.2-c | 45.6 | 0.37 |
| **Portus Traiani** | | |
| PTO.02-a | 50.1 | 0.58 |
| PTO.02-b | 44.2 | 0.49 |
| PTO.02-c | 52.8 | 0.32 |
| **Portus Neronis** | | |
| ANZ.02.1-a | 48.7 | 0.41 |
| ANZ.02.1-b | 43.8 | 0.45 |
| ANZ.02.1-c | 47.7 | 0.42 |
| ANZ.02.1-d | 44.5 | 0.31 |
| **Bay of Pozzuoli** | | |
| BAI.06.01 | 47.3 | 0.50 |
| BAI.06.02 | 42.7 | 0.37 |
| BAI.06.03 | 44.9 | 0.29 |
| BAI.06.04 | 55.8 | 0.49 |
| BAI.06.05 | 57.2 | 0.36 |
| **Chersonesos** | | |
| CHR.07.02 | 55.8 | n.d. |
| **Caesarea** | | |
| CAE.05.01 | 65.5 | 0.45 |
| CAE.05.02 | 63.3 | 0.39 |
| CAE.05.03 | 57.1 | 0.44 |
| CAE.05.04 | 50.9 | 0.39 |
| CAE.05.05 | 47.3 | 0.44 |
| **Alexandria[3]** | | |
| ALE.08.02 | 42.7 | 0.31 |
| ALE.08.03 | 44.9 | 0.33 |
| **Brindisi Reproduction** | | |
| BRI.05.01-Amiddle | 57.2 | 0.48 |
| BRI.05.01-Btop | 65.5 | 0.62 |
| BRI.05.01-Cbase | 63.3 | 0.66 |
| BRI.05.02top | 57.1 | 0.63 |
| BRI.05.02base | 50.9 | 0.66 |

[1] De Vita 2008. [2] Pellegrino 1967 (in DeVita 2008). [3] Peluso and Arienzo 2007.
[4] Oleson *et al.* 2004. [5] Gotti *et al.* 2008; Vola *et al.* 2010a.

The overall volume of pore space in the sea-water mortars is very high, and ranges from about 43 to 53% vol/vol, or about 390 $mm^3$ per gram, with slightly lower values for certain Portus Cosanus (PCO.2003.01C), Baianus Sinus (BAI.2003.03), and Alexandria (ALE.2007.02) specimens (Table 7.4). The porosity of the Flegrean pumiceous pyroclastic rocks ranges even higher, 43 to 68% (Pellegrino 1967, in Ottaviani 1988; Colella *et al.* 2001, 2009). Although a linear relationship exists between the porosity of glassy Italian tuffs and their compressive strengths (Ottaviani 1988), this does not seem to be the case for the ancient sea-water concretes, even for those with glassy tuff *caementa*. There seems to be no clear correspondence between the total porosity of the mortars and the compressive strength of the concretes measured in laboratory (Fig. 7.18c). This is possibly because failure along interfacial zones of the decimetre-sized tuff and limestone *caementa*, which commonly contain fine scale voids (Figs. 7.5, 7.8d), may control the deformational behaviour of the drill core specimens, at least in the laboratory setting.

The distribution of pore radii in the ancient mortars shows a broad maxima between about 4 and 120 nanometres (nm) in nearly all the specimens tested (Fig. 7.19a, Table 7.4), shown

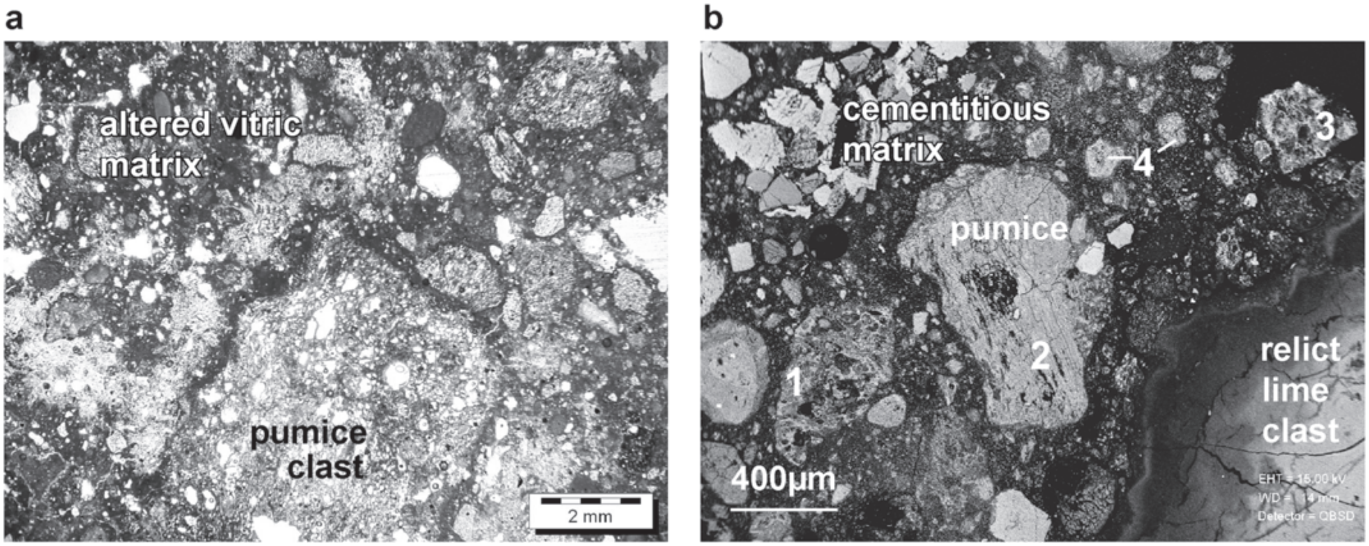


*Fig. 7.20. Images showing the pore structure of Flegrean tuff pozzolan and the pumiceous sea-water mortar fabric from a Portus Neronis core sample. a. Vesicular fabric of the Bacoli Tuff, showing the porous coarse pumice clasts and the altered vitric matrix, composed of fine pumiceous ash (petrographic image, plane polarized light). b. Cementitious matrix of the Portus Neronis mortar. Vesicles of pumice clasts (1, 2, 3) are lined with cementitious hydrates; vesicles of fine pumiceous ash particles (4) are filled with cementitious hydrates, mainly C-A-S-H and Al-tobermorite (SEM-BSE image).*

here for typical specimen from Santa Liberata (SLI.2004.01A) (Gotti *et al.* 2008), which is representative of most of the ancient mortar fabrics. The Alexandria mortars are offset to slighter larger values, 10 to 140 nm, perhaps the result of testing in a different laboratory (Rispoli 2011). The predominant pore size thus occurs at a very fine scale, about an order of magnitude smaller than modern conventional mortars (Fig. 7.19b). The overall porosity is much higher, as well. High porosity in modern mortars commonly correlates with poor durability, so it would be important to understand the basis for the unusual pore structure of the ancient mortars, given their extraordinary longevity.

The Bacoli Tuff and the Neapolitan Yellow Tuff have a pore structure that is defined by the vesicular structure of glass and pumice clasts and the fine ash particles that compose the altered vitric matrix of the tuff and unconsolidated ash (Fig. 7.20a). This is the material that forms the relict pozzolan within the cementitious matrix of the ancient mortars, shown here for the Portus Neronis mortar (Fig. 7.20b), whose pumiceous pozzolan likely derives from Campi Flegrei deposits (Fig. 7.12). Pore radii in the Neapolitan Yellow Tuff are mainly between 8 and 115 nm, with a maxima at about 35 nm (Colella *et al.* 2009). A second maxima occurs at a median pore size of about 40 micrometres, presumably as larger vesicles in pumice clasts (Colella *et al.* 2009). Measurements by Vola *et al.* (2011a) show the cumulative open porosity of the Bacoli Tuff to be about 40 to 63% vol/vol, and the peak pore size distribution is about 50 to 150 nm, with a maxima at about 60 nm.

Figure 7.19c compares the pore size distribution of the 2000-year-old Santa Liberata mortar, with its very young counterpart in the Brindisi concrete reproduction (Gotti *et al.* 2008). Both mortars are formulated with Flegrean ash; the trace element signature of the SLI.2004.01.P1 pumice specimen falls in the Bacoli Tuff compositional field (Figs. 7.10–12). The predominant pore size of the young Brindisi mortar is about 35 to 45 nm at six months hydration, nearly identical to the Neapolitan Yellow Tuff (Colella *et al.* 2009), and slightly smaller, 30 to 35 nm, at twelve months hydration. In comparison, the predominant pore size of the Santa Liberata mortar is much smaller, about 10 nm. This may suggest that the pore structure of the mortars is derived from relicts of the ash pozzolan, and that the smaller pore radii of the ancient mortars relative to those of the young Brindisi reproduction reflects pore refinement through formation of cementitious hydrates. In the Portus Neronis mortar, for example, cementitious hydrates have formed along vesicle surfaces of the coarse sand-sized pumice particles (Fig. 7.20b, 1, 2, 3) and they have almost completely filled the relict porosity of fine sand-sized particles (Fig. 7.20b, 4). This process likely began early in the hydration history of the concrete, shown by a decrease in cumulative pore volume and pore size from six to twelve months hydration in the Brindisi concrete reproduction (Gotti *et al.* 2008), as nanoscale voids in the ash pozzolan were filled with cementitious components, mainly C-A-S-H.

In Portland cement concretes the capillary porosity, defined as pores with radii 10 to 1000 nm, represents the residual space between cement and aggregate grains that was originally filled with interstitial water; large pores greater than 1000 nm generally represent air entrapment (Taylor 2004: 247–49). The large macropores influence compressive strength and permeability, while micropores influence drying shrinkage and creep (Mehta and Monteiro 2006: 32–35). The measured porosity of conventional mortars, floor screed mortars, and repair mortars formulated with Portland-type cement and relatively inert sand- and fine gravel-sized aggregate, is about 20 to 24% vol/vol and cumulative pore volume is about 123 to 98 $mm^3$/gram (Fig. 7.19a, b) (unpublished CTG Italcementi research, E. Gotti and R. Cucitore, 2007). Pore sizes typically range from 100 to 7500 nm, commonly in a bimodal distribution. In comparison, the ancient maritime mortars have a general paucity of pores in these size ranges. Even though their capillary porosity is about double that of conventional mortars, and the cumulative pore volume is about three times higher, the high overall porosity has not led to intensive decay, even in intertidal zones. The nanoscale pore size distribution measured in the mortars of the central Italian coast and the eastern Mediterranean harbour concretes thus appears to correlate more closely with the pore structure of the pumiceous ash pozzolan, as represented by the measured pore structure of the Bacoli and Neapolitan Yellow Tuffs.

As regards long-term endurance, the ancient mortars far surpass the longevity of conventional Portland-type cement based composites in sea-water (Massazza 1985; Mehta 1990). Roman maritime concretes do not contain steel reinforcements that are subject to chloride attack and corrosion. In addition, the results of porosity tests and microstructural observations (Figs. 7.18c, d, 7.19, 7.20) suggest that the vesicular structure of the pumiceous pozzolan forms an integral component of the complex pore structure of the cementitious matrix of the mortars. Interstital water may play a very different role in Roman maritime concrete than in Portland cement pastes: sea-water saturated the entire portlandite-volcanic ash system; it drove the pozzolanic reaction that produced C-A-S-H in the porous pozzolan; and the cementitious system remained saturated for an exceptionally long time. It may be that the vesicular, particulate nature of the ash led to low permeability, and slowed diffusion of fluids through the mortar over time, leading to a relatively stable chemical system through the massive *pila* structures.

## 7.6. Inferences regarding durability of the ancient sea-water concrete

Analytical investigations of the mortar fabrics and cementitious binding hydrates of the ancient maritime concretes reveal strong resemblances among all the harbour sites drilled by ROMACONS, ranging from the first century BC through second century AD and from the central Italian coast to the eastern Mediterranean region (Figs. 7.5–7.9). The results of these investigations provide new perspectives for understanding the extraordinary durability of the ancient pumiceous concrete in sea-water and shoreline environments, in terms of its cementing components, material characteristics and physical properties, and the apparently standardized procedures that Roman builders designed to prepare the raw materials and install the concretes in harbour structures.

***7.6.1. Al-tobermorite as a cementitious phase.*** Sea-water mortars from all the harbour concretes contain Al-tobermorite as a crystalline cementitious phase (Table A4.1; Figs. 7.1, 7.3). The difficulty of producing the crystals in modern conventional concretes (pp. 167–68)) suggests that builders likely followed specific protocols for the selection of pumiceous ash pozzolan, preparation and hydration of lime, mixing the mortars, and installation of the concretes. The $^{29}$Si magic angle spinning, nuclear magnetic resonance (MAS NMR) analysis of Al-tobermorite in a Baianus Sinus relict lime clast (Fig. 7.21a–c) indicates crystals with a double chain silicate structure, and alumina tetrahedra that substitute for silica tetrahedra in chain (($Q^2$(1Al)) and branching (($Q^3$(1Al), $Q^3$(2Al)) positions (Jackson *et al.* 2013a, b). The crystals have long chain lengths in the **b** [020] crystallographic direction, shown by the high intensity of $Q^2$(0Al) and $Q^2$(1Al) peaks relative to the $Q^1$ peak. The $^{27}$Al NMR analysis in the tetrahedral range of 50–80 ppm (Fig. 7.21b) clarifies that there is more aluminium in bridging $Q^2$(1Al) sites of the silicate chains, the 57.70 peak, than branching sites $Q^3$(1Al), the 65.63 peak. This also suggests that silicate chain polymerization may have occurred. The double silicate chain structure accommodates $Na^+$ and $K^+$, which balance $Al^{3+}$ substitution for $Si^{4+}$, and apparently leads to chemical stability in the sea-water concrete environment.

A thermal model of the Baianus Sinus *pila* submerged in the 14 to 26 °C sea-water of Pozzuoli Bay suggests that exothermic heat evolved through hydration of cementitious phases, mainly C-A-S-H, produced moderately elevated temperatures in the massive harbour structure (Fig. 7.21d) (Jackson *et al.* 2013b). The model calculates maximum adiabatic temperature, $\Theta = m_c Q_1 / C\rho$, in the block over time, where $m_c$ is unit weight of cementitious hydrates in the concrete, $Q_1$ is the evolution of heat of hydration from the C-A-S-H cementitious component based on an experimental concrete formulated with 40% by mass replacement of Portland cement with Italian volcanic pozzolan (Massazza 2002), C is the specific heat capacity of the whole concrete, and ρ is the unit weight of the BAI.06.03 drill core concrete. (An *adiabatic* process occurs without exchange of heat with its environment.) The model includes an initial 5 °C temperature increase from the sudden exothermic portlandite reaction that occurred with the submersion of the dry mix in sea-water (Table 7.2), and previously reported thermal and material properties of the volcanic rock, lime, and calcium-aluminate-cement paste. The maximum temperatures that developed at the center of the pila, about 86 to 98 °C, are in the lowermost range of experimental syntheses, and maximum temperatures at the specimen site, about 0.85 m below the upper surface of the pila, were about 56 to 68 °C (Jackson *et al.* 2013b). About two years after the installation of the concrete, the temperature of the pilae was the same as the sea-water, and precipitation of C-A-S-H was, perhaps, largely complete. This corresponds to the 24 month hydration specimen of the Brindisi mortar reproduction with relatively well-developed compressive strength, 6.2 MPa (Fig. 7.18b).

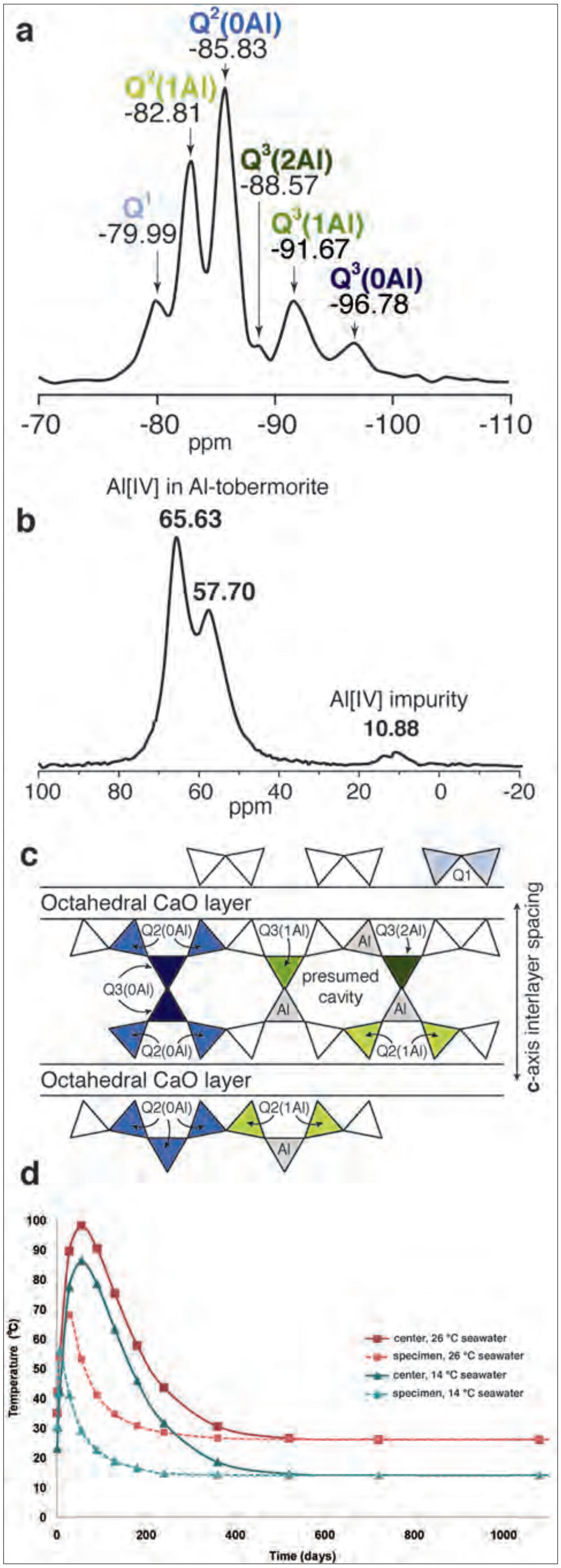


*Fig. 7.21. Results of magic-angle nuclear magnetic resonance (MASNMR) analysis, showing aluminium and silicon bonding environments in Al-tobermorite from relict lime clasts, Baianus Sinus mortar, and crystallization conditions based on temperatures computed in an adiabatic thermal model of the Bainanus Sinus pila (after Jackson* et al. *2013b). a. $^{29}$Si NMR study; $Q^1$ dimers or chain terminations, $Q^2$ chain middle groups, and $Q^3$ branching sites describe the connectivity of $SiO_2$ tetrahedra. b. $^{27}$Al NMR study. c. Schematic diagram showing types of measured linkages of tetrahedral $SiO_4^{-4}$ or $AlO_4^{-5}$ units (triangles). Light and dark gray triangles indicate examples of linkages of silicate tetrahedra and green triangles indicate linkages of silicate and aluminium tetrahedra. d. Maximum temperatures (Θ) at the specimen site and the body center of the 5.7 m thick Baianus Sinus block. The model configuration calculates heat evolved through formation of C-A-S-H cementitious binder. Exothermic hydration of lime produced an initial temperature of about +5 °C above ambient sea-water temperatures ($T_w$). The model block attained 14–26 °C sea-water temperatures about two years after installation.*

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Al-tobermorite has not yet developed in the Brindisi concrete pila reproduction, whose lime putty-volcanic ash mortar may have been prepared somewhat differently from the ancient mortars (Fig. 7.14a, b) (Oleson *et al.* 2006). It seems that this mixing procedure, the absence of relict lime clasts, and rapid loss of heat in the small structure produced obstacles to Al-tobermorite crystallization.

***7.6.2 Chemical and mechanical stability.*** The cementitious matrix of the mortars is composed mainly of poorly-crystalline calcium-aluminium-silicate-hydrate (C-A-S-H) that is inseparable from relicts of silt- to sand-sized pumiceous volcanic ash pozzolan (Figs. 7.1, 7.3, 7.15, 7.20). Fine and coarse gravel-sized ash particles have, themselves, developed interpenetrating pozzolanic cementitious components, so the ancient mortars have a very different fabric from modern cement paste with largely inert sand and gravel aggregate. Aluminium substitution for silica may be an important factor in the chemical durability of the ancient C-A-S-H binder and Al-tobermorite (Figs. 7.15, 7.21). The charge balance introduced by $Al^{3+}$ substitution for $Si^{4+}$ encourages binding of alkali cations, and seems to contribute to equilibrium in the sea-water concrete environment (Jackson *et al.* 2013a, b).

Crystalline microstructures that contain chloride and sulphate are commonly associated with the relict lime clasts (Figs. 7.1, 7.3). These seem to record migration of $Cl^-$ and $SO_4^{2-}$ from sea-water saturated portlandite to the perimeters of relict lime clasts. Crystalline hydrocalumite and ettringite microstructures have apparently sequestered these anions, which produce deleterious reactions, damaging expansions, and corrosion of steel reinforcements in modern Portland cement concretes. The crystalline microstructures may therefore contribute to the long-term chemical durability of the concrete. *In situ* crystallization of zeolite mineral, mainly phillipsite, which occurs in relict pores of the cementitious matrix appears to be a secondary process, perhaps associated with dissolution of volcanic glass (Fig. 7.4).

Laboratory tests of the uniaxial compressive strength of core samples from the concretes of the central Italian coast with volcanic tuff *caementa* give values of about 5 to 8.5 MPa (Fig. 7.18b). In comparison, tests of core samples from the Egnazia, Chersonesos, Caesarea, and Alexandria concretes with different types of carbonate rock *caementa* give lower strengths, about 2 to 3 MPa. The coherence of interfacial bonds between the *caementa* and the mortar seem to be a critical factor in determining the strength of the concretes in the laboratory. The tuff *caementa* are, themselves, pozzolanic materials and complex zones of cementitious hydrates developed along their ragged contacts with the enclosing mortars. In contrast, the limestone *caementa* commonly have rather smooth interfacial surfaces. Rupture along these contacts with the enclosing mortars evidently reduces compressive strength, at least in laboratory tests. Roman builders did not, however, generally make large structural demands on the maritime concretes structures in terms of their weight-bearing strength, and the loads generated by an overlying building would have been distributed over the surface area of a massive breakwater. The limestone *caementa* did not apparently detract from the long durability of the harbour structures.

The results of mercury intrusion porosity tests show a distinctive nanoscale capillary pore size distribution in nearly four dozen specimens of the ancient mortars and the Brindisi concrete reproduction (Fig. 7.19). The peak pore size is very small, mainly about 10 nm. This seems to reflect the pore structure of the pumiceous ash pozzolan, and correlates well with the 30 to 35 nm maxima in pore structure of the Bacoli Tuff and the Neapolitan Yellow Tuff – with progressive pore refinement through precipitation of C-A-S-H (Fig. 7.20) (Gotti *et al.* 2008; Vola *et al.* 2011). Although the overall porosity of the mortars is quite high, 40 to 60 volume %, the vesicular, particulate nature of the pumiceous ash may have lead to low permeability and slow diffusion of fluids through the ancient concrete.

***7.6.3. Pyroclastic rocks as pozzolan and* caementa.** The concretes show a great deal of similarity as regards the composition of their raw materials at the macroscale (Figs. 7.5, 7.6, 7.8). Most of the drill cores of the concrete structures show rather consistent mortar to *caementa* ratios in the range of 40 to 45 volume % *caementa* and 55 to 60 volume % mortar (Fig. 7.18a). In particular, the pumiceous tuff *caementa* of the Portus Cosanus, Santa Liberata, Portus Neronis, and Bay of Pozzuoli harbour concretes have very similar compositional fabrics at the petrographic scale, crystal assemblages, and presumably immobile trace element ratios (pp. 147–53). Although these are hybrid rocks, with variable proportions of juvenile components and extraneous rock fragments, a qualitative assessment of provenance suggests that the tuff may originate from the Campi Flegrei volcanic district (Figs. 7.10–12).

Vitruvius, writing about 30 BC, Strabo, writing in late first century BC and early first century AD, and Pliny the Elder, writing in mid-first century AD, emphasized the "natural qualities of the local sand near Puteoli", which comes from "the vicinity of Baia and the territory of the municipalities of Vesuvius", and the "hills of Puteoli", in the setting and hardening of the concretes in sea-water (pp. 17–23, 27, Passages 7–9, 16). Pumice clasts separated from the maritime mortars show a rather uniform crystal assemblage that correlates with Campi Flegrei and Somma Vesuvius pumice compositions (pp. 153–59). The primary phenocryst is sanidine (with occasional albite); the authigenic phases are zeolites (phillipsite, chabazite, analcite) and clay mineral (illite, halloysite, nontronite); and the cementitious phases are Al-tobermorite, calcite, aragonite, and vaterite. There is no leucite and analcite as from Monti Sabatini pumices, nor calcic plagioclase, amphibole, and olivine, as from Aeolian Island pumices, nor a sodic or calcic plagioclase and orthopyroxene assemblage, as from Aegean Island pumices. Presumably immobile trace element ratios of the pumice specimens separated from the mortars of the central Italian harbour concretes and one pumice specimen from a Caesarea mortar fall within the Campi Flegrei compositional field (Fig. 7.12). The compositions of pumice specimens removed from the mortars of the eastern Mediterranean harbour concretes at Egnazia, Chersonesos, Pompeiopolis, and Caesarea show variable trace element ratios that fall within the compositional fields of both the Campi Flegrei and Somma-Vesuvius volcanic districts (Fig. 7.13). These ratios are very different from those of Aeolian and Aegean Island pumice deposits (Fig. 7.11). It seems possible that builders did not select pumices from deposits more proximal to the eastern Mediterranean harbour sites but, instead, preferred the alkali-rich, trachytic pumiceous ash of Campi Flegrei and slightly more silica-enriched phonolitic Vesuvian deposits from the Gulf of Naples. The mineral assemblage is correct, and while the trace element compositions of the pumices cannot be identified with specific eruptive units, there is no better solution that can be proposed, as yet, based on the published compositional data in the volcanological literature.

Why might Romans have chosen to ship pumiceous ash from the Gulf of Naples to the far distant harbour sites of the Empire rather than employ pumice from more local sources? From the perspective of the *scientia* of the Roman builders, and the adept empirical expertise that they developed while working with local volcanic ash pozzolan to create a standardized formulation for the sophisticated concretes of the late Republican monuments of ancient Rome (Jackson *et al.* 2010, 2011; Jackson and Kosso 2013), it seems that practical experience may have led them to create a standardized formulation for the maritime mortars, as well.

State of the art technology in modern concrete science is focused on the importance of alkali-activated alumino-silicate reactions in environmentally-friendly concretes, in which Portland cement is partially replaced by inorganic aluminosilicate materials, such as blast furnace slag, fly ash, and zeolitized volcanic ash, to improve setting behaviour, workability and chemical and physical properties (Duxson *et al.* 2007; Snellings *et al.* 2012). The reaction mechanism involves the transformation of an aluminosilicate solid to produce a synthetic aluminosilicate cementitious compound, in much the same way that Bacoli pumiceous ash reacts with lime and sea-water to produce C-A-S-H (Sersale and Orsini 1969; Massazza and Costa 1979). Dissolution of the solid aluminosilicate occurs through alkaline hydrolysis, which releases aluminate and silicate species that are incorporated into an aqueous phase. Concentration of these species in solution produces a gel that continues to reorganize and transform, and grows in connectivity to form three-dimensional polymerized networks that are responsible for hardening of the concrete. This is, essentially, the hardening process that Vitruvius describes empirically for the consolidation of the sea-water concretes in *De Architectura* 2.6.4, and which is recorded by the C-A-S-H binding phase of the cementitious matrix. Alkali cations, mainly sodium, but also potassium, greatly assist the process of dissolution; $OH^-$ ions act a reaction catalyst for the formation of aluminous cementitious gel, while alkali cations act as structure-forming elements to balance $Al^{3+}$ substitution for $Si^{4+}$ (Duxson *et al.* 2007)

Volcanic ash from Campi Flegrei and Vesuvius deposits has unusually high alkali and low silica compositions: alkali-rich Flegrean pozzolanic ash commonly contains up to 12 weight % $Na_2O+K_2O$ (de' Gennaro *et al.* 2000) and the Ottaviano and Avellino pumices from Somma-Vesuvius, for example, can contain up to 14 weight % $Na_2O+K_2O$ (Paone 2006). The trachytic and phonolitic volcanic glass is less strongly polymerized than silica-rich rhyolitic and dacitic glass and, in addition, post-eruptive alteration processes have produced abundant zeolite minerals with excellent pozzolanic properties (Sersale and Orsini 1969, Massazza and Costa 1979). In comparison, the volcanic glass of the Aeolian Island and Aegean Island pumice deposits is enriched in silica, contains lower concentrations of alkali-cations, about 6 to 8 weight %, overall, and may be more strongly polymerized, so both dissolution and pozzolanic reactive capacity may be reduced. In addition, there are few reports of zeolitic alteration. Ongoing mineralogical investigations of the ancient maritime mortars are evaluating the role of alkali-activated processes in the development of their fine-scale cementitious fabrics. These could provide important guideposts towards improving the longevity of modern pozzolanic concretes.

It is possible that Romans experimented with different sea-water mortar formulations, and discovered that setting characteristics, chemical durability, and mechanical properties of the concretes with mortars formulated with alkali-rich ash from the Gulf of Naples were superior to those formulated with the more siliceous ash of the Mediterranean Island deposits – or quartz rich beach sand at Portus Cosanus. Builders seem to have determined a standardized formulation by the mid- to late-first century BC, as represented by the Bay of Pozzuoli and Santa Liberata harbour structures. This is about the same time that builders in Rome settled on the Pozzolane Rosse scoriaceous ash formulation for the mortars of the architectural concretes (Jackson *et al.* 2011). Once a standardized formulation was established, shipping of Gulf of Naples pumiceous pyroclastic rock could have occurred over vast distances to the incipient harbour projects, to assure their success and reduce the likelihood of failure with unknown pozzolans, such as more siliceous pumiceous ash from the Thera eruptions (Druitt *et al.* 1999). Hypothetically, ships would arrive in Rome and Naples full of grain and commercial trade goods from afar, and return to the eastern Mediterranean loaded with pumiceous volcanic ash as ballast that could be sold valuable pozzolan (Chapter 9).

## 7.7 Summary of analytical methods

Analytic evaluations of the drill core specimens of the maritime concretes include three principal arenas of investigation: descriptions of the fine scale fabric of the volcanic ash – hydrated lime mortars with observations at the microscopic scale, determinations of the compositions of the pumiceous pozzolan, mortars, and *caementa* with various chemical and mineralogical analyses, and assessments of the material and mechanical properties of the concretes with experimental tests.

Petrographic studies of polished thin sections of the mortars were performed with various polarizing light microscopes. Scanning Electron Microscopy studies used a Leo instrument equipped with a Sirius Energy Dispersive Spectrometer at CTG Italcementi Laboratories, Bergamo, Italy, and an EDAX TSL energy dispersive X-ray spectrometer on the Zeiss EVOMA10 Scanning Electron Microscope at the Department of Earth and Planetary Science at University of California at Berkeley.

Powder X-ray diffraction analyses (Table A4.1) identified the minerals present in the concretes with a Bruker D8-advance X-ray diffractometer at CTG Italcementi Laboratories, Bergamo, Italy, equipped with CuKa radiation, two sets of Soller slits (2.5° aperture) and a LynxEye™ PsD Detector on a Si-stray holder and front loading. All XRPD spectra were collected between 5–70°of 2θ with a step of 0.02° per second.

Major and trace element compositions of 3 to 5 gram powdered specimens of pumice clasts, tuff *caementa,* and certain bulk mortar specimens were performed at Activation Laboratories, Ancaster, Canada. Pumice clasts 0.8 to 3 cm diameter were carefully removed from the mortars, including both glass and crystals, and adhesions of cementitious hydrates were delicately scraped away. Munsell colours were described with the Geological Society of America Rock-Color Chart (1995). The powder specimens are mainly composed of many small pumice clasts. The compositions were determined with lithium metaborate/tetraborate fusion ICP whole rock for major elements as weight % oxides and ICP/MS for trace elements as ppm (Table A4.2). This blends HT-digestion in excess Li-borate with dissolution in strong acid to prepare for ICP-AES analysis. The lowermost trace element detection limit in the Code4B2 research package is 0.5 ppm for Y, 1 ppm for Zr, 0.2 ppm for Nb, and 0.1 ppm for La and 0.01 for Yb, as for the tuff specimens; however, the Code4B2 standard analyses of the pumice specimens have slightly lower resolutions.

The major element compositions of powdered specimens of the mortars and tuff *caementa* (Table A4.3) were determined as weight % oxides on powdered specimens with the X-Ray Fluorescence (XRF) spectroscopy method, using a Panalytical cubiX X-Ray Fluorescence spectrometer with M.h.T. = 50 kV and M.a.c. = 4 mA at CTG Italcementi Laboratories, Bergamo, Italy.

To provide a qualitative assessment of the volumetric proportions of mortar to rubble *caementa* in the diverse harbour installations (Table 7.1), two methods were developed by C. J. Brandon. First, a metre-rule was placed along each freshly drilled core and the total length of each chunk of aggregate and the mortar were measured. This was repeated for three equally spaced lines along the length of each core surface. The total lengths of *caementa* and mortar were then divided by three to determine the average proportion of each, expressed as a percentage. The second method measured the relative total surface areas of aggregate and mortar on each core using an analytical tool within Adobe Photoshop CS3 extended software, also expressed as a percentage. Voids were not counted and, in addition, only the large aggregate chunks were measured so, overall, the concretes contain a greater percentage of tuff or carbonate rock aggregate than recorded in Table 7.1. The macroscale map of Fig. 7.5 was made by wrapping transparent plastic around the surface of the core, and tracing the components of the concrete fabric.

The material and mechanical properties of the concretes were measured at CTG Italcementi Laboratories in Bergamo, Italy. Unit weight was determined following British standard EN 12390-7-2009 and a Mettler MS 32000 balance, for water saturated and oven-dried core segments about 85 cm long or 200 to 215 cm long. The mass and volume of the specimen were determined and the density calculated (Table 7.3). Uniaxial compressive strength was also determined following British standard EN 12390-3-2009, using a Uniaxial Press MC C8 Controls apparatus to 3000 Kilonewtons (KN/mm$^2$ give Megapascals (MPa) (Table 7.3). The variable lengths of the cores do not seem to have unduly influenced the testing results, but the heterogeneous fabrics of the 9 cm diameter cores may have had a strong effect (pp. 175–80). It is not clear how these laboratory results, measured under ambient conditions in the laboratory, can be translated to the actual strength of the massive concrete structures in the sea-water environment. The porosity of the pumiceous mortars was determined through measurements of the pore volume distribution by the intrusion of mercury under pressure following German standard *DIN 66133 (1993*–06), and a Pascal 140/240 Porosimeter and a Mettler MS 32000 balance (Table 7.4).

# Chapter 8

# Roman Formwork Used for Underwater Concrete Construction

*C. J. Brandon*

## 8.1. The role of formwork in Roman concrete construction

Because of the dynamic environment of building in the sea, even the highly stiff mortars developed by Roman engineers had to be placed within formwork when used for submarine construction. The design of the form and the materials used in formwork construction varied depending on the application, the nature of the site, the pozzolanic character of the concrete, and whether the form cladding was intended to be permanent or temporary.

On land, timber and board formwork was frequently used in foundations. Although the timber has rarely survived, the impressions of planks and posts and beams often do (Fig. 8.1). Walls were mostly constructed with brick or masonry cladding that acted as permanent shuttering, while vaults and domes were set on temporary falsework and centring (MacDonald 1982: 147; DeLaine 1997: 131–74; Lancaster 2005a: 22–50). These land-based building operations were relatively straightforward, but procedures for building underwater were considerably more difficult. Work in the water included driving in piles and side wall planking as well as fixing structures in the seabed or river bottom, often working in poor visibility and without knowledge of the character of the sub-bottom. Conducting operations from very restricted working areas, unstable construction platforms, and offshore from boats or barges or at the end of an ever-extending mole created its own set of challenges. Space for storing and preparing raw materials must have been at a premium and would have limited the number of labourers able to work simultaneously at mixing and laying a given sector of the concrete structure. Such restrictions may well have had an impact on the quality of the concrete and could possibly explain why the concrete found at Sebastos was somewhat inferior to the concrete used on land along the central coast of the western Italian peninsula. The uniaxial compressive strengths of the Caesarea cores, which can be considered a general measure of coherence and durability, show rather unpredictable behaviour, at least in the laboratory setting (p. 179). This seems to be mainly the result of poor coherence of the carbonate rock *caementa* with the enclosing pumiceous mortar. The poor quality could also be the result of difficulties with concrete installation and compaction at the offshore construction site, on an unprotected coastline (Hohlfelder *et al*. 2007: 414). There were also significant logistical and practical difficulties in transporting materials and labour to offshore sites. It took more time and expense to transport timber, pile-drivers, pumiceous ash pozzolans, lime, and aggregate to a marine site than to an equivalent terrestrial construction project.

*Fig. 8.1. Formwork impressions on a concrete foundation on the Palatine Hill, Rome.*

If there was a requirement for formwork to be dry inside, the problems involved in building a watertight structure that could be drained raised additional difficulties. The depth of water and the porosity of the seabed both had a direct impact on the rate of water percolating through the floor of the drained area, and the pumps had to cope with water ingress even after the initial drainage. A description by the eighteenth-century engineer Charles Labelye (1751: 49) of how problems raised by the nature of the Thames riverbed prevented him from using cofferdams to construct Westminster Bridge is reminiscent of the famous passage in Vitruvius (*De arch.* 5.12.5–6; see below).

> … To enclose the place intended for the foundation so as to keep the ambient water from coming in, that it may be drained dry, and kept so by pumping or other engines. Sometimes this enclosure is single, and sometimes double, with clay rammed between; sometimes the enclosures are made with piles only, driven close by one another; sometimes those piles are notched or dove-tailed one into another; sometimes the piles are grooved, and driven at a distance, and boards let down between them…The first inconvenience attending this method is, that if the enclosure be not strong enough, or not sufficiently propped or braced in the inside, it will not be able to support the pressure of the external water (especially if it be water agitated by stormy winds)…But what would have rendered it entirely useless, or ineffectual, is the nature of the ground under the bed of the River Thames; which at the place where the bridge is, is everywhere a gravel, covered over on the Surrey side with a sort of loamy sand; all which would suffer the water to ooze up (notwithstanding the sides of the Batterdeaux or Cofferdams should be perfectly tight) so fast, especially through the gravel, as to put it out of the power of any engine or engines to drain the Batterdeaux or Cofferdams: Indeed where the ground under the foundation is a stiff clay, or an earth of a sufficient consistency to hold water, Batterdeaux or Cofferdams, have been used with success…

It was, however, the unpredictable nature of the sea that created the biggest set of problems. Wave damage could be devastating, and even in relatively calm conditions currents would make pile-driving operations difficult and gradually weaken formwork enclosures. The structure of flooded formwork did not have to support the weight of the concrete as it set, since the ambient water pressure balanced this, but the form needed to be strong enough to contend with the movement of the sea.

Vitruvius provides the only detailed description of how Roman builders constructed formwork for casting concrete structures in and under the sea in his *De architectura* 5.12.2–6. In this passage he outlines three techniques for constructing formwork, of which only two are supported by archaeological evidence. Although this passage has been presented and discussed above (pp. 20–23, Passage 9), the translation of the relevant portions is repeated here for convenience.

> Those concrete structures that are to be in the water must be made in this fashion. Pumiceous volcanic pozzolan (*pulvis*; lit. "powder") is to be brought from the region that runs from Cumae to the promontory of Minerva and mixed in the trough in the proportions of two parts earth to one of lime. (3) Next, in the designated spot, formwork (*arcae*) enclosed by solid (*or* "oak") posts and tie beams (*stipitibus robusteis et catenis*) must be let down into the water and fixed firmly in position. Then the area within it at the bottom, below the water, must be levelled and cleared out, [working] from a platform of small crossbeams (? *ex trastilis* or *trastillis*). Afterwards aggregate broken in the trough (*caementis ex mortario*) and mortar (*materia*) mixed as specified above is to be placed within, until the space inside the form has been filled with the concrete structure. The locations that we have described above, then, have this natural advantage.
>
> But if because of waves or the force of the open sea the anchoring supports (*destinae*) cannot hold the forms together, then a platform must be built out from the shore itself or from the foundations of the mole, and made as firm as possible. This platform is to be built out with a level upper surface over less than half its area. The section towards the shore is to have a sloping side. (4) Next, retaining walls one and one half feet thick are to be built at the end facing the sea and on either side of the platform, equal in height to the level surface described above. Then the sloping section is to be filled in with sand and brought up to the level of the retaining walls and platform surface. Then, a concrete block (*pila*) of the appointed size must be built there, on this levelled surface, and when it has been formed is left at least two months to cure. Then the retaining wall that holds in the sand is cut away, and in this manner erosion of the sand by the waves causes the block (*pila*) to fall into the sea. By this procedure, repeated as often as necessary, the breakwater can be carried seaward.
>
> (5) But in locations where pumiceous volcanic ash (*pulvis*) does not occur naturally, one must use the following procedure. Let double-walled formwork (*arcae duplices*) be set up in the designated spot, held together by close set planks and tie beams (*relatis tabulis et catenis conligatae*), and between the anchoring supports have clay packed down in baskets made of swamp reeds. When it has been well tamped down in this manner, and is as compact as possible, then have the area bounded by the cofferdam emptied and dried out by means of water-screw installations and water-wheels with compartmented rims and bodies. The foundations are to be dug there, within the cofferdam. If the foundations are to be on earth, the area to be excavated and drained must be wider than the wall that will stand above. Then fill in the form with concrete composed of aggregate, lime, and sand (*structura ex caementis calce et harena*). (6) But if the bottom is soft, the foundations should be covered with charred alder or olive wood pilings and filled in with charcoal, as described for the foundations of theatres and city walls. Then the wall must be built of squared stone with joints as long as possible, so that the stones in the middle may be well tied together by the joints. The space inside the wall is to be filled with rubble packing or concrete. Thus it will be possible to build a tower upon it.

The frequency of instances where timber shuttering is still in evidence around maritime concrete suggests that the formwork was left in place and not removed after the concrete had set. It is apparent that permanent or semi-permanent cladding was often part of the finished structure. The concrete reproduction at Brindisi (Chapter 5) provides a quantitative assessment of the rate at which the concrete gained strength: it achieves about 70% of its compressive strength, measured through uniaxial tests of 9 cm diameter cores in the laboratory, after 6 months hydration. After 24 months, the initial hydration and development of cementitious phases in smaller structures, such as the Baianus Sinus *pila* in the Bay of Pozzuoli, was largely complete, and the laboratory compressive strength is about 6 MPa (pp. 178–80). Roman builders would have certainly been aware of the steady, but slow, gain in strength and may have opted to leave the timber formwork in place on maritime structures to protect the concrete from erosion and general wear and tear (Oleson *et al*. 2006: 49).

It is intriguing that there are a number of sites where underwater concrete structures appear to have been built with *opus reticulatum* stone facing. In the sea between the Roman harbours of Baiae and Portus Iulius in water that is at present over 9 m deep, there is a cluster of pilae known locally as Secca Fumosa that are clad in *opus reticulatum* and *opus vittatum* (Fig. 8.2; Scognamiglio 2002: 52–55; Brandon *et al.* 2008: 376–77). At least one of the *pilae* of the long mole at Puteoli was faced in the same manner (Döring 2003: fig. 11). The harbour mole at Ponza had a *quasi-reticulatum* finish, as did the *pilae* protecting the harbour at Nisida (Gianfrotta 1996: 71; Gianfrotta 2002: 70–72). The outer *pila* at the harbour of Egnazia is faced with *opus reticulatum* in water that is currently over 4 m deep over the top (Fig. 4.42; Auriemma *et al.* 2004a: 45). The location and current depth of these structures suggests that their deep water environments cannot simply have been the result of post-construction subsidence or relative sea level rise. Exactly why or how the builders used stone facing in relatively deep water cannot be explained. It would have been very difficult to install *opus reticulatum* facing on concrete laid in an inundated form. If the *pilae* noted above were produced above sea level on shoreline platforms in the method described by Vitruvius and possibly mentioned by Horace and Virgil (pp. 21–24), and then allowed to fall into the sea, the *opus reticulatum* facing could possibly have been applied above water as the block was formed. It is not clear how the concrete would have been hydrated during such a procedure, or how long it would have had to cure before being displaced into the sea.

*Fig. 8.2.* Opus reticulatum *facing on the sides of a concrete* pila *at Secca Fumosa near Baiae.*

## 8.2. A Typology of Roman formwork design for marine construction: Fixed forms

In order to identify regional variations and understand how concrete was laid on the shoreline or in the sea, various formwork solutions have been categorised according to the following typology (Brandon 2011: 121–38, esp. 124): Category 1: Inundated form constructed *in situ,* in wood or, less often, masonry; Category 2: Cofferdam formwork constructed *in situ*, designed for dewatering prior to placement of concrete; Category 3: Prefabricated forms floated into position as a unit or in pieces. Although specialized in purpose, many details of the design and execution of marine concrete formwork also appeared in ancient ship construction (below pp. 215–20) and in presses for oil or wine described by Columella, Pliny, and Heron (Drachmann 1932: 60–65, 150).

***8.2.1. Category 1: Inundated form constructed in situ.*** This class of formwork includes the type described by Vitruvius (5.12.3; Fig. 8.3), employed in the marine concrete construction of extensions to harbour moles, jetties, isolated blocks (*pilae*), and walls of fish-ponds (Table 8.1). The formwork was usually constructed with timber, although permanent forms constructed in dimension stone (i.e. ashlar) marginal walling, such as at Pompeiopolis, fall within this category. In the version constructed of timber, piles were driven into the seabed and framed with horizontal beams against which vertical boards were set while being pounded in. This type of form was mainly used in sheltered sites and in relatively shallow water (about 3 m depth or less) and ideally with a sandy bottom. There are, however, several instances where these forms were built on rocky seafloors. The design of the ROMACONS experimental *pila* built in the harbour of Brindisi was based on this technique (above pp. 107–8; Hohlfelder *et al*. 2005: 123–27; Oleson *et al*. 2006). The remains of the forms that have survived and the impressions left in the concrete they shaped allow deductions about how they were built and the sequence in which they were assembled.

*Destinae.* At the start of construction, piles (*destinae*) were driven into the seabed within the designated confines of the form to provide rigidity and support horizontal tie beams, as well as to prop up any temporary construction platforms that had been set above sea level (Fig. 8.4; Vitruvius pp. 20–23). There is some ambiguity in Vitruvius about *destinae*, since in *De architectura* 5.12.5 he indicates that these members are part of the double wall surrounding the caisson area to be drained of water. Perhaps because these supports were within the shuttering, rather than on the exterior, they are called *destinae* rather than *stipites*. The piles, with diameters that ranged between 10 and 30 cm, mostly comprised fir logs, often with the bark still adhering to them, with their bottom ends sharpened and occasionally fitted with iron shoes. Evidence for *destinae* usually exists embedded within the concrete and survives at several locations. In this list and those that follow, place names without indication of country are in Italy; the locations without explanatory descriptions in parentheses can be found on the map Fig. 6.1.

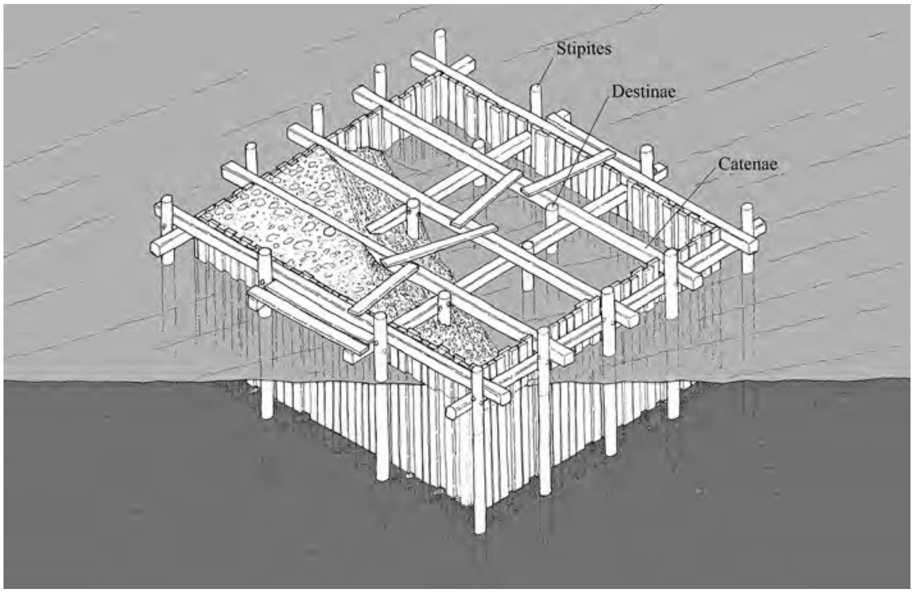

*Fig. 8.3. Reconstruction of a Category 1 inundated form constructed* in situ *(C. J. Brandon).*

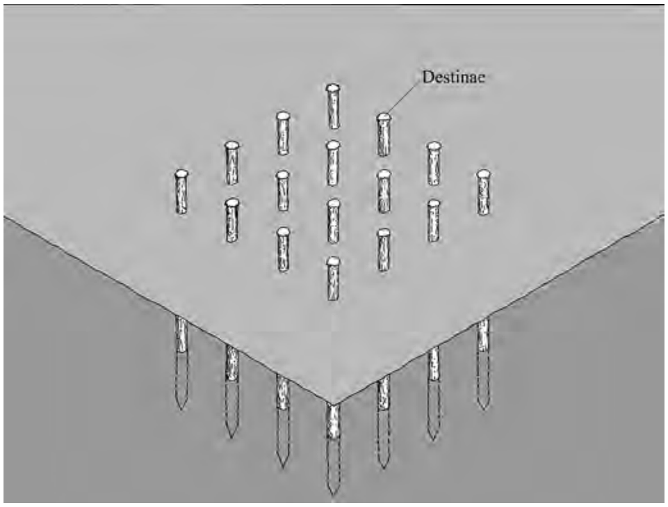

*Fig. 8.4. Reconstruction of piles (*destinae*) installed in the first phase of building a Category 1 form (C. J. Brandon).*

- Portus: the remains of 18 cm diameter vertical oak posts were found in the concrete mass that made up part of the *Molo Sinistro* of the Claudian harbour, near the present museum (Testaguzza 1970: 108).
- Anzio: on the eastern mole there are three rows of pile impressions spaced at between 2 and 2.5 m apart across the width of the structure and 2.5 m centre to centre along its length (Fig. 8.5). The western mole reveals a similar configuration, as well as having additional postholes that were once the locations of vertical timbers that supported the formwork for the upper, brick-faced concrete elements (Felici 1993: 74–88).
- Paola (near Circeo): several vertical postholes mark the locations for *destinae* in the complex concrete structure that marks the entrance to the channel leading to the lagoon at Paola (Felici 1993: 93, pl. II).
- Miseno: a *pila* off Punta Terone, at the entrance to the ancient harbour of Misenum, carries a line of cylindrical holes left by the piles that were once located around the inner edge of the block, set at between 0.5 and 1 m centre to centre (Fig. 8.6; Gianfrotta 1996: 73–75).
- Baia: on the southern pier, on the port side of the entrance channel leading into the harbour of Baianus Lacus, there are holes left by vertical piles with diameters that vary between 20 and 25 cm, set out in five rows across the width of the mole and aligned with the horizontal tie beams. The piles are set out on either side of these horizontal beams, alternating from one side to the other (Fig. 8.7; Scognamiglio 2002: 47–55).
- Baia: on top of the outer *pila* on the western side of the channel leading into Portus Iulius, cored during the ROMACONS 2006 season, there is a row of 30 cm diameter vertical postholes at 1.5 and 1.8 m centre to centre (Figs. 8.8–9).
- Sapri: the concrete mole preserves vertical circular postholes that originally contained 16 to 18 cm diameter piles, and one of only 10 cm diameter (Scognamiglio 2008: 142).
- Capri, Palazzo a Mare West, "Bagni di Tiberio." Set within the concrete quay are rectangular post holes for 25 cm × 28 cm shaped piles located adjacent to horizontal beam impressions (Figs. 8.10, 6.57; Scognamiglio 2010: 123).
- Egnazia: circular postholes, approximately 30 cm in diameter can be seen in the upper surface of the southeast mole. They are set at between 1.5 and 2 m distance centre to

*Table 8.1. Gazetteer of Category 1 formwork.*

| **Site** | **Location** | **Description** |
|---|---|---|
| Anzio (Antium) | Outer moles | Horizontal cross beams about 1 m above sea level. Vertical piles at 2.5 m intervals (Felici 1993: 76–88). |
| Anzio (Antium) | Inner quay | Vertical planks 0.23–0.5 m wide by 0.07–0.08 m thick (Felici 2002: 110–11). |
| Astura | Mole | Vertical planks and horizontal tie beams secured by vertical piles (Felici 1998: 334–35: and Felici 1993: 89–92). |
| Baiae (Baianus Lacus) | Entrance channel jetties | 60–70 cm diam. horizontal beam impressions at 2.5 m centres and 20–25 cm diam. internal vertical piles set at alternating sides of the horizontal tie beams at 2 m spacing. Stiffened with 20 cm diam. raking braces. Continuous run laid in sections with the end bulkhead removed after each casting, the next section being cast against the finished face of concrete (Sognamiglio 2002: 47–49). |
| Baiae (Baianus Lacus) | Quay side | Vertical planks 25–30 cm wide × 5 cm thick fitted to horizontal beams 9 cm × 9 cm fixed to vertical piles 16 cm × 18 cm in section set at approximately 1 m centres (Scognamiglio 2002: 50). |
| Sebastos (Caesarea, Israel) | CAHEP Survey Line No. 3 | Horizontal tie beam impressions, some with single beam and some with a cross tie beam notch (Oleson in Raban *et al*. 1989: 213, figs. IV. 8–13). |
| Carthage (Tunisia) | Wall C Shuttering | Corner shuttering comprising vertical fir planks 30 cm wide, 2–3 cm thick with the bottom ends roughly tapered with an axe. Horizontal beams, one of fir and one of pine were half lapped at the corner (Yorke *et al*. 1985: 161). |
| Carthage (Tunisia) | Neptune Block | 0.25 $m^2$ and 0.25 m × 0.14 m horizontal beams (Yorke *et al*. 1985: 163). |
| Chersonesos (Crete) | Mole A | Vertical recesses at regular intervals of 6.8 m. Alternating large and small recesses to 1.5 m deep and 0.6–0.8 m wide (Leatham and Hood 1958/59: 267). |
| Cosa (Portus Cosanus) | Pier 1 Western face | Vertical impressions 0.10–0.15 m wide and 0.15–0.20 m deep (Gazda 1987: 76–77). |
| Cosa (Portus Cosanus) | Pier 2 | Two square beam holes 4 m apart. *Ca.* 0.26 m × 0.25 m (Gazda 1987: 76–77). |
| Cosa (Portus Cosanus) | Spring House | Vertical and horizontal planked shuttering (Oleson 1987: 100–1, figs. V4, V6, V7 and V12). |
| Graviscae |  | Vertical boards fixed to horizontal beams (Incitti 1986: 199). |
| Egnazia | Harbour mole | Beam, pile, and tie beam impressions (Auriemma 2003: 77–97; 2004a: 38–59). |
| Kyme (Turkey) | Harbour mole | Ashlar walls (Esposito *et al*. 2002: 1–38). |
| Lepcis Magna (Libya) | Mole | Ashlar walls (Bartoccini 1958). |
| Miseno (Misenum) | *Pilae* | Beam and post impressions (Gianfrotta 1996: 71–75). |
| Miseno (Misenum) | Punta Pennata | Vertical planking, piles, and horizontal rail (Benini *et al*. 2010: 114–15; Benini 2006: 20; Scognamiglio 2006: 67). |
| Paola (Circei) | Canal jetty leading to lake | Complex shaped form impressions of vertical piles and planking and voids formed by horizontal beams (Felici 1993: 93). |
| Pompeiopolis (Turkey) | Harbour mole | Ashlar walls (Boyce 1958: 68–73). |
| Portus | Claudian NW mole | Vertical planks with horizontal tie beams and external collar beams (Testaguzza 1970: 114–20; Meiggs 1973: Plate XIX; Felici 1993: 94–95). |
| Portus | SW corner of the Darsena Basin | Vertical planking (cypress or alder) widths varying between 19 and 30 cm (Verduchi 2005: 255–57). |
| San Cataldo | Harbour mole | Ashlar walls (Auriemma 2004b: 155–76). |
| San Marco di Castellabate | Harbour mole | 6–8 m long by 4.5 m wide forms used to cast concrete in sequence to create a continuous pier. Each bulkhead shuttering section removed (for re-use) to allow concrete to be cast up against concrete face. Horizontal cross beams at 1.5 m centres. 15 cm diam. diagonal braces set at 22°. Vertical 15 cm diam. piles some set into rock platform seabed between 45–60 cm (Benini 2008: 39–46). |
| Santa Severa | Fish pond | Vertical planks 0.10–0.40 m wide and 0.03–0.045 m thick (Pellandra 1997: 21–26). |
| Thapsus (Tunisia) | Mole | Horizontal circular beams at 1.3 m centres (Dallas *et al*. 1968: 25). |

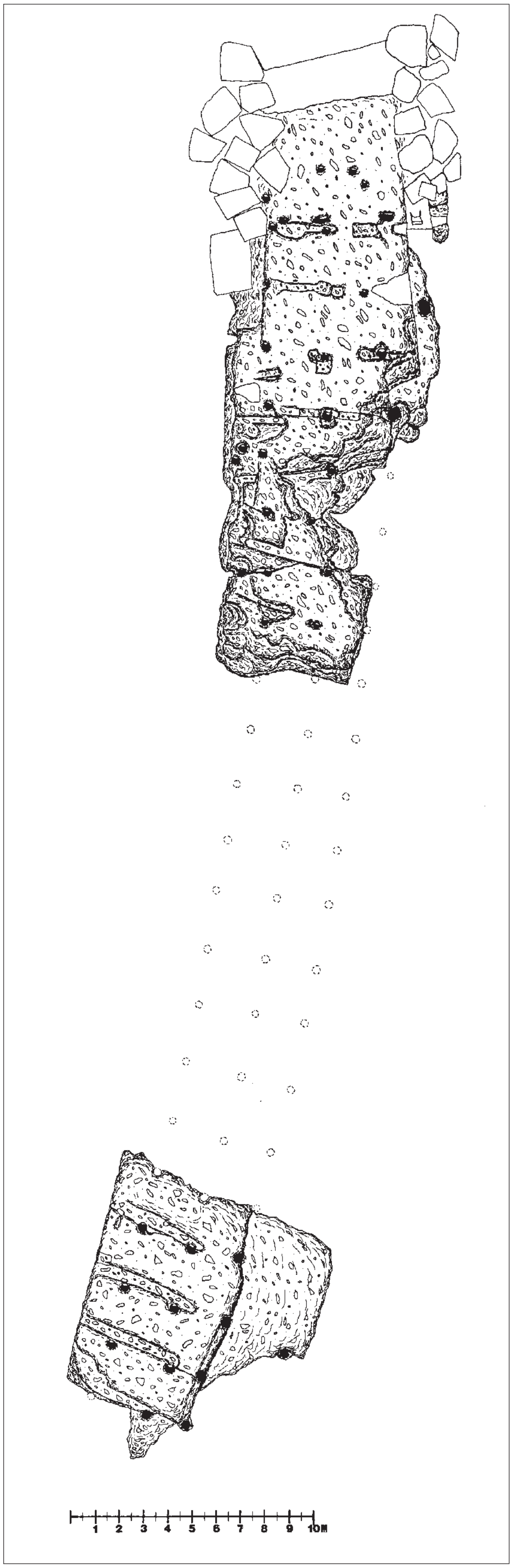

*Fig. 8.5. Plan of the eastern mole at Anzio (Felici 1993: fig. 8; used with permission).*

centre and correspond with the positions of the horizontal crossbeams (Figs. 8.11–12; Auriemma 2003: 89–96).

- Carthage (Tunisia; Fig. 3.2): a large concrete platform on the shoreline has cylindrical holes in the top surface left behind by vertical posts 13 to 16 cm in diameter; some of these abutted the horizontal tie beams while other were apparently free standing (Yorke and Davidson 1985: 163).

*Stipites.* Once the *destinae* were in position, a line of piles (s*tipites*) was driven in around the outside of the enclosure, set approximately 30 to 70 cm outside of the planned location of the outer face of the shuttering (Fig. 8.13; Vitruvius pp. 20–21). The piles held horizontal rails that supported the line of vertical sheet piles that formed the shuttering and also secured the ends of the horizontal tie beams. The evidence for s*tipites* is not as common as for *destinae*, since they were located outside the form, but impressions or postholes can sometimes be found on the seafloor surrounding the concrete. A number of examples survive; the sites appear on the map Fig. 6.1.

- Santa Severa: the remains of timber formwork in the fishpond on the north breakwater include evidence of *stipites* with diameters that range between 10 and 14 cm (Fig. 8.14; Oleson 1977: 304; Pellandra 1997: 24–25).

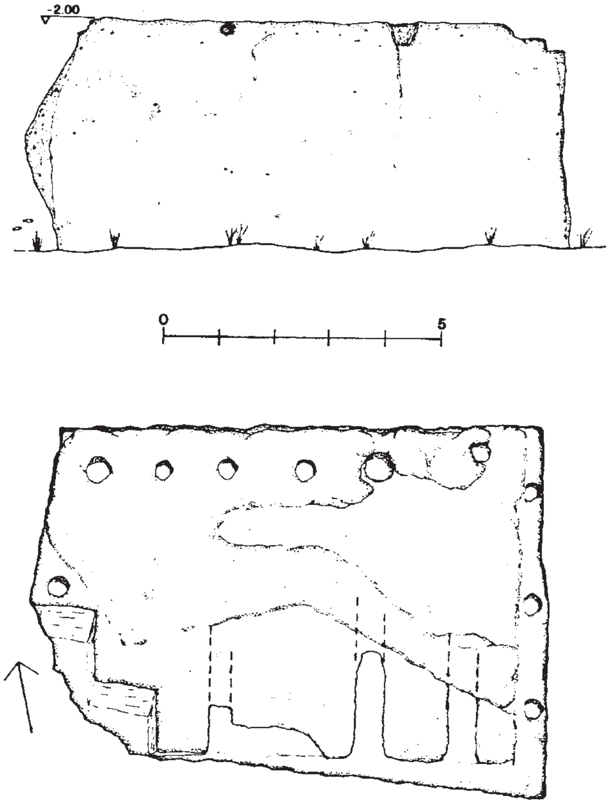

*Fig. 8.6. Misenum, Punta Terone, details of a* pila *with vertical and horizontal pile and beam impressions (Gianfrotta 1996: fig. 8; used with permission).*

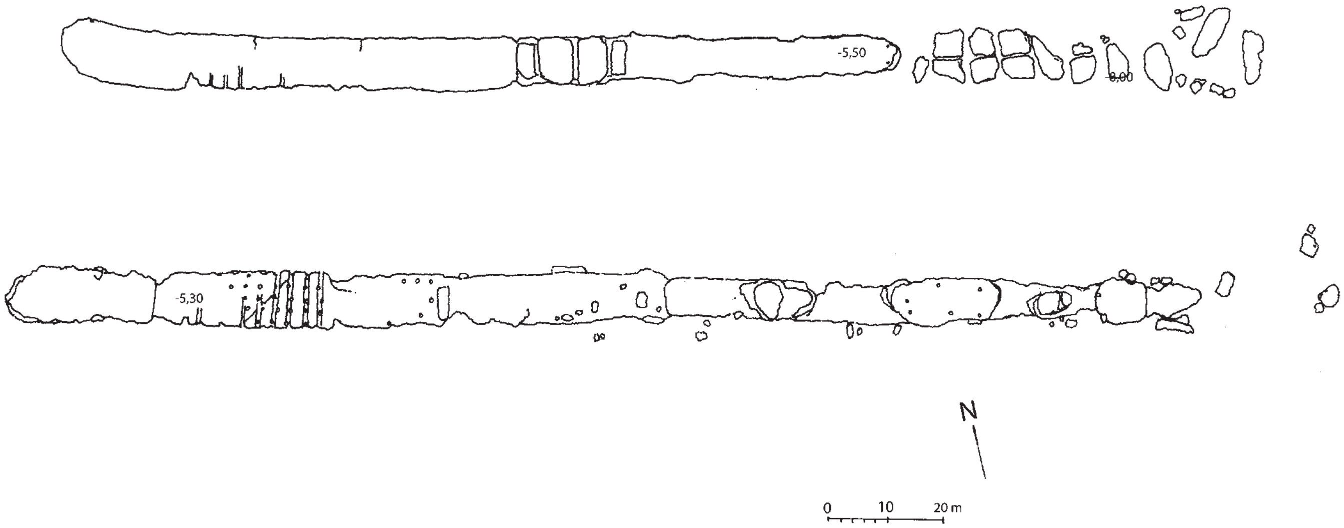

Fig. 8.7. Plan of the entrance channel moles to the harbour of Baianus Lacus (Scognamiglio 2002: pl. 1; photo E. Scognamiglio).

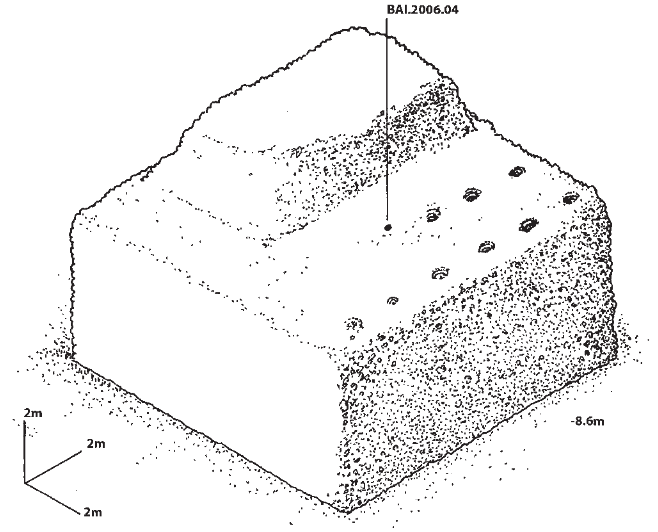

*Fig. 8.8. Portus Iulius, outer* pila *on the western side of the entrance channel with positions of vertical pile impressions (C. J. Brandon).*

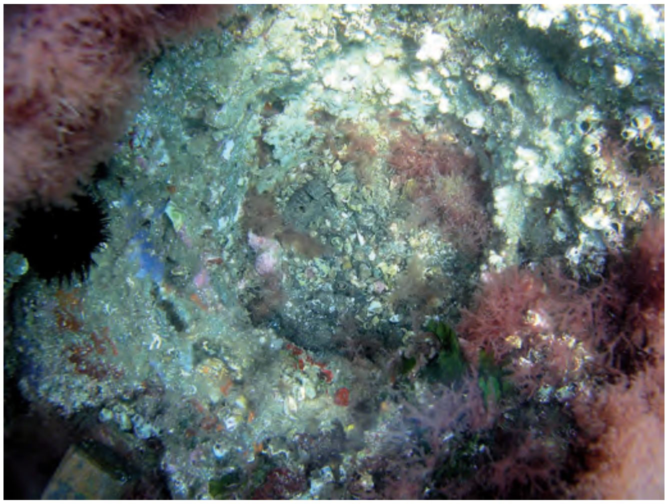

*Fig. 8.9. Portus Iulius, top of a 30 cm diameter pile on the outer* pila *on the western side of the entrance channel.*

- Portus: Testaguzza (oral communication) recorded a section of formwork within the Claudian harbour that showed *stipites* arranged around the outside of the vertical timber shuttering, with the remains of an external horizontal rail and two *destinae* evident within the mass of concrete (Fig. 8.15).
- Anzio: the remains of the lower section of 10 to 20 cm diameter log piles with bark still adhering to their sides survive just outside the concrete jetty within the inner harbour. They had been driven into the seabed 1.2 m apart centre to centre, positioned 50 to 70 cm away from the face of the shuttering (Fig. 8.16; Felici 2002: 108–11).
- Baia: there is a concrete dock to the south of the entrance channel that led into the harbour of *Baianus Lacus* that was constructed within a timber form with vertical piles 16 to 18 cm diameter, set at 1 m centres along the outside of the line of shuttering (Fig. 8.18; Scognamiglio 2001: 45–46).
- Miseno: along the edge of the quay on Punta Pennata are the remains of the formwork against which the concrete quay was cast. On the outer face is a line of *stipites* that ranged in diameter from 18 to 23 cm (Scognamiglio 2006: 67; Benini and Lanteri 2010: 114–15).
- San Marco di Castellabate: along either side of the concrete pier and set at a distance of approximately 30 cm from the

outer face of the concrete, are the impressions of a line of piles (*stipites*) in the rocky sea floor. They appear to align with the horizontal tie beams (*catenae*) in the adjacent concrete. An iron-tipped pile was initially used to form a socket in the rocky seafloor, and scour marks can still be seen within the holes. Logs with a diameter of approximately 15 cm had their bottom end shaped to fit into the pre-drilled bedding. The holes are between 45 and 60 cm deep, and in one case a hole was begun but not finished. Traces of lead found within the post holes might indicate that the ends of the wooded piles were sheathed in lead before being driven into the stone socket holes, helping to wedge them in place (Figs. 8.19–21; Benini 2002: 43–46).

- Egnazia: along the sides of the southeast pier in the harbour, piles circular in section were fitted at their lower ends with unusual iron spiked caps, which were then fixed to the rocky sea floor (Figs. 8.11–12; Auriemma 2003: 89–93).

*Lower Horizontal Rail.* In Category 1 forms, a horizontal timber rail was set at the base of each side of the form, just above the seabed, and fixed to the inner face of the outer line of piles (*stipites*; Fig. 8.22). These rails have survived at several locations, since they were installed at seabed level and were often rapidly covered in silts and preserved. The sites appear on the map Fig. 6.1.

- Portus: Testaguzza recorded examples of these rails during the excavation of the *Molo Sinistro* in the Claudian harbour (Fig. 8.23).

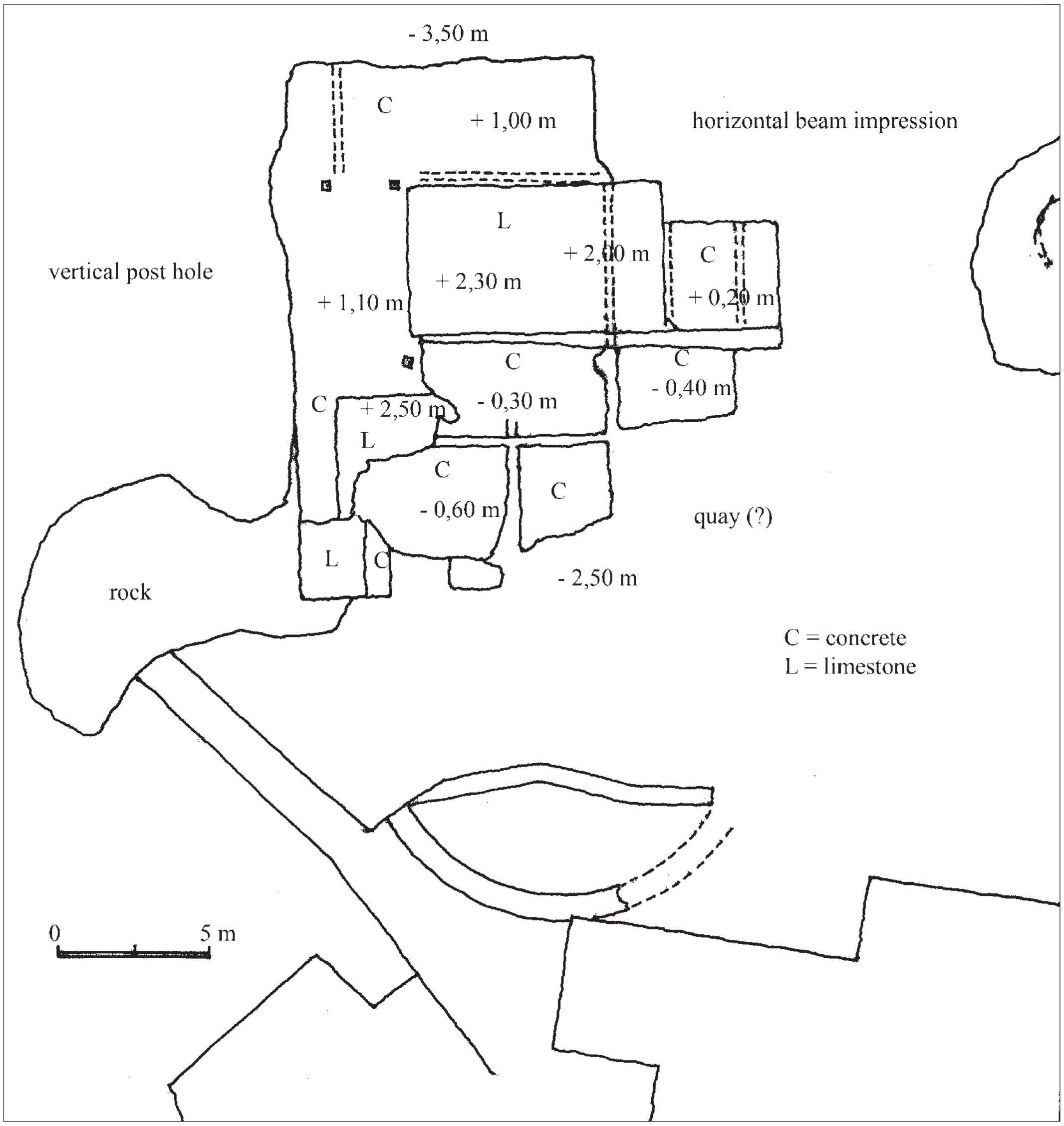

*Fig. 8.10. Plan of a concrete* pila *at Bagni di Tiberio on Capri (after Scognamiglio 2010: 123).*

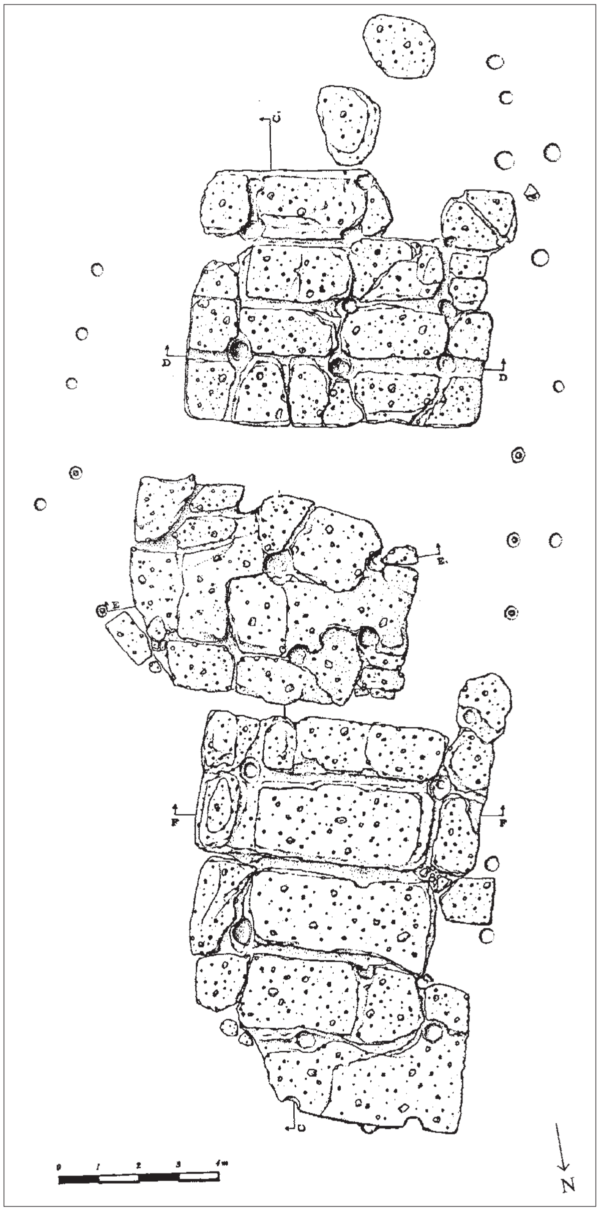

*Fig. 8.11. Plan of the southeast mole at Egnazia (Auriemma 2004: 48, fig. 29; used with permission).*

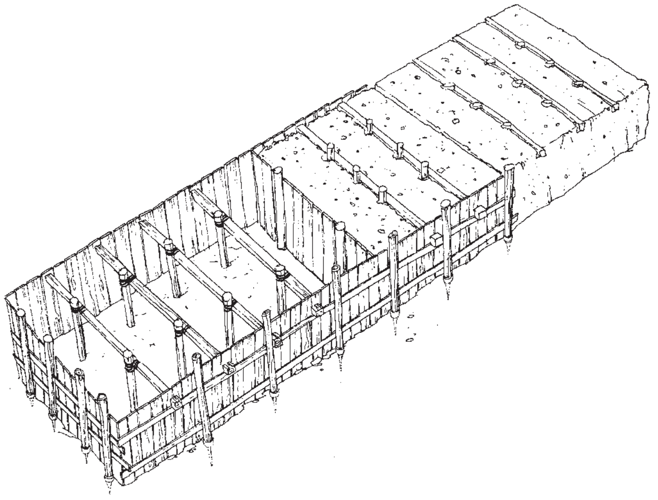

*Fig. 8.12. Reconstruction sketch of the southeast mole at Egnazia (Auriemma 2004: 52, fig. 35; used with permission).*

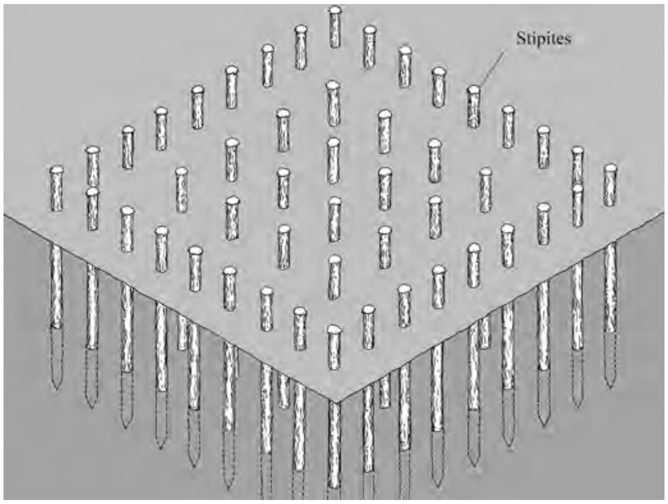

*Fig. 8.13. Reconstruction of the outer piles (*stipites*) installed in the second phase of building a Category 1 form (C. J. Brandon).*

- Baia: along the edge of a quay south of the entrance channel leading into *Baianus Lacus* are the remains of the lower section of a timber form that includes vertical shuttering, piles (*stipites*), as well as a horizontal timber rail (Fig. 8.18). The rail, with a width of 9 cm, was made by cutting a log in half lengthwise. It was fixed, at seabed level or just above, to piles (*stipites*) that had been set out in a line at 1 m apart centre to centre. The rail was fixed either directly to the piles or by means of a bracket that was composed of two wooden struts secured with lead fasteners (Fig. 8.24). It is probable that the holes for the fasteners were pre-drilled, as the installation and fixing of this rail was carried out entirely underwater. Additional rigidity was obtained by hammering a wooden wedge between the rail and the pile (Miniero 2001: 32; Scognamiglio 2001: 45–46; 2002: 50).
- Miseno: a detail very similar to that at Baia for a rail fixed with brackets and making use of struts and wedges was found on the Roman quay off Punta Pennata (Figs. 8.25–27; Benini 2010: 114–15).

*Upper Horizontal Rail.* While there is no surviving evidence for external rails at the top of the formwork, they must have existed as a means to secure the tops of the timber sheet piles and to transfer lateral loads to the *stipites* and the *destinae,*

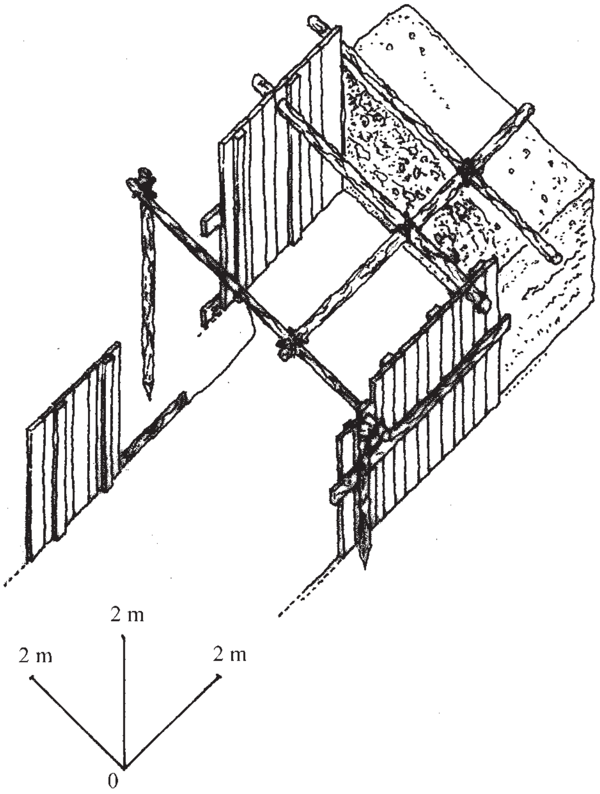

*Fig. 8.14. Reconstruction of the fish-pond formwork at Santa Severa (after Pellandra 1997: pl. II a–b).*

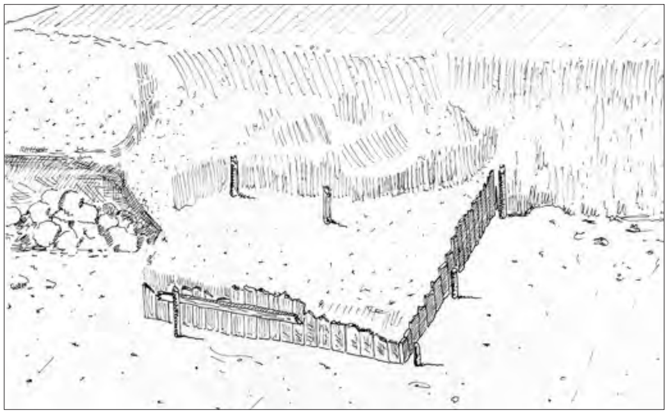

*Fig. 8.15. Sketch of concrete formwork on the* Molo Sinistro *of the Claudian harbour of Portus (O. Testaguzza, used with permission).*

in addition to supporting the ends of the *catenae*. Fitted inboard of the *destinae* and vertically above the bottom rail, they would have been set at a level above sea level, just below the height of the *catenae* (Fig. 8.22). Unlike the lower sections of the form, which were buried in sand and silts that preserved the timber elements or were imbedded in the concrete to leave negative impressions of the wooden structures as they rotted away, the upper rails were exposed to the elements and decayed without leaving any evidence of their existence. It is also possible that some of this accessible wood was salvaged for reuse.

*Shuttering.* Shuttering, forming the surface against which the concrete was cast, could only be installed after the upper and lower horizontal rails had been fixed. Initially it was thought that it was fitted once the framework had been completed; however, it is now realised that the shuttering had to be in place before the *catenae*, the horizontal tie beams, were fixed. It would have been very difficult to drive in the planks down the inside face of the horizontal beams. The shuttering generally comprised vertical timber planks that were set against the inner edge of the horizontal rails and driven into the sea-bed side by side, in a similar manner to sheet piling, and most probably fixed at the head above sea-level to the upper rail (Fig. 8.28). The shuttering preserved around the concrete Spring House platform at Cosa consisted of horizontal planks, but this formwork was relatively small in scale, and installed in shallow water or a swamp (Fig. 8.29; Oleson 1987: 100–1). Vertical planks were used to hold back the swampy soil and allow installation of the platform formwork (Fig. 8.30). The planks varied in size, usually within a range from 15 to 30 cm wide although sometimes wider, and 5 to 8 cm thick. Impressions from vertical shuttering are preserved on the exterior of Pier 1 at Cosa (Fig. 4.12).

Slab-cut along the length of a log, the planks often had un-squared edges and in some instances still had the bark adhering to them (Fig. 8.31). Sometimes even the outer section of the log was used as a sheet pile plank, with the flat saw-cut surface facing outwards and the curved bark face turned in towards the concrete. In this manner, the outside face of the shuttering was straight and aligned with the horizontal external rails, and the irregular surface was imbedded in the concrete. Although the joints between the boards were usually reasonably tight, within 1.5 cm, the Roman builders were concerned about loss of mortar paste through these joints and in some instances took preventative steps. These measures included an arrangement of staggered and lapped, abutted boards (Fig. 8.32), as seen in the impression of boards in the concrete at Cosa (Fig. 4.12), Portus (Fig. 8.35), and Anzio (Fig. 8.33), and on the reproduction *pila* at Brindisi (Figs. 5.16–17). At Miseno, on the edge of the concrete quay that ran along the southern side of Punta Pennata, battens were inserted to help seal the joint between the un-finished shuttering planks (Fig. 8.36). During the construction of the experimental *pila* at Brindisi, the ROMACONS team found that the mortar was viscous enough that it did not ooze through openings several centimetres wide. Finally, the top of the shuttering was trimmed above the *catenae*, to facilitate access by workers. Examples of vertical timber boarded shuttering have been found at a number of sites (see map Fig. 6.1).

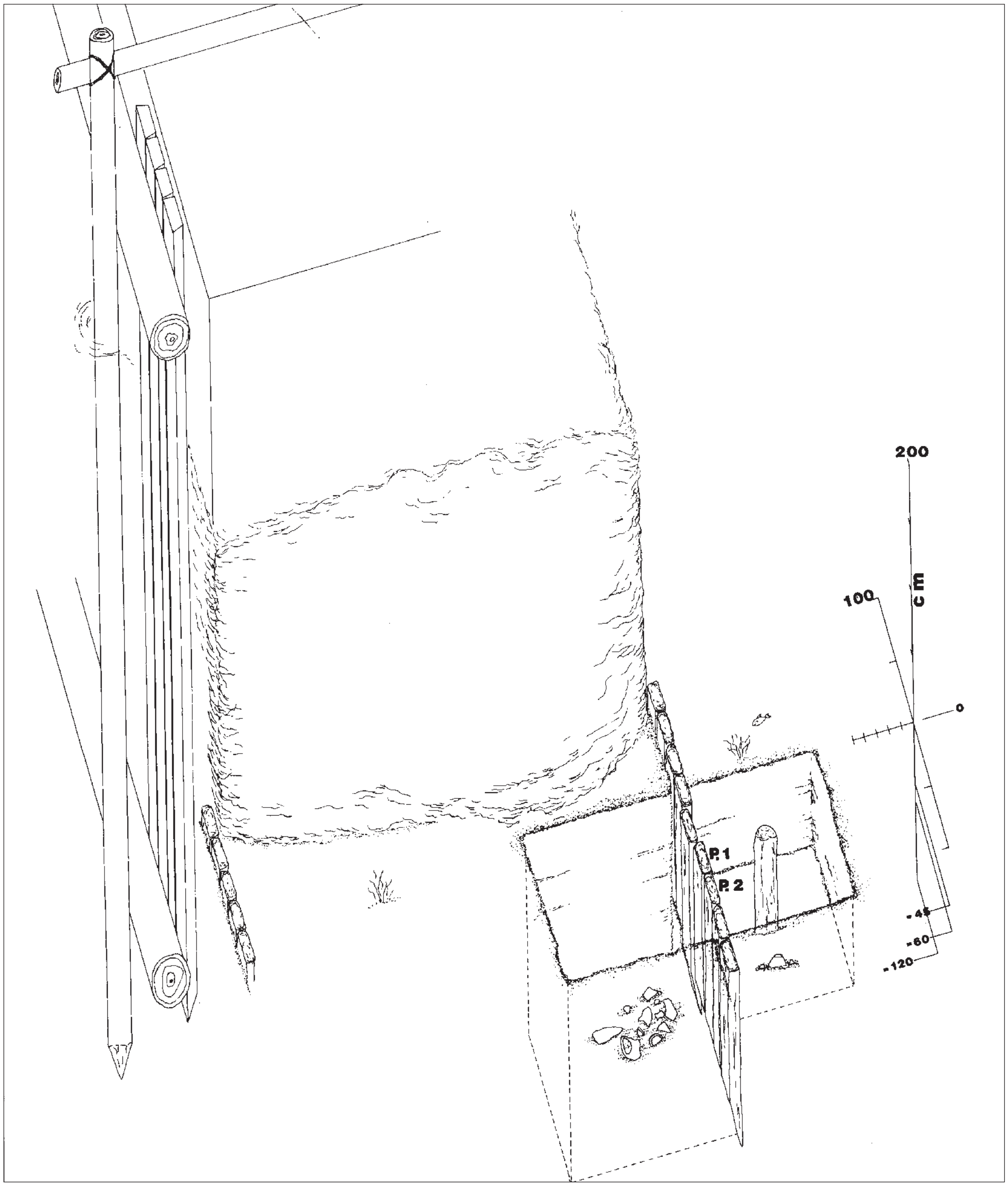

*Fig. 8.16. Reconstruction of the inner harbour concrete pier at Anzio (Felici 2002: fig. 8; used with permission).*

- Cosa: impressions of lapped vertical planking on the lower portion of Pier 1 were formed with boards 11 to 15 cm wide (Fig. 4.12; Gazda 1987: 76–77).
- Cosa: platform in front of the Spring House. A retaining wall of vertical planks 3.2 to 5.5 cm thick, 21 to 46 cm wide and more than 2 m long survives along the south end of the platform (Fig. 8.30; Oleson 1987: 101, fig. V.6–V.7). The planks were pounded into the soil 10 to 14 cm out from the wooden forms into which the concrete was poured, perhaps as a retaining wall to hold back soil.
- Cosa: platform in front of the Spring House. A simple formwork survives around most of the platform, consisting of horizontal spruce, oak, and pine planks, 3 to 5 cm thick, 34 cm wide, of varying lengths, held in position by vertical, untrimmed posts 10 to 14 cm diameter, serving as *stipites* (Fig. 8.29; Oleson 1987: 100–1, fig. V.4–V.12). Some of the planks were fixed to the posts with iron nails. Similar formwork survives inside the Spring House basin.
- Graviscae (north of Civitavecchia): offshore from the town there is evidence of vertical timber planking and horizontal rails associated with remnants of concrete (Incitti 1986: 199).
- Santa Severa: the remains of upright timber planks along the dock (Fig. 8.34), 16 cm wide and 3.5 cm thick (Oleson

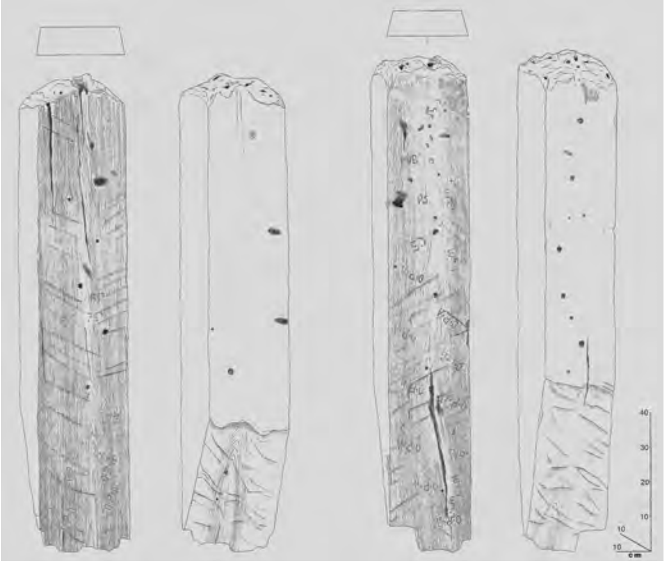

Fig. 8.17. Inner harbour concrete pier at Anzio, details of lower portion of two vertical timber planks from the shuttering (Felici 2002: fig. 14; used with permission).

Fig. 8.18 . Base of shuttering on the side of a concrete dock south of the Baianus Lacus entrance channel (Scognamiglio 2002: fig. 2; photo E. Scognamiglio).

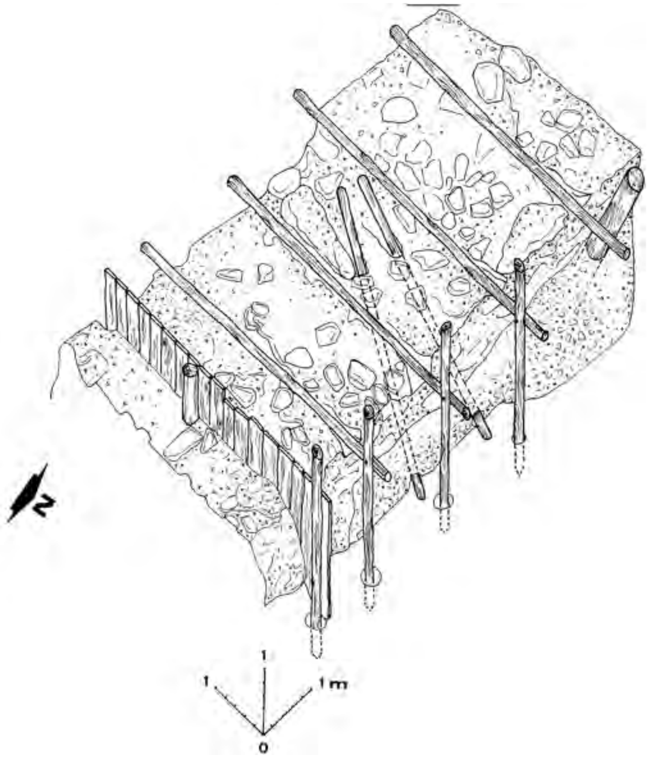

Fig. 8.19. Reconstruction of a section of the harbour mole at San Marco di Castellabate (after Benini 2002: pl. 3; used with permission).

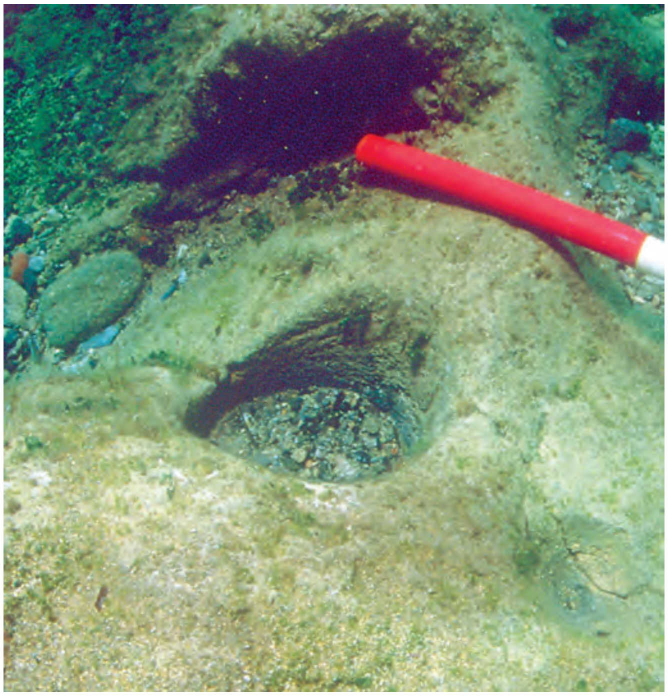

Fig. 8.20. Remains of a timber pile driven into the rock seabed at San Marco di Castellabate (after Benini 2002: fig. 10; used with permission).

*Fig. 8.21. Post hole drilled into the rock seafloor at San Marco di Castellabate (After Benini 2002: fig. 11; used with permission).*

*Fig. 8.23. Remains of the lower section of formwork on the northern mole at Portus (O. Testaguzza, used with permission).*

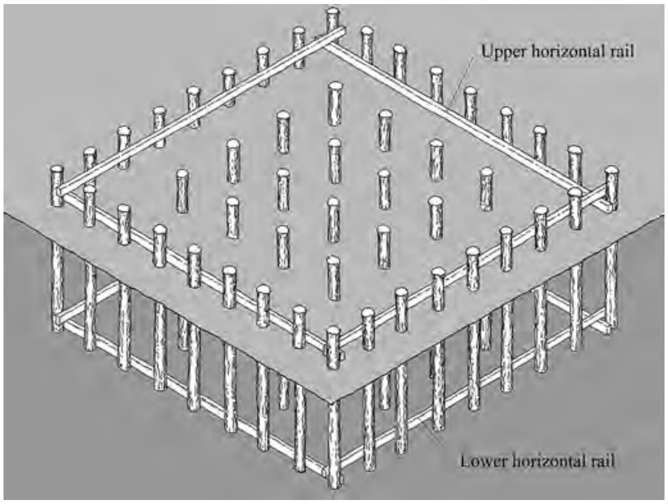

*Fig. 8.22. Reconstruction of the upper and lower horizontal rails fixed to the outer piles (*stipites*) installed in the third phase of building a Category 1 form (C. J. Brandon).*

1977: 304); and of timber planks 10 to 40 cm wide and 4 to 4.5 cm thick along the fish-pond (Fig. 8.14; Pellandra 1997: 24–5).

- Portus: photographs taken by Testaguzza during the excavation of the Claudian harbour, prior to the construction of Leonardo da Vinci airport, clearly show vertical timber plank shuttering still in place at a number of different locations. This feature is also confirmed in sketches he did at the time (Figs. 8.15, 8.23).
- Portus: a recent excavation at the southwest corner of the *Darsena* basin uncovered the tops of preserved vertical timber plank shuttering set against the sides of the dock. The thick boards were either cypress or alder and varied in width between 19 and 30 cm (Fig. 8.35; Verduchi 2005: 257).
- Anzio: there are impressions of lapped vertical boarding on block III on the western mole (Fig. 8.33; Felici 1993: 83–86; 1998: 307, fig. 38). Also at Anzio, along both sides of the narrow inner harbour pier are the remains of the lower sections of shuttering that consists of vertical planks 23 to 50 cm wide and 7 to 8 cm thick set edge to edge. The edges were not finished or cut square, but the lower end that was driven into the seabed was shaped with an adze. Letters made with a punch are visible on the preserved face of the two planks recovered for study (Fig. 8.17; Felici 2001b: 121–28; 2002: 108–115).
- Baia: along the base of a section of a quayside on the outside of the harbour basin Baianus Lacus are the remains of a length of timber shuttering comprising fir planks 25 to 30 cm wide and 5 cm thick set vertically edge to edge (Fig. 8.18; Miniero 2001: 32–33; Scognamiglio 2002: 50–51).
- Miseno: along the edge of the concrete quay on the southern side of Punta Pennata is the preserved lower section of timber formwork consisting of sections of slab-cut logs, all used with minimal wastage including the outer edges, and varying in width from 30 to 40 cm and 6 to 7 cm thick. Wooden battens were positioned upright on the inside of the junction between each vertical plank to seal the joint and prevent mortar from oozing out before it set solid; these were between 11 and 5 cm wide, although in the main between 6 to 7 cm, and only 0.2 to 0.5 cm thick (Fig. 8.36; Scognamiglio 2006: 67; Benini and Lanteri 2010: 114–5).

*Catenae.* One of the most widely preserved types of evidence for Roman concrete formwork, and one that is primarily linked

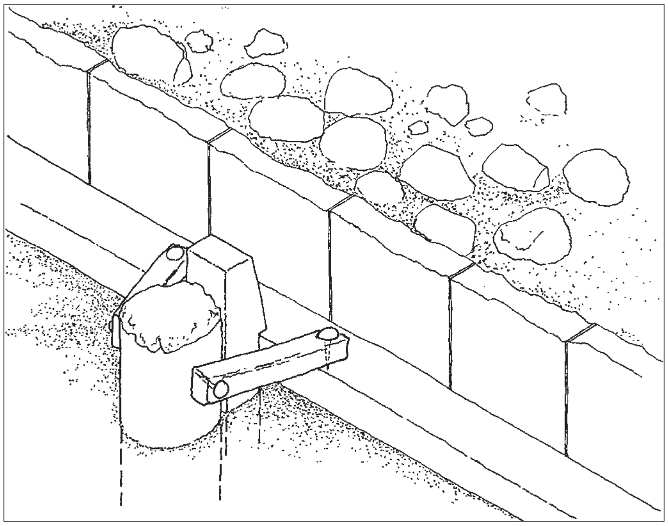

*Fig. 8.24. Detail of the fixing bracket securing the lower rail to a* stipes *on the formwork on the side of a concrete dock to the south of the entrance channel into the harbour of Baianus Lacus (C. J. Brandon after Miniero 2001: fig. 5).*

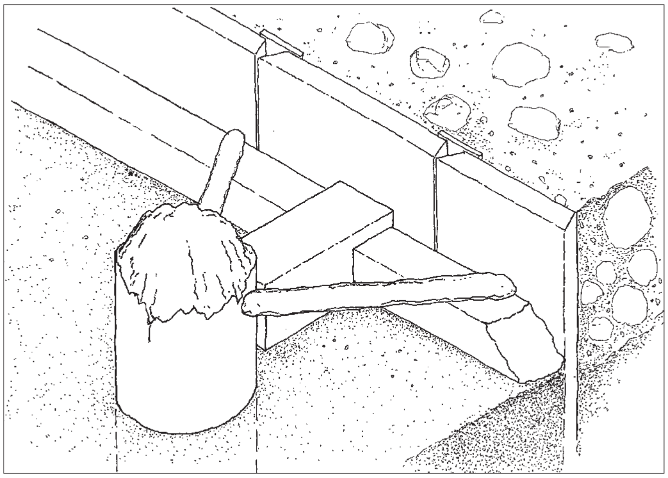

*Fig. 8.25. Detail of the fixing bracket securing the lower rail to a* stipes *on the formwork on the side of a concrete quay to the south of Punta Pennata at Misenum (C. J. Brandon after Benini and Lanteri 2010: 114–15).*

to the Category 1 type form, is the negative impression of horizontal tie beams (*catenae*) that were mounted just above sea level and designed to provide lateral rigidity to the structure until the concrete had been placed and had cured. Fixed to either the *destinae* or *stipites* or both, as well as to the upper external rail, they ran from side to side and occasionally they were also arranged longitudinally (Fig. 8.37). They were fixed at a convenient height to support a working platform from which basket loads of mortar and aggregate could be lowered into the flooded enclosure to build up the mass of concrete layer by layer. While the *destinae* and *stipites* were

*Fig. 8.26. Fixing bracket securing the lower rail to a* stipes *on the formwork on the side of a concrete quay to the south of Punta Pennata at Misenum (Benini and Lanteri 2010: fig. 14; used with permission).*

*Fig. 8.27. Detail of the fixing bracket securing the lower rail to a* stipes *on the formwork on the side of a concrete quay to the South of Punta Pennata at Misenum (Benini and Lanteri 2010: fig. 14; used with permission).*

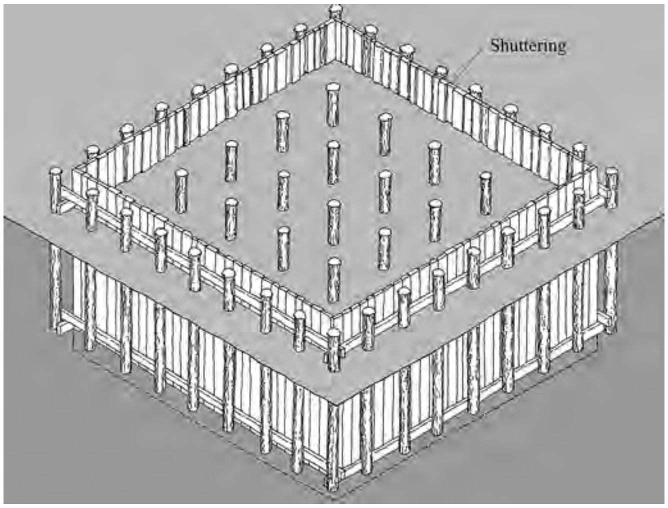

*Fig. 8.28. Reconstruction of vertical timber board shuttering fixed to the upper horizontal rail installed in the fourth phase in building a Category 1 form (C. J. Brandon).*

mainly circular in section and often simply sharpened logs, the *catenae* comprised both rectangular sectioned timbers and circular sectioned beams. There is evidence of *catenae* at the following sites (see map Fig. 6.1).

- Cosa: on the sides of Piers 2 and 3 there are two square horizontal beam holes 26 cm × 25 cm, *ca.* 4 m apart, each at about 3 m from the ends of the pier, and now just above sea-level, although originally they would have been approximately 1 m above the sea (Figs. 4.13–14; Gazda 1987: 76–77).
- Portus: at the Claudian harbour, set into the upper surface of the *Molo Sinistro* on the northern side of the Claudian basin, are the impressions of 19 cm × 21 cm rectangular horizontal beams that span the 5.8 m width of the mole and are arranged 2.25 m apart centre to centre with a longitudinal beam impression on axis (Fig. 8.38; Felici 1993: 94–95). In 2003 Brandon with the backing of D.ssa Cinzia Morelli, Soprintendenza per i Beni Archeologici di Ostia and the assistance of D.ssa Antonia Arnoldus-Huyzendveld, surveyed the levels in the Claudian and Trajan harbours and established that the *catenae* were all set approximately 1 m above the sea-level in the Roman era.
- Portus: on the northern mole of the Claudian basin, within the large mass of concrete that was originally suggested by Testaguzza to be Caligula's obelisk barge, but subsequently found to be a rectangular form, are holes that were once filled with 30 cm × 18 cm horizontal cross beams (*catenae*) set between 1.6 m and 2.2 m apart centre to centre, along with 26 cm × 15 cm rectangular and 18 cm diameter circular sectioned longitudinal beams (Fig. 4.2; Testaguzza 1970: 108).

*Fig. 8.29. Horizontal planked formwork around the platform in front of the Spring House at Cosa (McCann* et al. *1987: 100–1, fig. V.4–V.12) (Photo: A. M. McCann, used with permission).*

*Fig. 8.30. Vertical timber retaining wall around the concrete platform in front of the Spring House at Cosa (McCann* et al. *1987: 101, fig. V.6–V.7) (Photo: A. M. McCann, used with permission).*

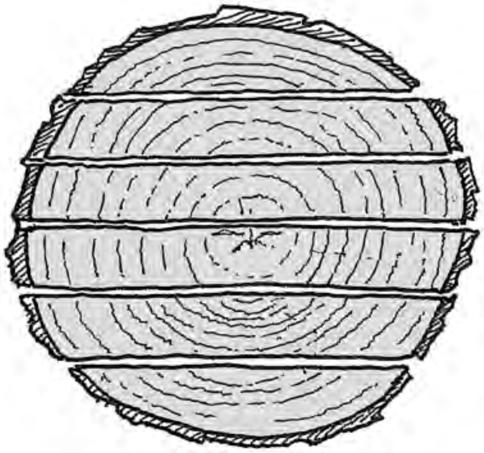

Fig. 8.31. Log cut into slabs (C. J. Brandon).

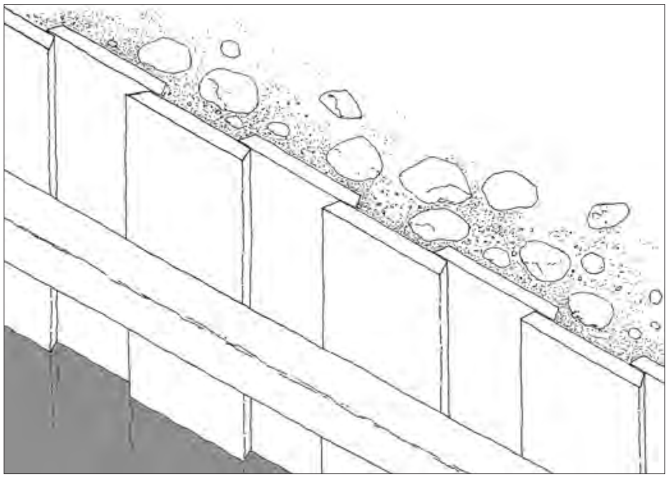

Fig. 8.32. Staggered and lapped vertical board shuttering (C. J. Brandon).

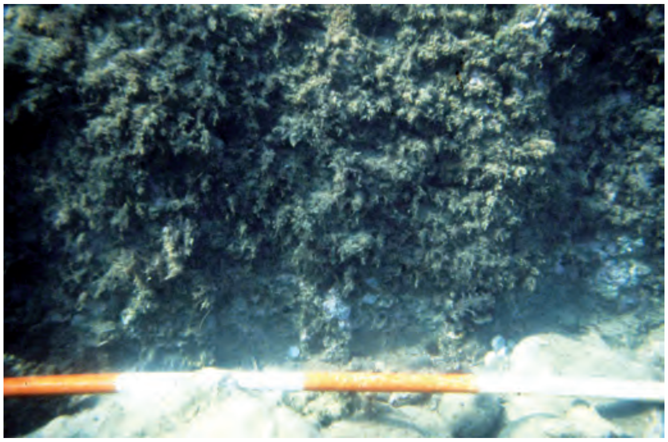

Fig. 8.33. Impressions of lapped vertical boarding on Block III of the western mole at Anzio (after Felici 1998: 307, fig. 38; used with permission).

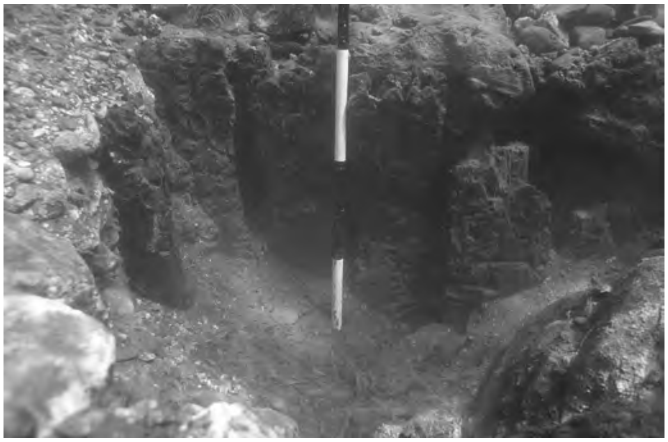

Fig. 8.34. Vertical planked formwork around the concrete dock at Santa Severa (A. M. McCann; used with permission).

- Anzio: embedded in the remains of the concrete outer moles are the impressions of circular sectioned horizontal beams set at a height of 1 m above ancient sea-level at 2.5 m apart centre to centre (Felici 1993: 74–88).
- Paola (near Circeo): there is a complex arrangement of impressions of horizontal tie beams in the concrete structure at the end of the jetty that marked the canal entrance to the lagoon harbour (Felici 1993: 93).
- Astura: there are impressions of circular horizontal beams set into the concrete embankment and in the northern mole at the Roman port (Fig. 8.39; Felici 1993: 89–92).
- Baia (Baianus Lacus): there are 60 to 70 cm diameter horizontal beam impressions 2.5 m apart centre to centre that cross the width of the concrete moles that lead into the ancient harbour (Fig. 8.7; Scognamiglio 2002: 47–49).
- Miseno: there are horizontal beam impressions in the upper section of the *pilae* off Punta Terone (Fig. 8.6; Gianfrotta

Fig. 8.35. Remains of vertical timber planking shuttering at the southwest corner of the Darsena basin at Portus (Verduchi 2005: 257; used with permission).

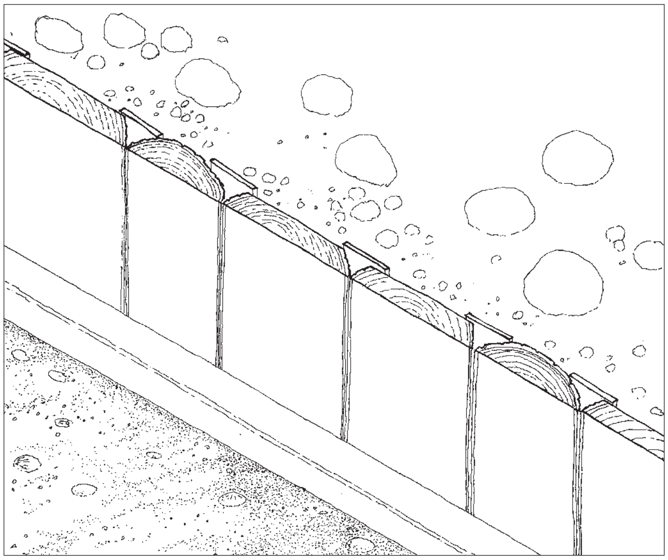

*Fig. 8.36. Miseno, formwork comprising untrimmed timber slab cut planks with vertical battens sealing the joints between boards (C. J. Brandon after Benini and Lanteri 2010: 114–15).*

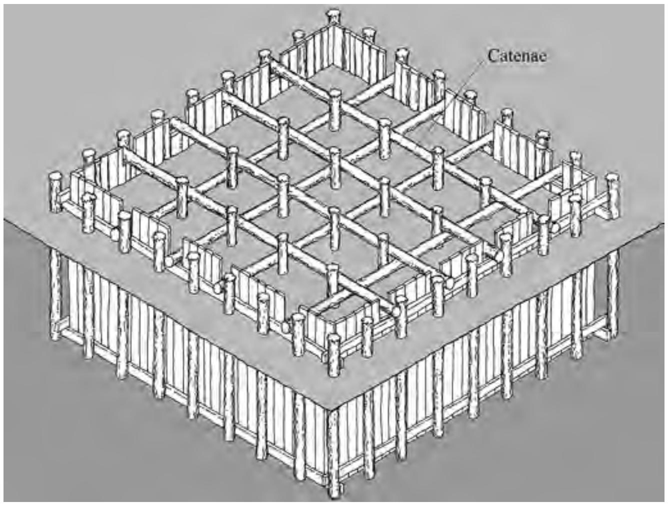

*Fig. 8.37. Reconstruction of horizontal tie beams (*catenae*) fixed to the upper horizontal rail installed in the fifth and final phase of building a Category 1 form (C. J. Brandon).*

1996: 70–75). Alongside these *pilae* is the curvilinear end of a concrete pier. Set into its sides are a row of large circular horizontal beam impressions that run from side to side at approximately 1 m centres and between 2 to 2.5 m from the top finished surface of the dock (Caputo 1995/96: 238–40).

- Puteoli: a late nineteenth-century engraving by Consalvo Carelli (Döring 2003) shows sockets for *catenae* in one of the *pilae* forming the harbour mole. This *pila* is also shown as having *opus reticulatum* facing.
- San Marco di Castellabate: horizontal cross beams (*catenae*) span the width of the concrete harbour mole and are arranged at 1.5 m centres (Fig. 8.19; Benini 2002: 39–46).
- Sapri: on the upper surface of the remains of the concrete pier are horizontal beam (*catenae*) impressions, 16 to 18 cm diameter; two are 20 cm wide (Scognamiglio 2008: 142–44).
- Egnazia: impressions of rectangular or square sectioned beams, 20 to 30 cm in diameter that span the width of the southeast concrete pier, are set out 1.5 to 2.0 m apart centre to centre (Figs. 8.11–12; Auriemma 2003: 89).
- *Sebastos*, Caesarea Palaestinae (Israel; Fig. 3.2): on the southern end of the encircling mole are a line of concrete blocks that have horizontal tie beam impressions, some with a single beam and some with a cross tie beam notch (Figs. 4.29–30; Oleson in Raban 1989: 209–28 and figs. IV.8–10).
- Carthage (Tunisia; Fig. 3.2): on top of a large concrete block at the shoreline north of the main harbour are the negative impressions of 25 cm × 25 cm section horizontal beams that span the width of the block with 25 cm × 14 cm beams set at right angles to them and notched into them by 10 cm (Figs. 6.79–80, 8.40; Yorke and Davidson 1985: 163).
- Thapsus (Tunisia; Fig. 3.2): along the concrete stretch of the very long mole, now buried under a modern marina, are a row of horizontal circular holes that run across the width and spaced 1.3 m apart centre to centre (Fig. 8.41; Dallas and Yorke 1968: 25; Davidson and Yorke 2014).

***8.2.2. Masonry enclosures as formwork.*** In some situations dimension stone blocks were used as a permanent facing in addition to forming the enclosure within which the concrete was cast. The principle is similar to that of Category 1 forms in wood, but the materials and procedures are very different. At Pompeiopolis and Kyme in Turkey, and at San Cataldo (near Lecce) in Italy ashlar marginal walls were built out into the sea to form inundated cells, in a similar manner to timber formwork, that were in-filled with hydraulic concrete. The blocks were heavily clamped to bind the stones together, particularly before the concrete core had been placed, when they were most exposed to damage from the sea. Since there are few surviving examples, it is not clear whether this procedure was the result of local innovation, a response to local conditions, or an imitation of concrete placement on land. Since both the Pompeiopolis and San Cataldo moles seem to date to the reign of Hadrian, the procedure may be a relatively late development in marine concrete placement.

The moles at Pompeiopolis were circa 23 m wide and framed on the outside by double walls of dimension stone masonry cut from the same travertine bedrock that underlies the harbour site (Figs. 4.46–49). Cross-walls constructed at irregular intervals divided the area into large boxes to be filled with hydraulic

*Fig. 8.38. Impression of horizontal tie beams on* Molo Sinistro *of the Claudian basin at Portus.*

*Fig. 8.39. Fragment of the northern mole of the harbour at Astura.*

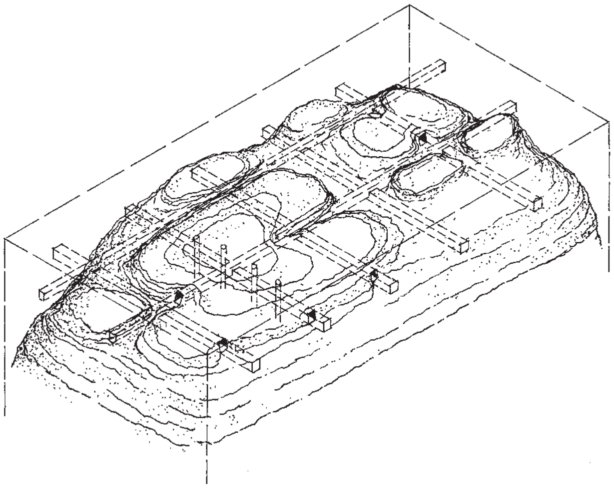

*Fig. 8.40. Axonometric sketch of the large concrete block on the shoreline north of Carthage (C. J. Brandon after R. A. Yorke; used with permission).*

concrete. The lower portions of the outside walls appear to be up to 2.8 m thick, constructed with approximately uniform stone blocks 1.6 m long by 0.6 m wide and 0.6 m deep. The arrangement of the blocks in the walls consists of two outer and inner stretcher blocks laid on either side of five headers followed by a double row of headers. The courses above appear to step in slightly, reducing the wall-thickness to 2.2 m while maintaining a vertical outer face. A distinctive feature is that each block was secured to the adjacent blocks with large butterfly-clamps set into the upper surface of the stone. No clamps have survived, but deep cuttings remain visible, 35 cm long by 5 cm deep and varying in width from 6 cm at the ends to 3 cm at their midpoints; there were up to 6 clamps per block (Fig. 4.49). The extraordinary size of the clamp-sockets suggests that the clamps were made of wood rather than metal (Vann 1994: 72). Four cross walls are clearly visible on the exposed surviving length of the western breakwater, set at 34 to 30 m apart to form the cells into which the concrete was placed (Fig. 4.47). Most of the cross-walls are 1.6 m thick, built with alternating courses of headers and a line of double stretchers alternating with a header. One cross-wall on the landward end is only 60 cm thick on the upper course, consisting of a single line of stretchers, while it widens to a double row at a lower level. The cells were probably built out into the sea one-by-one and in-filled with concrete as each was completed. This form of enclosure was not watertight, and the compartments would

*Fig. 8.41. Thapsus; horizontal beam impressions in the upper section of the concrete mole (R. A. Yorke; used with permission).*

have been flooded, requiring that the lowest stratum of the concrete be laid underwater (Brandon *et al*. 2010a: 390–98).

The construction techniques used to build the mole at the harbour of Kyme are not so easily interpreted. The ashlar walls that formed the permanent shuttering to the concrete and rubble fill have been extensively robbed out, leaving discontinuous stretches of walling that do not align (Fig. 8.42). The remains currently extend over a length of 190 m in widths that vary between 8 and 20 m. The end of the mole comprises a mass of concrete that Esposito suggests was cast within a timber form at a date later than the construction of the stone-faced pier (Esposito *et al* 2002: 1–37). The blocks along the length of the pier are generally arranged in a header fashion, although only the lower courses remain. Towards the shore end of the mole, hydraulic concrete makes up the core of the structure with heavily clamped and mortised stone blocks forming the enclosure in a similar manner to the mole at Pompeiopolis. The central section is missing, as is almost all of the exposed outer section of walling along with all the core material.

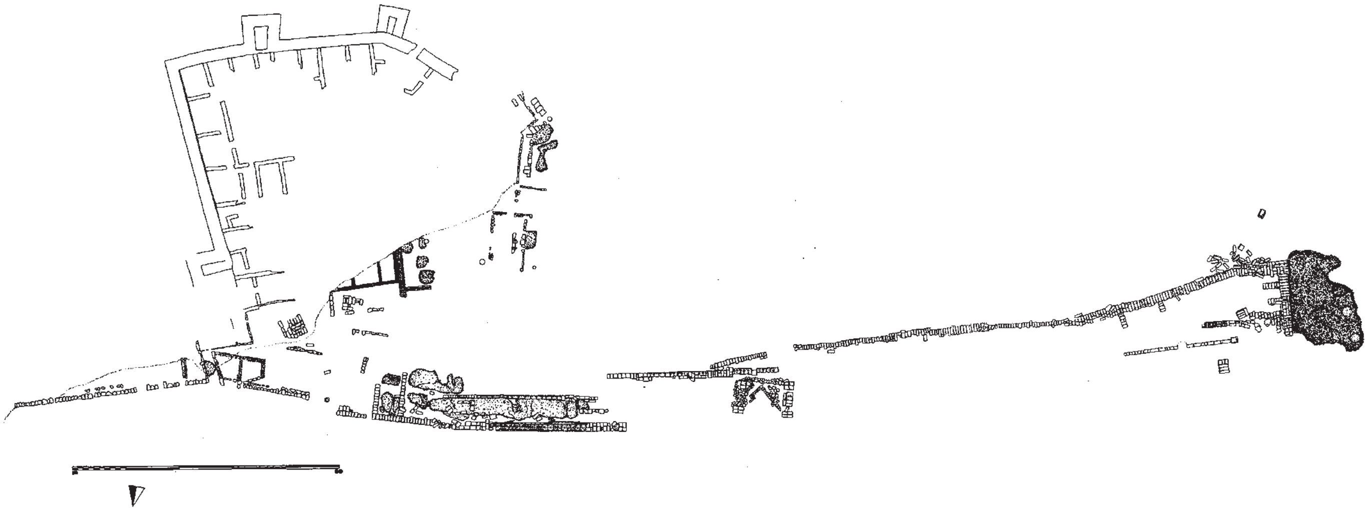

*Fig. 8.42. Plan of the mole at Kyme (Esposito* et al. *2002: pl. II; used with permission).*

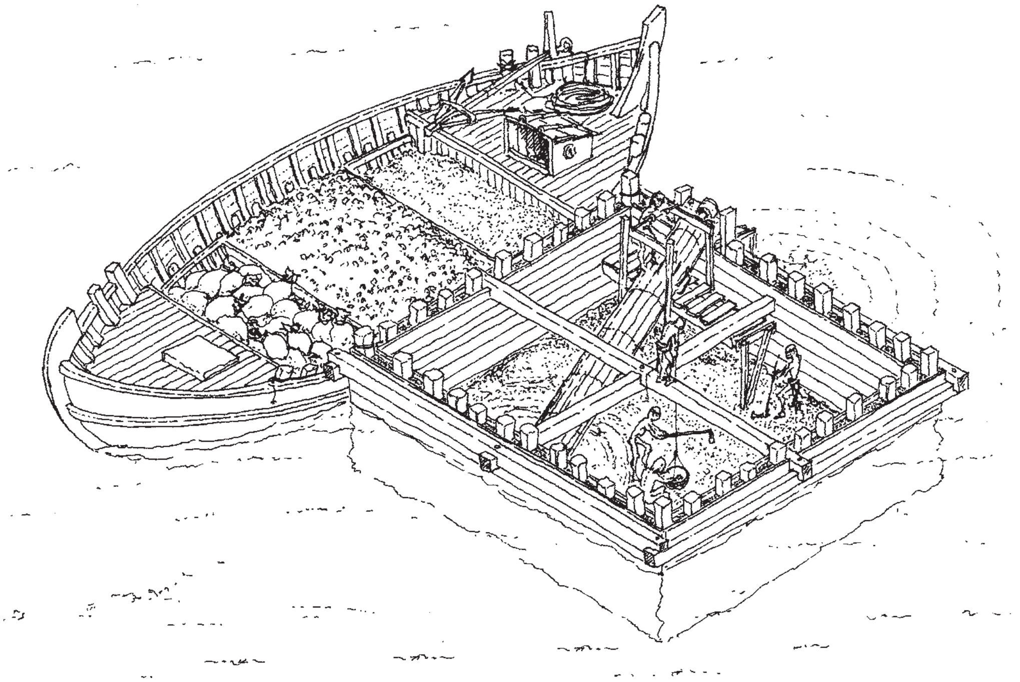

*Fig. 8.43. Reconstruction of a Category 2 cofferdam constructed* in situ *and dewatered (C. J. Brandon).*

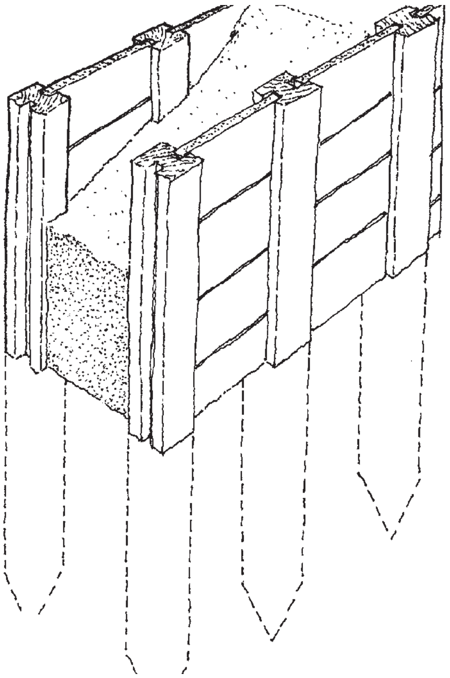

*Fig. 8.44. Grooved piles into which horizontal boards are slotted (C. J. Brandon).*

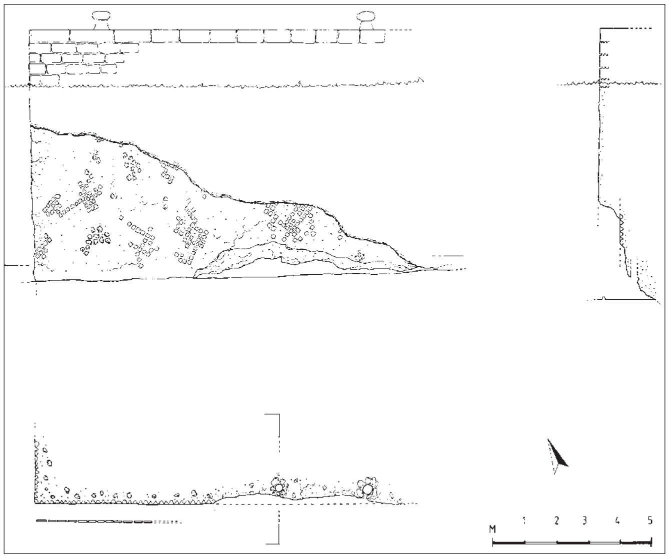

*Fig. 8.45. Offset shuttering used to form the quasi-*opus reticulatum *faced concrete pier in the harbour at Ponza (Gianfrotta 1996: 71; used with permission).*

The harbour mole at San Cataldo near Lecce was over 64 m long and constructed with two parallel exterior walls made with local stone blocks, 1 m wide and 0.5 m tall and up to 3 to 4 m long, 16.60 m apart, and filled with concrete (Fig. 6.61). There is no evidence of any clamps fixing the blocks together, although these might have been present in the length of mole further offshore that was destroyed to make way for a modern breakwater begun in 1901 but never finished. The Roman ashlar faced mole is attributed to Hadrian (Auriemma 2004: 155–62).

***8.2.3. Category 2: Cofferdam formwork constructed in situ, designed for dewatering.*** Like Category 1 forms, Category 2 forms were constructed *in situ*, but they were watertight and could be drained of water for both hydraulic and non-hydraulic concrete (Fig. 8.43). Vitruvius (*De arch.* 5.12.5–6; pp. 22–23, Passage 9) describes the construction of a double-walled cofferdam form that was pumped dry for casting non-hydraulic concrete in areas where volcanic ash pozzolan was not available. This category includes formwork with watertight enclosures that were constructed with single and double walls. In addition to being used for casting non-hydraulic concretes, they were used also for revetments, bridge footings, and other applications where a dry working environment was required underwater (Table 8.2).

The simplest type of cofferdam was that described by Vitruvius. Piles were driven vertically into the seabed (or lake or riverbed) at regular spaces around the area to be enclosed and drained, either as a single line or double row. Horizontal timber planks were then secured to the piles on both faces, internal and external. The void in between the boarding and the piles was packed with puddled clay. The Romans also developed rebated or grooved piles into which boards could be slotted, making it considerably easier to set them underwater (Fig. 8.44). Elaborate interlocking piles were also used, some with continuous dovetails where additional strength was required.

Category 2 forms might have been used to build the *opus reticulatum* or brick faced structures deep underwater. At Ponza there appears to be evidence of a second line of timber sheet piles set off from the face of the wall, but within the line of the modern over-cladding, to provide the dry working space needed to lay the quasi *opus reticulatum* faced concrete (Fig. 8.45; Gianfrotta 2002: 70–72). It is difficult to comprehend how the Roman engineers resolved the practical problems associated with creating very large watertight enclosures and manually pumping out large, deep cofferdams, such as the one needed to construct the outer *pila* at Nisida with *opus reticulatum* facing on the sides (*ca.* 15 m × 9 m by 9 m deep; Gianfrotta 1996: 71). An alternative for smaller *pilae* is to produce them above sea level on shoreline platforms in the method described by Vitruvius and possibly mentioned by Horace and Virgil (pp. 21–24), and then allow them to fall into the sea.

## 8.3. A Typology of formwork design for underwater construction: Prefabricated and floating forms

***8.3.1. Category 3: Prefabricated forms.*** Vitruvius makes no mention of the use of prefabricated forms or prefabricated formwork elements in his chapters on harbour construction (*De arch* 5.12.1–6). He does, however, describe how blocks

*Table 8.2. Gazetteer of Category 2 formwork.*

| **Site** | **Location** | **Description** |
|---|---|---|
| Alexandria (Egypt) | North-eastern part of the Poseidium peninsula | Double wall cofferdam comprising slotted timber piles with tenon ended planks inserted in-between (Fabre *et al*. 2010: 56–57, figs. 5.3–6). |
| Alexandria (Egypt) | In the "Ball Trap" sector | Formwork of 15 cm × 15 cm square piles with vertical grooves on opposite faces to accommodate planks 2 cm thick by 30 cm long. Close to the shore the oak piles (*Quercus sp*. [*alnifolia* or *coccifera* or *ilex*]) and the pine planks (*Pinus sp*.) date from AD 135–333. At the end of the dock the oak piles (*Quercus t. ilex*) and the pine planks (*Pinus sp*.) date from AD 83–229 (Fabre *et al*. 2010: 61–2, figs. 5.9–10). |
| Cosa, Portus Cosanus | Spring House Basin Platform | Oak, spruce and pine horizontal planks (*Picea abies, quercus, pinus*) 0.03–0.05 m thick *ca.* 0.34 m wide. Held in place by vertical piles (Oleson 1987: 100). |
| Marseilles (France) | Quay side cofferdam F.28 | Double wall form with horizontal planks fitted to two parallel rows of 149 vertical pine piles (*pinus halepenis*), 13–14 cm in diameter and 5.5–6 m long braced externally with 3 large angled braces (Hesnard *et al.* 2004: 181–85). |
| Marseilles | Cofferdam F.63 and foundation to F.120 (M.79) | Cofferdam most likely temporary works associated with the construction of the formwork for foundation F.120 that was constructed with random width horizontal planking fixed to vertical piles (Hesnard *et al.* 2004: 186). |
| Minturnae | Embankment | Vertical oak posts with horizontal oak planks edge fixed with mortise and tenon joints (Ruegg 1988: 221). |
| Lake Nemi | Lake embankment or revetment | Cofferdams formed with a double wall spaced 0.75 m apart formed with vertical 30 cm × 20 cm interlocking piles in filled with clay. Also a double wall set 0.75 m apart formed with 5 cm thick planks fitted to close piled vertical timbers 52 cm × 25 cm in section with the second wall formed with 40 cm × 20 cm piles at 90 cm centres with oak panels in between (*abies pectinata* and *quercus cerris*) (Ucelli 1952: 119–30). |
| Nisida | *Pilae* | Impressions of posts and beams for a double walled watertight cofferdam (Gianfrotta 1996: 71), or possibly for a prefabricated (Category 3) form. |
| Rome, Pons Cestius | Bridge pier footing | Cofferdam comprising a double row of oak piles (Blake 1947: 347–48). |
| Rome, Ponte Elio | Bridge pier footing | Cofferdam comprising a double row of timber piles (Brizzi 1999: 115, fig. 82). |
| Ponza | Harbour mole | 0.27–0.36 m wide × 0.05 m thick vertical boards; possibly the outer wall of a double walled cofferdam (Gianfrotta 2002: 70–72). |
| Portus, Trajan's Harbour | Dockside wall | Two watertight wooden bulkheads 1.0 m apart that were constructed with vertical boards nailed to 10 cm square horizontal joists and to 16 cm diameter piles driven into the soil. The void inbetween the bulkheads was made watertight and the land behind it drained to enable construction of the dock side (Calza 1925: 54–80, esp. 55–56). |
| Rome, near Ponte Elio | Tiber quay | Double wall cofferdam formed with interlocking piles circa 45 cm × 70 cm with back braced 50 cm × 55 cm piles at 3 m centres (Marchetti 1891: 45–60, pls. III–IV). |
| Rome, near Ponte Sublicio | Tiber quay | Horizontal tie beams (Carpano 1982: 157, fig. 7). |
| Trier, (Germany) | Bridge pier footing | Double walled cofferdam with vertical "H" slotted piles with horizontal boards (Cüppers 1969: 152). |

could be constructed above sea level and, only after they had cured and set solid, be tipped into the sea (Figs. 8.46–50). Vitruvius suggested that the method was intended for sites where the seas were too rough for *in situ* construction of concrete formwork (Vitruvius, *De arch.* 5.12.3–4; pp. 20–22). The procedure sounds impractical, both time-consuming and difficult to control, and there is no further evidence for it other than possible allusions in Horace and Virgil (pp. 23–24, Passages 10–11). It is possible, but not verifiable, that the procedure behind Vitruvius' description was a prefabricated form that could be launched from the shore (Fig. 8.51), rather than a pre-cast block, and that Vitruvius misunderstood the procedure when he wrote this passage.

Driving piles into the seabed at an exposed site offshore, and keeping the pile-driving barge on station without the benefit of modern powered winches and anchors must have been challenging. Fixing beams and planks underwater in situations with strong currents or rough seas would also have been very difficult. It would have been impossible to pump dry a Category 2 evacuated cofferdam enclosure where the

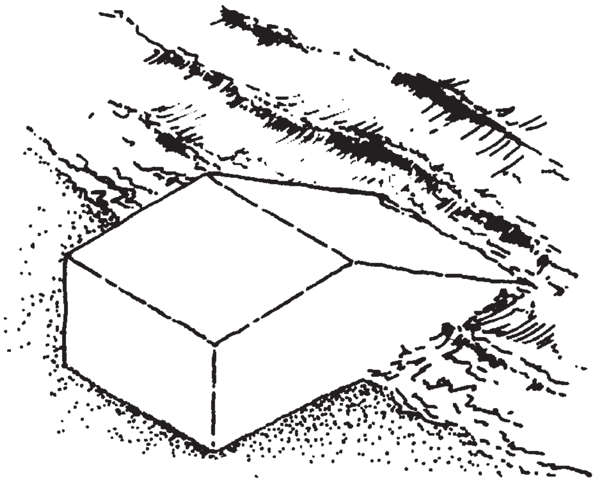

*Fig. 8.46. Category 3 form, stage 1, after Vitruvius 5.12.3–4: "A platform is to be built out with a level upper surface over less than half its area. The shoreward section is to have one side sloping" (C. J. Brandon).*

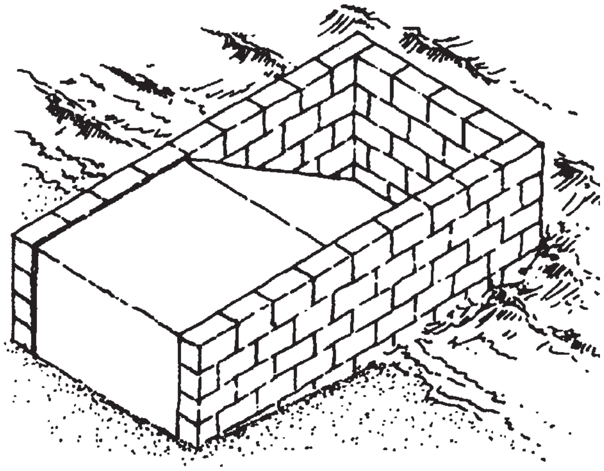

*Fig. 8.47. Category 3 form, stage 2, after Vitruvius 5.12.4: "Retaining walls one and one half feet thick are to be built at the end facing the sea and on either side of the platform, equal in height to the level surface described above" (C. J. Brandon).*

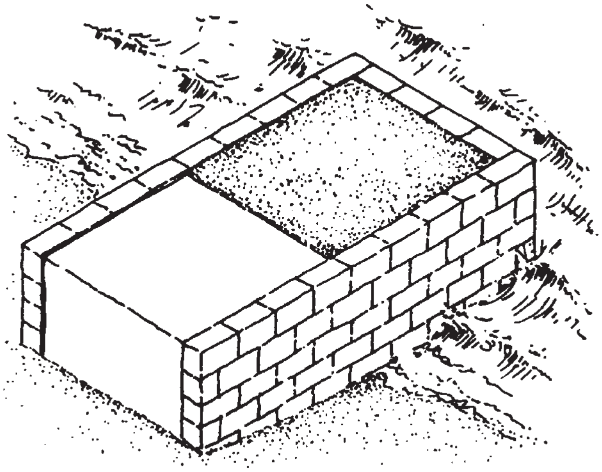

*Fig. 8.48. Category 3 form, stage 3, after Vitruvius 5.12.4: "Then the sloping section is to be filled in with sand and brought up to the level of the retaining walls and platform surface" (C. J. Brandon).*

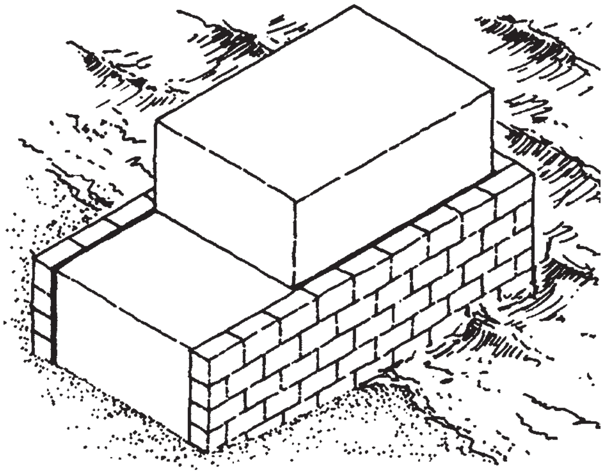

*Fig. 8.49. Category 3 form, stage 4, after Vitruvius 5.12.4: "Next, a concrete block (*pila*) of the appointed size must be built there, on this levelled surface, and when it has been formed it is left at least two months to cure" (C. J. Brandon).*

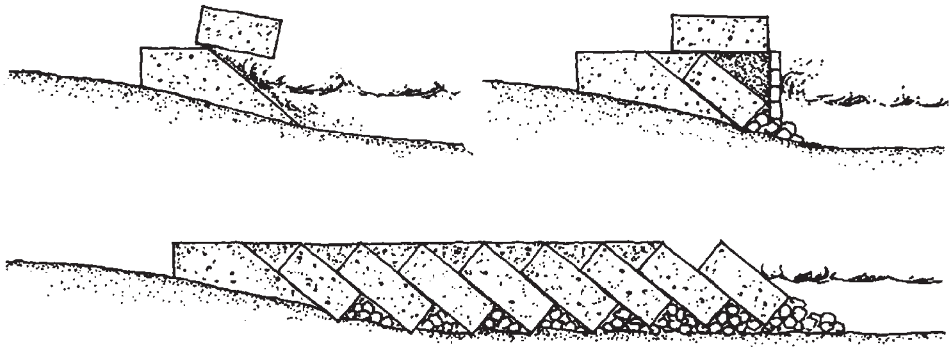

*Fig. 8.50. Category 3 form, stage 5, after Vitruvius 5.12.4: "Then the retaining wall that holds in the sand is cut away, and in this manner erosion of the sand by the waves causes the block (*pila*) to fall into the sea. By this procedure, repeated as often as necessary, the breakwater can be carried seaward" (C. J. Brandon).*

*Table 8.3. Gazetteer of Category 3 Prefabricated Formwork.*

| **Site** | **Location** | **Description** |
|---|---|---|
| Alexandria (Egypt) | Quay, SW Antirhodos Island | Caisson circa 15 m × 8 m; beams 10 cm × 12 cm and (*pinus* sp.) planks, 44–45 cm wide, 3.5–4 cm thick edge fixed with mortise and tenon joints at 21 cm centres, treenails 5 cm apart. 10–15 cm beams. Chine beam heavily eroded (Goddio *et al*. 1998: 32–37; C. J. Brandon, pers. comm. 2005). |
| Astura (Italy) | Harbour mole | Impressions of horizontal tie beams, vertical posts on sides and cross beams at low level near base. No internal structure. Felici (2006: 59–84) suggests that this is evidence for a prefabricated form. |
| *Sebastos,* Caesarea (Israel) | Area G, Caisson | Open bottom double walled caisson 11.5 m wide × 15 m long. 0.13 m$^2$ and 0.18 m$^2$ horizontal tie beams at 1.6 m centres. Pine and fir sleeper beams *ca.* 0.29 m$^2$ interlocked at corners with a simple lap joint. Series of pine and fir uprights *ca.* 0.12–0.15 m × 0.23 m at 1.6 m centres mortised into horizontal beams. Horizontal pine planking 0.08 m thick and 0.14 m wide. Lowest plank mortise and tenon jointed into sleeper beam (Oleson 1989a: 127–30, figs. III. 50–63). |
| *Sebastos,* Caesarea | Area K, Caisson | 0.19–0.26 m deep and 0.08 m thick horizontal pine boards secured with mortise and tenon joints and treenails and iron nails to vertical frame timbers 0.19–0.26 m wide and 0.055 m thick planking on the bottom. 0.26 × 0.2 m chine beams. 0.20 × 0.25 m pine floor timber frames spaced between 0.3–0.7 m apart. 0.25 m diam. stringers (Brandon 1997a: 45–58; 1997b). |
| Carthage (Tunisia) | Wall C, Jointed wooden shuttering | 0.43 m wide vertical tongued and grooved planks with a thickness of 4–5.5 cm have a continuous mortise slot on one edge and a central tongue 2.5 cm wide on the other. A vertical rectangular post 7 × 10 cm braced the structure at the corner. Yorke and Davidson (1985: 162–63) suggest that this complex, continuous mortise and tenon edge joint make it likely that the form was pre-fabricated. |
| Carthage | Pier F | 0.045 m thick horizontal planks, 0.3 m wide horizontal beam 0.08 m sq (Hurst 1976: 188–89). |
| Chalon-sur-Saône (France) | Bridge pier footing | Caisson, with mortise and tenon edge fixed planks to side walls and bottom. Used to construct ashlar bridge piers (Bonnamour 2000). |
| Istanbul, Yenikapi (Turkey) | Harbour pier caisson | Horizontal boarded, double walled prefabricated cofferdam with a clay infill. Sole plates, circa 12 cm wide are set approx 60 cm apart into which vertical posts were set at approx 60 cm centres that were fixed in with tenons, onto which the horizontal boards were set (J. P. Oleson, pers. comm. 2011). |
| Istanbul | Caissons | Procopius (p. 35, Passage 30) describes how Justinian used very large, prefabricated box-shaped formwork (“cribs”) in the construction of harbour moles at Constantinople, sometime between 527 and 553. |
| Laurons (France) | Caisson | 22.90 m long × 2.20 m wide caisson, 32 upright posts set into chine beam with dovetailed and tenon joints. The floor planking was nailed to the underside of the floor frame (0.11 × 0.18 m and 0.14 m × 0.18 m horizontal frame timbers) and vertical side wall planking was let into grooves cut into the top surface of the chine beam. 0.13 m × 0.11 m vertical posts (Ximenes *et al*. 1988: 229–52). |
| Lechaion, Corinth (Greece) | Caissons | 4.35–4.65 m × 9.2 m caissons, 22–23.5 cm wide × 4–6 cm thick planks fixed on top of 15.5 cm wide horizontal beams at approximately 60 cm centres. Possibly post-Medieval. |
| Portus (Italy) | Re-used ship’s hull | One of Caligula’s obelisk carrying ships was used as the formwork for the concrete foundations of the lighthouse at the entrance to the harbour of Portus (pp. 26–28, 32, Passages 15, 17, 24). |
| Side (Turkey) | Harbour mole | Horizontal planking fixed to vertical piles 0.3 m × 0.15 m at 0.8 m intervals (Knoblauch 1977: 28–31). |
| Toulon (France) | Re-used ship hulls | Rubble filled ship hulls used in the construction of the harbour mole at Toulon (Brun 1999: 797–803). |
| Ventotene (Italy) | Prefabricated panel | Pre-fabricated panel comprising vertical boards edge fixed with mortise and tenon joints and stiffened with horizontal beams (Zarattini *et al*. 2010: 6). |

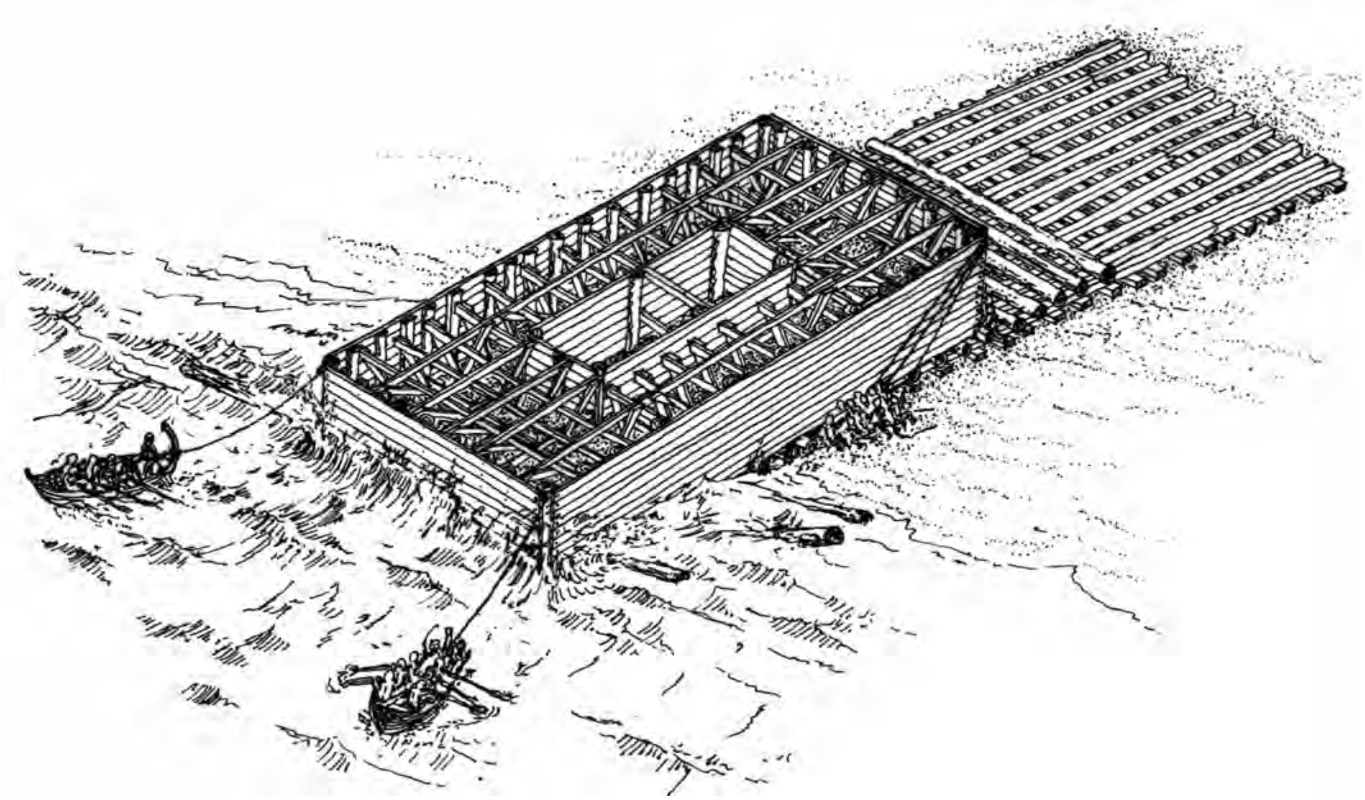

*Fig. 8.51. Reconstruction of a prefabricated floating caisson being launched into the sea near Sebastos (C. J. Brandon).*

sea or riverbed consisted of gravel or had an equally porous substratum. Faced with these problems the Roman marine engineers developed a range of solutions that included floating boxes (Figs. 8.51–52), double-walled floating forms (Figs. 8.59–61), expendable ship hulls, and prefabricated elements such as panels or side walls.

Compared with the extensive evidence for the use of Category 1 type forms, there are fewer instances of the clear use of Category 3 forms (Table 8.3). Nevertheless, there is archaeological evidence for several examples of flat-bottomed, box-shaped single mission barges that could be floated to the designated construction site. They were built by shipwrights with traditional ship-building techniques: the timber planks were edge-joined with tenons set into mortises and transfixed with treenails. The interior was then stiffened with floor beams, stringers, ties, and raking struts (Figs. 8.62–71). The floating forms at Caesarea were intended to cope with obvious difficulties that would have been encountered in working at a very exposed site. The same type of caisson was also used in a more sheltered situation in the Eastern Harbour of Alexandria, in the lee of Antirhodos Island, but this location too could be subject to significant wave action. The Alexandria forms were built in exactly the same manner as the Caesarea single-mission barges, although with slightly larger dimensions (Figs. 8.53–54). The Caesarea caissons were 14 m long × 7 m wide × 4 m tall, while the Alexandrian version was 15 m long × 8 m wide; the original height is unknown as only the bottom 1 m has survived. Another example of this type of form is a long prefabricated box that was filled with rubble to form a finger jetty at Laurons in the South of France (Fig. 8.55; Ximenes and Moerman 1988: 229–52). Similar caissons were used in the construction of the early third-century Roman bridge piers at Chalon-sur-Saône (Figs. 8.56–57; Bonnamour 2000). At this last site the forms were used primarily because the riverbed was very porous, and it would have been impossible to pump out a more traditional cofferdam enclosure faster than the water percolated in through the bottom.

One of the most innovative solutions to the need for this type of form is documented in the construction of the end of the northern breakwater at Caesarea. The forms used here were built as floating, open-bottomed enclosures with a double-walled perimeter that acted as the flotation collar (Figs. 8.58–60). They were floated into position and sunk in a controlled manner by gradually filling in the void between the two walls. By omitting the floor, such a form could cope with an uneven seabed, although the frame would have been liable to raking, so this design may only have been used in relatively sheltered waters. Evidence for these forms so far is unique to Caesarea, and they may have proved too difficult to manoeuvre to have been used elsewhere.

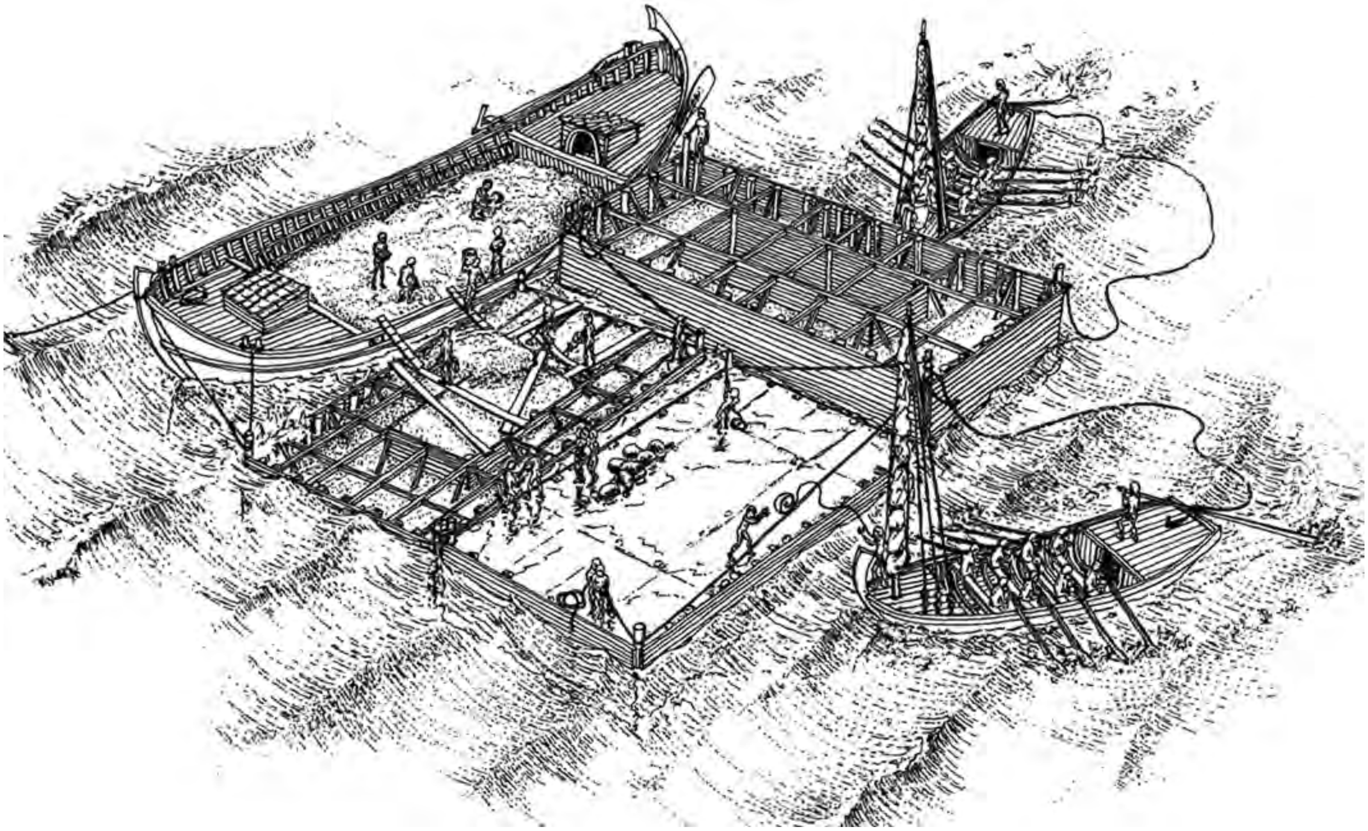

*Fig. 8.52. Reconstruction of prefabricated caissons being positioned and loaded with concrete at Area K at the northern end of the main enclosing mole at Caesarea (C. J. Brandon).*

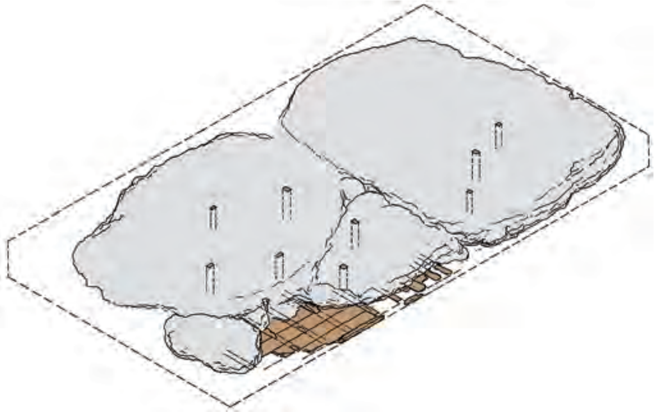

*Fig. 8.53. Axonometric sketch of the concrete block and caisson at Antirhodos Island in the Eastern Harbour of Alexandria (C. J. Brandon after Goddio* et al. *1998: 32–37; used with permission).*

*Fig. 8.54. (right) Base of caisson, Antirhodos Island, within the eastern harbour of Alexandria (C. J. Brandon).*

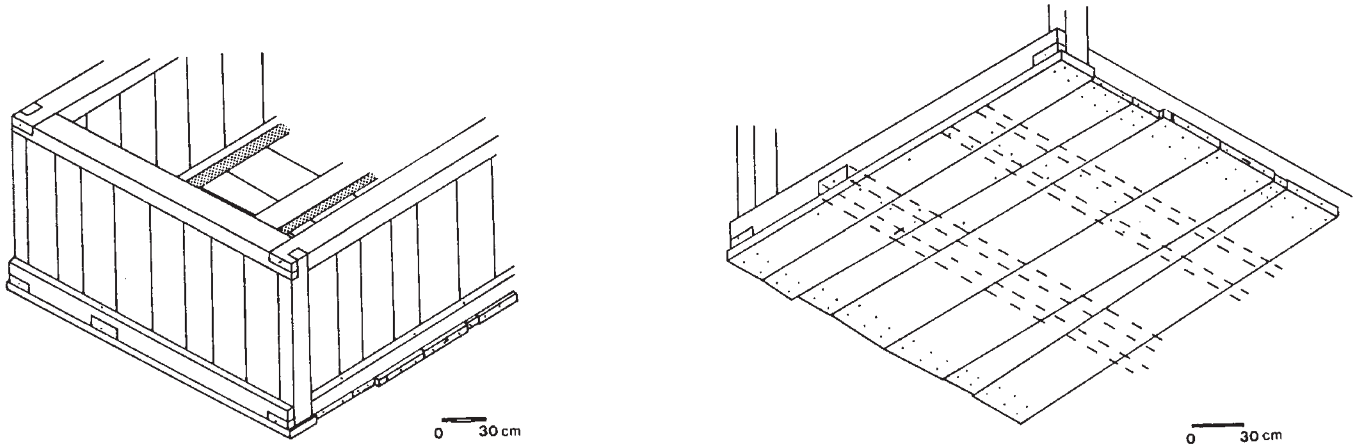

Fig. 8.55. *Axonometric details of the caisson used to build a long rubble jetty in the harbour of Laurons (Ximenes and Moerman 1988: 229–52; used with permission).*

Fig. 8.56. *Model of the bow section of the caisson used to construct the bridge pier at Chalon-sur-Saône (C. J. Brandon).*

Fig. 8.58. *Concrete block with remains of double-walled floating caisson in Area G at Sebastos (Courtesy of CAHEP).*

Fig. 8.57. *Detail of the floor timbers and keel on the model of the bow section of the caisson used to construct the bridge pier at Chalon-sur-Saône (C. J. Brandon).*

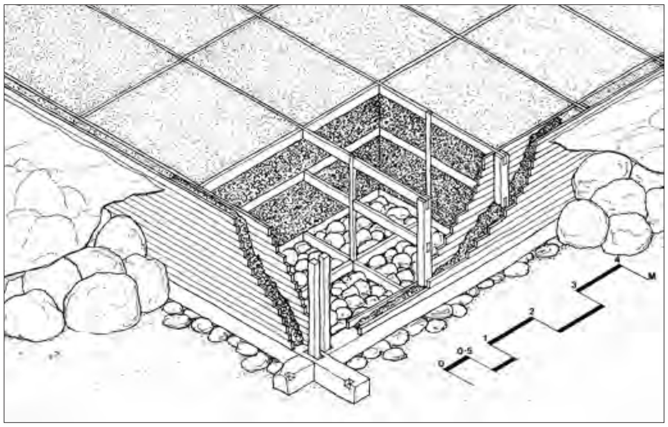

Fig. 8.59. *Reconstruction of double-walled floating caisson in Area G at Sebastos (C. J. Brandon after S. Talaat).*

A variant on this technique of constructing large floating box forms was used in the late Roman, Byzantine and Medieval periods in marine engineering projects. Often described as cribs or chest work, these were timber frames without planking designed to be floated to position then filled with stone rubble rather than concrete. Procopius describes the use of a number of large, box-shaped forms of this type, called coffers (*kibotoi*), in the construction of the Justinian harbour at Constantinople (Procopius, *On Buildings* 1.11.18–20; above p. 35, Passage 30).

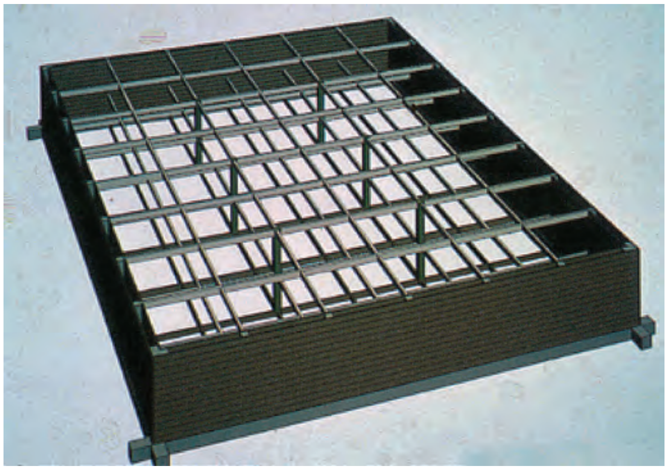

*Fig. 8.60. Reconstruction of the framing of a double-walled, prefabricated floating caisson in Area G at Sebastos (Courtesy of CAHEP).*

Redundant ship hulls also fall into this category. Although not purpose built for concrete construction, they achieved the same objective. The most renowned example was the hull of a very large ship in which Caligula to transported an obelisk to Rome, and which subsequently was used as floating formwork in the construction of the outer breakwater of the Claudian harbour of Portus (Pliny, *HN* 16.201–2, 36.70; Suetonius, *Claud.* 20.3; pp. 26–28, 32, Passages 15, 17, 24). Abandoned hulks filled with rubble were used to form part of the harbour mole at Toulon (Brun 1999: 797–803).

Prefabricated sections of formwork that could be assembled on site are included in this category. Examples of their use can be seen at Carthage, in the Roman widening of the bridge piers in the circular harbour (Yorke and Davidson 1985: 162–63), and at the island of Ventotene (Fig. 6.1) in the modifications to the fish-pond (Zarattini *et al*. 2010: 6).

*Fig. 8.61. Reconstruction of floating formwork being manoeuvred into position over Area G at Sebastos (Hohlfelder 1987: 264-65) (National Geographic Society, used with permission).*

### *Examples of Floating Box Forms.*

*Floating Caisson 1: Area K, Sebastos (Caesarea)*. A significant amount of the timber structure of the caissons found in Area K has been extraordinarily well preserved, protected by the seabed silts into which the loaded forms sank (Brandon 1996; 1997a–b; 1999; 2011). Because of their unique character, detailed construction information is provided here, obtained during their observations by Brandon in the 1990s. There are minor variations in the construction among the three caissons studied, possibly due to evolutionary improvements in design or simply because they were built by different shipwrights. These barges were rectangular, flat-bottomed craft 14 m long, with a beam of 7 m and a height of approximately 4 m. At least one of the barges had an inner central compartment that was 2.5 m wide and 5 m long (Fig. 8.62). The wooden formwork consists of a single watertight hull built with a floor in the same manner as shell-first ship construction. All the timber planks were edge-joined with tenons let into mortises and transfixed with treenails. The interior was then stiffened with floor beams, stringers, ties, and raking struts. The pine boarding ranges in size between 19 and 26 cm wide and 8 cm thick on the sides of the caisson and 19 cm to 26 cm wide and 5.5 cm thick on the bottom and on the walls to the inner compartment. No end joints in the planking were observed, and, therefore it is not possible to say if they were scarfed, as would have been expected in this method of construction. The tenons, which are made of hardwood, are on average 8 cm × 10 cm long and spaced at 20 cm apart centre to centre, although the upper boards on K5 have tenons spaced 30 cm apart. The tenons are secured with 11 mm diameter treenails, and are arranged so that they are staggered from board to board. There is no evidence of any caulking material between the boards, although the remains of a lime-based cement slurry has seeped out through the joint between the chine beam and the first plank and solidified, thus effectively sealing the gap.

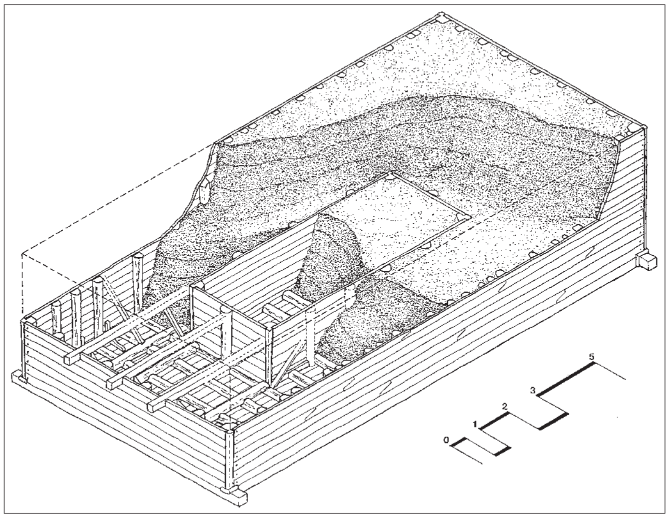

*Fig. 8.62. Reconstruction of a prefabricated rectangular caisson as found in Area K at Caesarea (C. J. Brandon).*

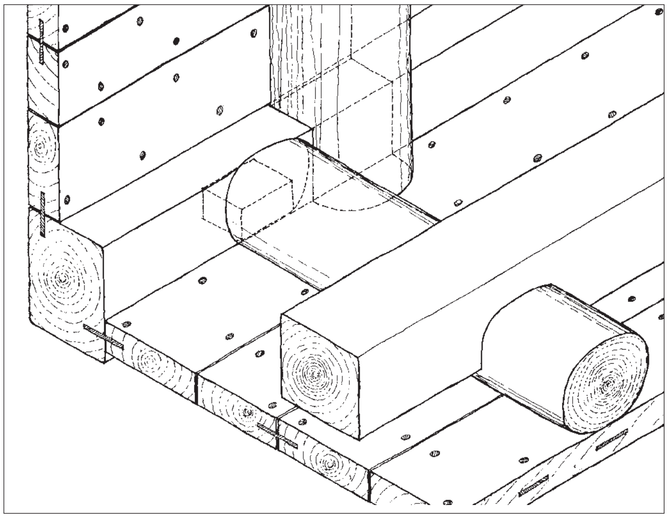

*Fig. 8.63. Detail of Area K caisson, junction of chine with side wall and flooring (C. J. Brandon).*

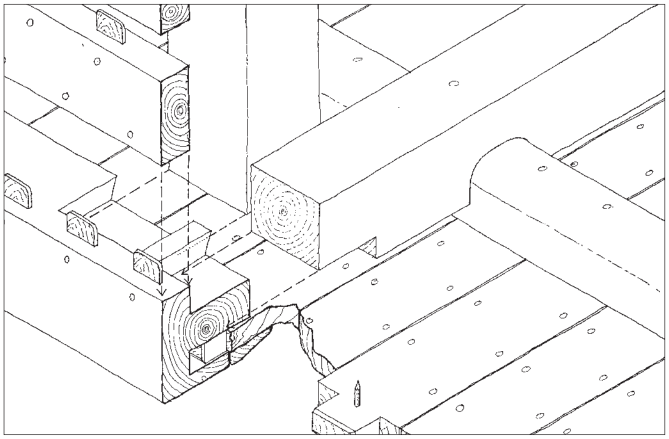

*Fig. 8.64. Detail of Area K caisson, junction of chine with end wall and floor planking, caisson K-2, Caesarea (C. J. Brandon).*

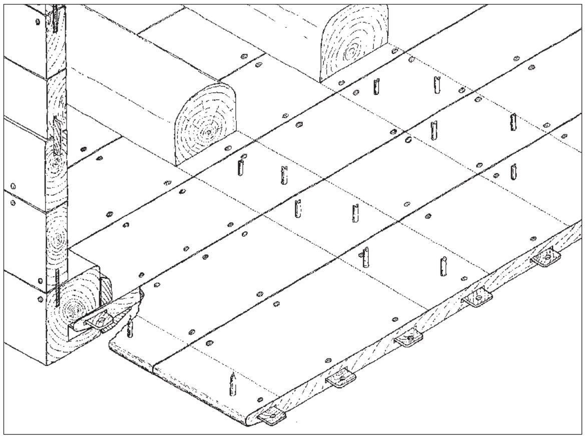

*Fig. 8.65. Detail of Area K caisson, junction of chine with end wall and floor planking, caisson K-3, Caesarea (C. J. Brandon).*

*Fig. 8.66. Detail of a floor frame, Area K caisson, Caesarea (A. Raban).*

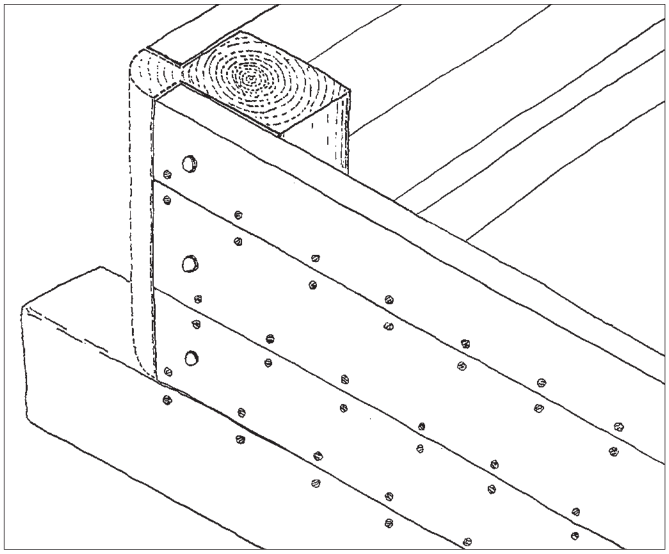

*Fig. 8.67. Detail of an external corner stanchion with side wall planking let into it, Area K caisson, Caesarea (C. J. Brandon).*

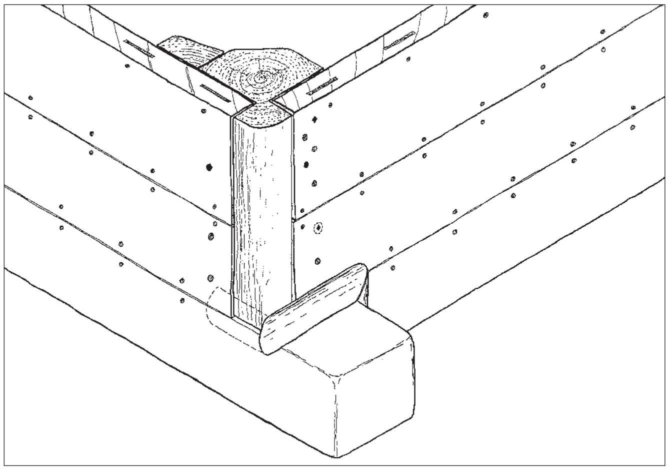

*Fig. 8.68. External corner detail with cover-piece over junction of chine beams, Area A caisson, Caesarea (C. J. Brandon).*

A 26 cm × 20 cm chine beam forms the junction between the side walls and the floor (Fig. 8.63–65). The planking on the sides is fixed to the chine beam with mortise and tenon joints secured with treenails. This also applies to the floor planking, which runs parallel to the chine and long axis of the caisson. The ends of the bottom boards, however, are set into the chine beam at bow and stern. This section is rebated along its length and in the case of K2 has mortises cut to take the projecting tenons that were cut into the ends of each plank (Fig. 8.64). K3 has a different design in which the ends of the planks have been rounded on section and let into a similar rebate on the side of the chine (Fig. 8.65).

The floor frames are formed by rough-hewn pine logs 20 to 25 cm × 20 cm, some still with bark adhering, set at an irregular spacing varying from 30 to 70 cm (Fig. 8.66). The presence of bark indicates that the timbers were not in secondary use. The frames are fixed to the bottom planking with at least one treenail per board. The ends of the frames are let into the chine beam with a tenon that protrudes from the lower half of the frame (Fig. 8.63). It is therefore apparent that the frames were fitted before the chine beam was offered up and fixed to the sides.

The inner face of the chine beam at bow and stern, which projects down below the level of the bottom planking, has a furring strip set against it to protect it from damage when the structure was launched (Figs. 8.64–65). This detail does not appear on the underside of the side chine beams, clearly indicating the direction and method by which the caissons were launched.

*Fig. 8.69. Corner of caisson K-3, Caesarea (A. Raban).*

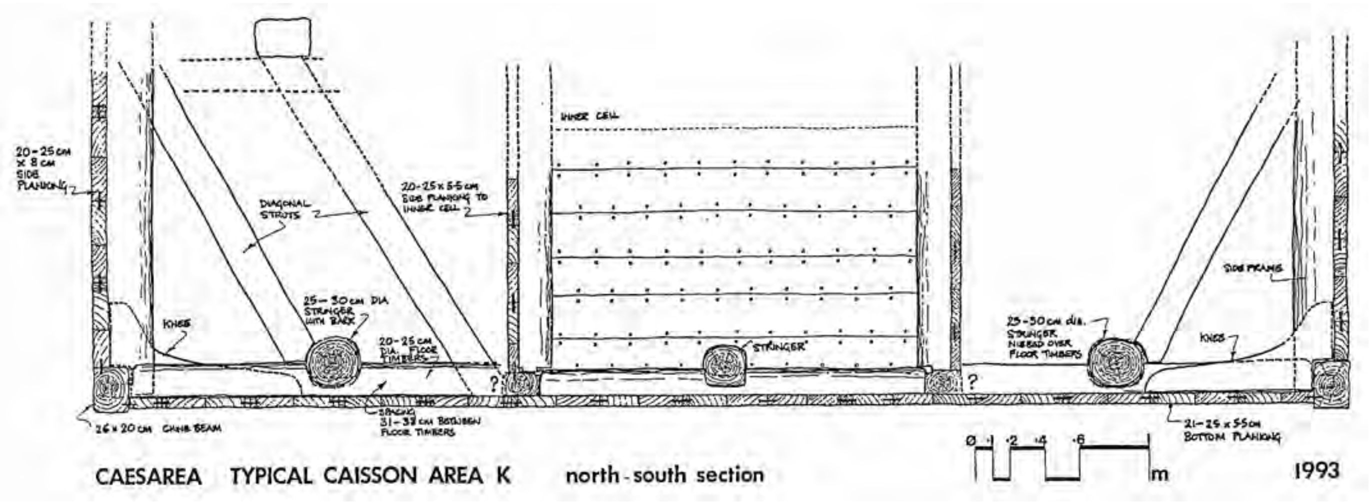

*Fig. 8.70. Cross section through Area K caisson, Caesarea (C. J. Brandon).*

The chine beam on the bow and stern projects out from the sides of the caisson by between 20 cm and 30 cm, and the complicated joint between the junction of the chine beams and the side wall planking is capped with a 4 cm × 5 cm quadrant section of timber that has been mitred and fixed around the chine beam (Figs. 8.67–69).

Stringers of approximately 25 cm diameter, with bark still adhering, were notched over the frames and fixed to them with treenails and their ends let into and over the chine beams (Figs. 8.70–71). Timber knee sections provided rigidity to the junction of the side planking, chine beam and bottom planking and were fixed in place with treenails and iron nails. Diagonal bracing or raking members strengthened the outer side wall planking. These raking props were braced off the frames, stringers, or knees, and secured at their heads by beams or directly onto the side frames. Horizontal beams, not the same as the *catenae* of box forms, were fixed in between the inner compartment and the outer side frames at a height of approximately 2 m above the floor timbers.

The inner cell, of which evidence remains in K2 but not K5, is formed directly off the bottom planking, and the floor frames are discontinuous on either side of it. The function of the inner cell, which was built with the same watertight construction as the main part, can only be surmised. It could have served as a central stabilising chamber to allow the barge to be loaded and sunk in a controlled manner. Within the compartment, the floor frames are similar to those outside but are set into protruding edge beams onto which the corner posts and stringer are also fixed (Fig. 8.72). A stringer runs on axis (approximately) and is notched over the floor frames and fixed to them and to the edge beam of the inner compartment with treenails. The corner posts are formed from pine trunks into which rebates are cut to take the side planking. The posts are set onto the edge beam with a tenon that is wedged in place (Figs. 8.73–74).

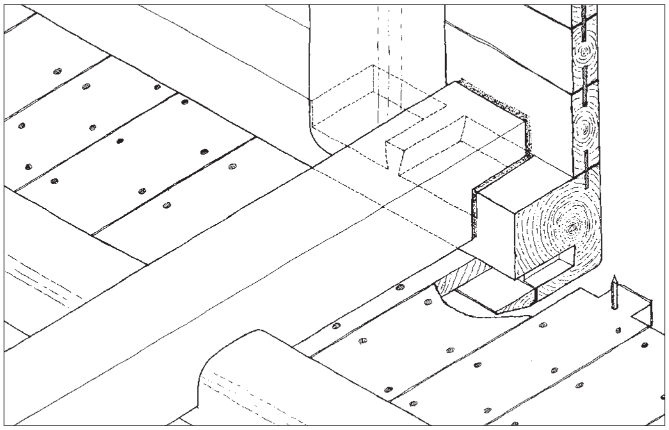

*Fig. 8.71. Detail of stringer let into chine beam at bow and stern, Area K caisson, Caesarea (C. J. Brandon).*

The exterior corner posts are of a similar design to those found in the inner cell. The ends of the side wall planking are let into the rebates running on either side of the corner post and are fixed in place with a combination of metal nails and treenails (Fig. 8.68). This cutaway stanchion, however, leaves a weak nib that was easily damaged or broken off. The side frames range in size, shape and spacing, being either rectangular, square, semi-circular, or quadrant shaped posts approximately 18 to 20 cm by 18 cm, and are fixed to the side planking with both treenails and metal nails. These side frames are notched into and over the chine beams (Figs. 8.63, 71, 75).

*Floating Caisson 2: Antirhodos Island in the Eastern Harbour of Alexandria.* Only part of the base of the caisson is still in evidence, although the upper works can be reconstructed. An area of the floor approximately 3 m long × 1.3 m wide is visible, beneath the western edge of a large block that was originally approximately 15 m long × 8 m wide (Figs. 8.53–54). The

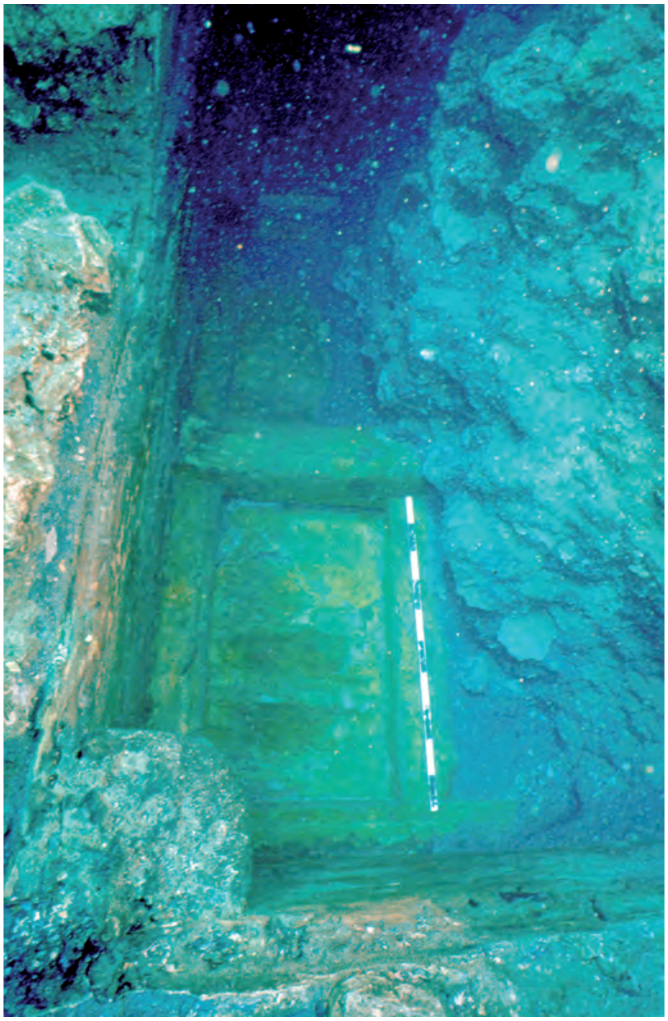

*Fig. 8.72. The inner cell within caisson K-2, Caesarea (A. Raban).*

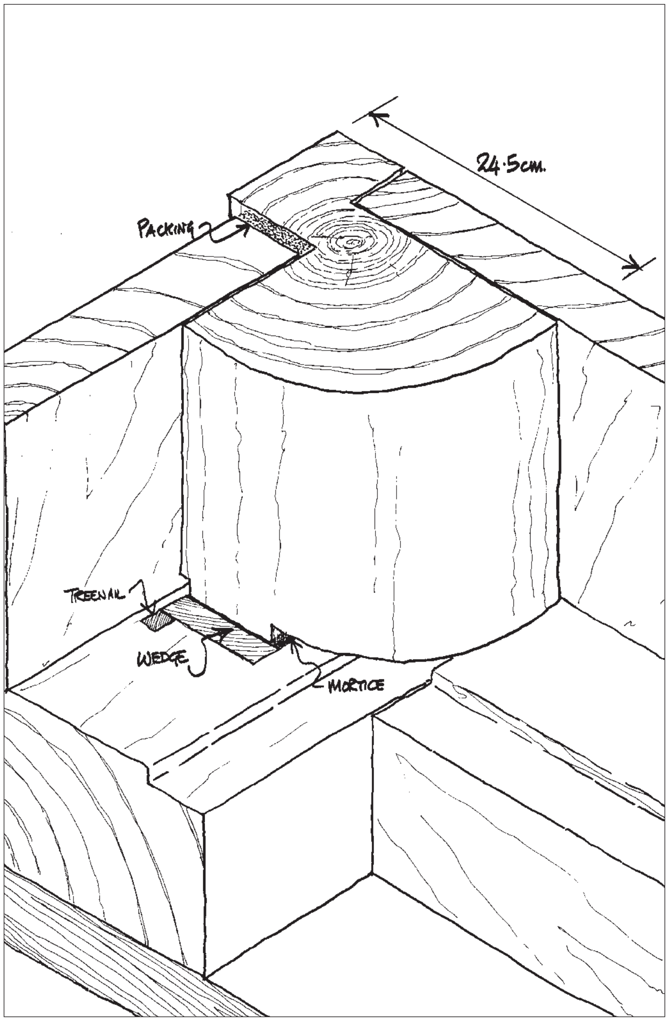

*Fig. 8.73. Detail of the corner of the inner cell within caisson K-2, Caesarea (C. J. Brandon).*

original height is unknown; the current remains are only 0.7 to 1 m high.

The pine floor planks are wide, varying between 44 to 45 cm, and 3.5 to 4 cm thick. They are edge jointed, with tenons 21 cm apart centre to centre that are transfixed with treenails 5 cm apart. The frames are comparatively small, 10 to 15 cm square, and mostly cut from logs with minimal working, although there was no evidence for any bark.

The heavily eroded remains of a chine beam just over 1 m long by 13 cm deep shows the impression of a recess to secure a lapped horizontal beam or footing for a vertical or raking post. Two tenons appear on the surface 60 cm apart that could have fixed the ends of vertical posts or the horizontal side wall planking.

A timber member projecting from beneath the caisson and interpreted by Goddio and de Graauw as being part of an out-rider structure, on closer inspection appears to be a displaced frame (Goddio *et al*. 1998: 32–35, 56).

*Floating Caisson 3: River Saône at Chalon.* The caisson was at least 6 m wide × 12 m long with a shaped bow that formed the upstream cutwater. The bottom planks range in width from 40 to 48 cm and 8 cm thick and are edge-fixed with staggered mortise and tenon joints set that were set 60 to 120 cm apart (Fig. 8.56). The floor comprised 13 longitudinal planks, the central plank an upside down "T" shape in section, 11.5 cm thick by 22 cm wide at the stern of the caisson (Fig. 8.57). This extra thickness is sharply accentuated upstream, towards the bow, and makes this piece of timber look like a proper keel. In the bow, a stem post with a trapezoidal section is inserted vertically into the keel and sole pieces using three tenons. As this early third-century caisson was intended for the construction of one of the masonry piers of the Roman bridge across the Saône, it was necessary that the stones were laid on a level base. As a result, in place of frames that would normally strengthen the floor planking, flat planking was substituted that went from side to side on top of the longitudinal planking and

*Fig. 8.74. Detail of the corner of the inner cell within caisson K-2, Caesarea (A. Raban).*

*Fig. 8.75. Section of the side of caisson K-2, Area K, Caesarea (A. Raban).*

notched over the upstanding section of the keel to provide a flat deck. The crossways planks are approximately 12 cm thick and nailed to the longitudinal planks in a staggered fashion. Vegetable fibre caulking (cyprus or sedge leaves) was rammed in between some of the planking to improve water-tightness. A series of knees, very similar to those used in boat construction, were set out along the inside of the caisson to strengthen the joint between the bottom and the side walls. Nailed to the decking, these knees gave vertical support and were mortised into the oak chine pieces nailed to the walls of the caisson. The oak chine piece is 35 cm × 40 cm and the side wall is made of pine planks approximately 50 cm high and between 6 and 8 cm thick. These boards were assembled using mortise and tenon joints 50 to 60 cm apart. They were made watertight with 5 to 6 cm wide and 1.5 to 2 cm thick pine cover strips that were held in place with small flathead nails, not staggered but in a single line and systematically driven into the lower board. This method, used in shipyards, is designed to prevent the timber from splitting due to any movement in the hull. Partially overlapping the chine piece and the first plank of the side wall is another piece of oak 46 cm high and 9 cm thick that acted as a wale.

Even though the Chalon-sur-Saône caisson was built for masonry work rather than casting concrete and was intended for use in a flowing river (hence the cutwater or bow shape), it was similar in design and construction to the Caesarea and Alexandria caissons. Its use in the western half of the Roman Empire suggests that this engineering approach involving floating caissons was not limited to the Eastern Mediterranean but was more widely used than the limited evidence suggests (Bonnamour 2000: 273–306). Most Roman bridge foundations involved woodwork of various designs and purposes (Kroes 1990), but a synthetic study is still lacking.

*Floating Caisson 4: Laurons.* The Laurons caisson is of a completely different design from the Caesarea, Alexandria, and Chalon-sur-Saône caissons, although intended for a similar use. There is no reported date for this structure. The harbour was in use between the first century BC and the seventh century AD. It is likely that this caisson was built in the Late Roman era since it was filled with rubble rather than consolidated concrete. The elaborate detailing of the joints is more in keeping with terrestrial joinery than nautical architecture. The caisson is 22.9 m long × 2.2 m wide, with a floor of wide planks that are nailed to the underside of two long edge or chine beams and two longitudinal stringers (Fig. 8.55). The floor was constructed upside down, and once all the planks had been nailed in place it was flipped over. A chine beam was then fitted to the two short ends and lapped over the long edge or chine beams and the two longitudinal stringers. Corner posts are notched and let into the junction of the end and side edge or chine beams. On each side of the caisson are fourteen rectangular uprights that are dovetailed into the chine beams. Markings, consisting of numbers and triangles, on the frames and on each post were most probably used by the construction team in assembling the caisson, matching the proper upright with the correct mortised joint in the chine beam. In between the uprights on the upper surface of the edge or chine beams, long rebated slots take the shaped ends of vertical side wall planks. Ximenes and Moerman (1988: 229–52) proposed a reconstruction of the caisson with a frame securing the tops of the uprights and side wall planking. They suggest that the caisson was built on the shore and then pulled into position and held in place with piles driven in around it before being filled with rubble and mortar. It is not clear whether this is a distinctly regional variation, or an evolution or simplification of the floating forms.

### *Examples of Double-Walled Floating Forms.*

*Double-Walled Floating Forms 1: Area G at Sebastos (Caesarea).* At Area G on the east side of the entrance to the harbour of Caesarea Maritima are the remains of two unique concrete-filled caissons 11.5 m wide (east to west) and 15 m long (Figs. 8.58–61). The formwork comprised massive pine (*pinus*) and fir (*abies*) sleeper beams approximately 29 cm square that ran along the base of each side of the caisson and interlocked at the corners with simple lap joints. A series of pine and possibly fir uprights, 12 to 15 cm by 23 cm in section, were mortised into the horizontal sleeper beams at 1.6 m intervals; horizontal pine planks, 8 cm thick and 14 cm wide, were fixed to the uprights on both sides, creating a double wall. The lowest of the planks on the inner face of the formwork was inset slightly into the upper surface of the large sleeper beam and fastened with mortise and tenon joints. The tenons were of oak (*quercus*) and poplar (*populus*).

A regular series of channels and holes approximately 18 cm square can be seen in the upper section of the block. The channels were made by horizontal wooden tie beams that crossed the formwork in an east-west direction, spaced approximately 1.6 m apart. The holes were left by uprights spaced at 1.3 m centres, intended to support and reinforce the form until the concrete had set.

There was no floor to the caisson, and it was floated to its final destination at the end of the northern breakwater buoyed by the enclosing double wall that acted as a flotation ring. Once on site, the void inbetween the two planked enclosing walls was filled with hydraulic mortar (without coarse aggregate) and the formwork gradually settled onto a prepared bed of sand on the seabed. It has been suggested that the upper sections of the timber formwork were removed in antiquity.

The second caisson, less well known but constructed in a similar manner, was built with sleeper beams 15 cm square. The west face of this block has several holes left by horizontal tie beams 13 cm and 18 cm square at 1.3 and 1.5 m above the base of the caisson. No beam holes were found on its southern face and it might only have had tie beams on an east-west orientation (Oleson 1989a: 127–30).

Could the extended ends of the tie beams have served a purpose? If stout piles had been driven into the ocean floor to mark the spot where the floating caisson was to be located, the form could have been floated into a position where the L-shaped tie beam extensions locked against the piles. When the double walls were filled and the forms sank, the form would have anchored against the piles as it descended, and its precise positioning on the ocean floor would have been easier to ensure.

### *Redundant Ship Hulls Used as Formwork.*

Similar in principle to the floating box caissons is the re-use of large ships that had become redundant. The most famous example of formwork that falls within this category was the enormous ship used by Caligula to transport an obelisk from Heliopolis in Egypt in AD 37, and described by Pliny and Suetonius (pp. 26–28, 32, Passages 15, 17, 24). After delivery – the obelisk still survives, moved to the piazza in front of the Vatican by Domenico Fontana in 1586 – the ship was laid up in Puteoli, perhaps because she was too unwieldy for practical use. Eventually she was towed to Ostia, on the order of Claudius, already loaded with *pozzolana* ballast from Puteoli or its environs. The literary sources omit the construction details, but the ballast was probably unloaded at the harbour construction site to allow mixing with lime in the appropriate proportions; then the mortar would have been reloaded in the hull along with tuff or heavier weight aggregate, forming a maritime concrete. When the ship was only slightly buoyant, it probably was towed a few hundred metres to the gap between the two breakwaters and sunk with the addition of more concrete, to serve as the foundation of a large lighthouse. Testaguzza (1970: 105–23) suggested that a section of the concrete breakwater to the northwest of the Museo delle Navi Romani was cast within this hulk, but the marks left by formwork suggest that this particular section of the harbour was cast within a conventional Category 1 form, and the ROMACONS coring did not encounter any heavy wood appropriate to a ship's hull (Fig. 4.2). The entrance channel itself with its lighthouse was recently located by archaeological survey beyond the Viale di Coccia di Morto at a depth of between 3 and 15.5 m, but the structure and any evidence for formwork have not yet been confirmed by archaeological investigations (Goiran *et al*. 2011: 42).

***8.3.2. Prefabricated elements used to construct formwork.*** In instances where an isolated section of shuttering was required to close off an area that was to be filled with concrete it was obviously easier to use a panel that could be inserted and wedged in place rather than attempt to build it up *in situ* under water. Prefabricated panels were built of timber planks, edge-fixed with mortise and tenon joints that were held in place with treenails. This type of formwork was used in sheltered situations where the panel could be easily secured while the concrete set.

### *Examples of prefabricated formwork elements.*

At Carthage, on the circular harbour causeway that was widened by the Romans, Yorke and Davidson (1985) found the remains of formwork that was set against the earlier Punic pier. Whether this was part of a prefabricated box or simply a panel has not been clearly established. The horizontal fir planks were edge-fixed with a half lap joint and secured with loose tenons set into mortises held in place with treenails (Yorke and Davidson 1985: 157–64). A horizontal beam was fixed to the inner face of the shuttering panel 0.52 m below the top of the pier. The corner uprights were missing, and there is no evidence of the side shuttering formwork other than horizontal beams that would have secured it in a similar manner to *catenae* in a Category 1 form.

In the Roman fish-pond at Ventotene, Zarattini found the remains of a prefabricated panel that had been used to seal off one of the channels with concrete. The prefabricated shuttering consists of strong vertical planks held together with mortise and tenon joints and horizontal beams. The assembly was wedged in place against vertical posts that were set into notches in the bed of the tank. Vertical planks on the inner face of the shuttering stiffened the structure where the wedges were inserted (Zarattini *et al*. 2010: 6).

Prefabricated timber structures were used as the structural elements of embankments, quays and bridge footings in the Roman port on the Thames at London during the later first century AD. Although not designed as formwork, they share some of the same designs and were built in and under the water and along the shoreline with large prefabricated timber sections that interlocked (Milne 1982: 7–23; Milne 1985: 55–67).

The majority of marine concrete structures were built using what are described as Category 1 forms. There is considerable evidence to support this procedure, and it shows that the Romans were surprisingly consistent in their designs. It is not known why Vitruvius did not include Category 3 formwork in his treatise on architecture, despite his obvious interest in the topic and his thorough knowledge of pozzolanic concrete. It is also unclear whether his reference to pre-cast blocks was actually meant to refer to prefabricated caissons.

The Category 1 inundated enclosures were suitable for sheltered areas or situations where moles were being extended section by section. In more exposed locations there would have been a real need for some type of prefabricated structure to cope with the difficulties of working in rough seas. It is unclear why, where, and when the Category 3, single-mission barge caissons found at Caesarea, Alexandria, Laurons, and Chalon-sur-Saône first came into use. Goddio (Goddio *et al*. 1998: 37) originally dated the caisson found in Alexandria to 250 BC, but he now rejects that early date. Analysis by ROMACONS of the pozzolanic concrete fill, however, identifies it as made with pumiceous volcanic pozzolan possibly imported from Italy, which would make a much later date necessary. Furthermore, a fragment of wood embedded in the ROMACONS core ALE.2007.02 provided a $^{14}$C date of 1990 ± 54 years, equivalent to AD 31 ± 54 years. Since the composition of the *De Architectura* falls at the lower end of this range, it may be that these technical methods were not yet well-established or widely enough known for Vitruvius to mention them.

The use of Category 2 or possibly even Category 3 forms to enable concrete *pilae* or harbour moles to be constructed with *opus reticulatum* facings is not supported by irrefutable evidence, but it is difficult to imagine how this could have been achieved below water in any other way than within a dry enclosure, either behind a cofferdam or within a box caisson. As noted above, isolated *pilae* could have been built with *opus reticulatum* facing above water on temporary platforms according to the procedure described by Vitruvius and possibly alluded to by Horace and Virgil (pp. 23–24). But the hydration methods of these concrete structures remain unclear. The cementitious fabrics of the Baianus Sinus *pila* faced with *opus reticulatum* at Secca Fumosa, for example, are quite similar to those of structures that were known to have hydrated in sea-water, such as at Santa Liberata and Caesarea (pp. 167–75).

## 8.4. Conclusions

The practicalities of building even temporary structures in the sea as moulds for casting concrete led Roman engineers to develop standard techniques, but these were influenced by the conditions of a particular site, the availability of skilled experienced labour, and regional traditions. Category 1 forms, which were not watertight and were fabricated *in situ*, were by far the most common type. They were used in the shallow, sheltered sites where the majority of concrete marine structures were built, such as fish-ponds, quays, jetties, and elements of harbour moles. There is only circumstantial evidence for the use of Category 2 forms in a maritime setting. This type of form, designed to be watertight and pumped dry, was built *in situ*, possibly for use most often in rivers and lakes. The Category 3 prefabricated forms are the most intriguing. The evidence for this type is elusive, and only a few examples can be conclusively identified, yet this technique must have been more widespread than can currently be documented. There were many sites where it was not feasible to construct Category 1 forms, for example, in locations that were exposed to the weather or those in deeper water, such as the outer sections of the harbour moles of Sebastos, Portus, and Astura. Category 1 forms were used for continuous cast concrete placed, for example, as a wall enclosing a fish-pond, or as a jetty or a mooring pier, whereas discontinuous castings such as *pilae* could be built within Category 1 or 3, or even possibly in Category 2 forms if an exterior stone facing was required.

Roman maritime concrete structures did not resemble those built of modern cast concrete. It seems likely that Roman concrete was rarely if ever fair faced (i.e. had an exposed, self-finished exterior surface). Most examples would have resembled a timber structure sitting in the sea supporting a masonry superstructure, since the extent of timber shuttering that survives suggests that it was kept as a semi-permanent cladding. The upper sections of timber would have gradually eroded away over time.

Regional differences are more difficult to identify. By far the majority of concrete structures were built along the western Italian coast, and it is apparent that specialist Roman concrete engineers travelled the length of the Mediterranean bringing with them Italian methodologies. Greek architectural traditions around the eastern Mediterranean may have contributed to a local style of stone-clad concrete harbour moles such as those found at Pompeiopolis and Kyme.

The evidence for a specific type of formwork is often difficult to establish, particularly where the concrete has been gradually eroded over time and is covered with marine organisms that burrow into the exterior of the structure, obliterating any surface feature and even covering over beam and post holes. There are numerous questions outstanding, including how *opus reticulatum* cladding was built underwater, and where physical evidence can be found for Category 2 and 3 type forms. Clearly there is still enormous scope to develop this area of study and to devise techniques for establishing how these ephemeral formwork structures were designed and built.

# Chapter 9

# Roman Maritime Concrete Technology in its Mediterranean Context

*R. L. Hohlfelder and J. P. Oleson*

## 9.1. Trade in *pozzolana*, pumiceous ash pozzolan, and *caementa* (R. L. Hohlfelder)

The first massive maritime transport of bulk items in the Roman world, primarily amphorae with wine from Italy sent to Gaul in exchange for slaves, seems to have begun *ca.* 100 BC and then tapered off around the time of Caesar's final conquest of this region in the late 50s BC (Wilson 2011a: 39). With the victory of Augustus in the last round of civil wars in 30 BC, construction materials, largely marble and decorative stone, and grain became the largest maritime cargoes to move along the Mediterranean trade corridors to meet the demands of the Roman capital, its civilian population, and the military. This direct or commissioned trade stood at the top of maritime commercial trade ladder (Wilson 2011b: 217), requiring the largest merchant ships, of *ca.* 340 tons and possibly even larger, as well as harbours large enough to accommodate them. Although not controlled by the Imperial government, since there was no Imperial merchant marine, trade at this level was closely monitored because it addressed various imperatives necessary for the Empire's survival and stability. Coastal trading, which had always formed the bulk of ancient maritime commerce, was not challenged by this long haul variety, and it continued through the Late Empire. Smaller ships, less than 100 tons in cargo capacity and normally in the 20–50 ton range (Arnaud 2011: 73), moved goods from smaller maritime communities to large emporia such as Rome, Antioch, Carthage, Ephesus, Alexandria, and to second-tier ports such as Patara, Myra (Andriake), Paphos, Massilia, and Caesarea. The ships returned from these international trading nodes with other cargoes for secondary redistribution to the same smaller ports where they had laden their ships initially, or to other pre-arranged local markets. Their routes and destinations were usually fixed in advance. Often, various merchants might place mixed cargoes aboard the same ship after ensuring that the loading of their merchandise had been done appropriately to accommodate the ship's scheduled stops (Arnaud 2011: 69). The sailing routes were altered primarily by weather and by the market conditions for the products they transported. Opportunistic sales or trades along these prescribed routes were less likely but still possible for enterprising sea captains or sea-going merchants. This type of spontaneous trade was more likely for the *caboteurs*, the grassroots entrepreneurs of the sea who sailed from one maritime community to another looking for opportunities to buy local cargoes for resale elsewhere and to sell products previously purchased en route.

This overview is a very general and simplified presentation of how trade goods moved about the Mediterranean in the Augustan Age (and later). It masks the complexity of the reality of trading activities and obfuscates many details concerning ancient trade. Some of these are the following: how often were secondary or even tertiary cargoes "piggy-backed" on primary cargoes, and who owned these cargoes? Was it common to have multiple owners of a single cargo? What sort of financial and administrative substructure sustained maritime trade? How large a role did the bankers of Puteoli have in structuring maritime trade throughout the Roman Empire, when the Gulf of Naples area was the centre of international maritime commerce? The Imperial government created the imperatives that sustained markets for various commodities such as grain and marble, but what controls over the actual distribution systems did it exercise and how was this accomplished? How much influence did individual shippers have on setting market price by withholding commodities until their shortage guaranteed a better price? Finally, and directly relating to the interests of ROMACONS and the ancient harbour concretes, how were *pozzolana*, other pumiceous ash pozzolans and rock aggregates for maritime construction transported throughout the Roman world, and what was the nature of this trade?

We know that the marine concretes of the harbours at Egnatia, Pompeiopolis, Caesarea, and Alexandria contain large volumes of pumiceous volcanic rock, but that no such deposits occur locally at any of these sites. This indicates that a very large transport and trade in this material must have existed for at least 100 years, over the course of the construction of the more massive harbour installations. A somewhat similar situation exists for the harbours along the central Italian coast. The compositions of the pyroclastic rocks of the central Italian volcanic districts – Volsini, Monti Sabatini, and Alban Hills (Fig. 7.7), for example – do not closely resemble the pumice and tuff components of the harbour concretes (pp. 147–59). Only at Chersonesos and, of course, the Bay of Pozzuoli harbour structures, do pumiceous volcanic ash deposits crop out nearby. For the harbours of the central Italian peninsula – Santa Liberata, Portus Cosanus, Portus, and Anzio – mineralogical and geochemical studies indicate that the volcanic ash shares many characteristics with the pumiceous deposits of the Campi Flegrei volcanic district (Figs. 7.10–13). But where did the enormous amounts of pumiceous volcanic ash originate that were needed for the harbour concretes far distant from the Gulf of Naples? How did a shipping trade develop around this very important commodity during the early first century BC through early first century AD, when harbour infrastructure around the Mediterranean was being intensively developed? Although mineralogical and chemical analyses of the pumiceous ash pozzolan of the Eastern Mediterranean harbours suggest that an origin from the Gulf of Naples is possible (Figs. 7.10–13), further analytical investigations are needed to confirm this origin fully. None of the ROMACONS samples so far analysed seem to show characteristics corresponding to volcanic origins from the Aeolian or Aegean Islands, so a hypothesis suggesting export from the Gulf of Naples seems reasonable based on the present evidence. There are few extant literary sources to help answer these questions, since trade and transport of mundane commodities such as concrete aggregates were not the subject of polite literature. Vitruvius, Strabo, Seneca, and Pliny, however, all praise the advantageous characteristics of *pulvis* originating in the Campi Flegrei and the larger Gulf of Naples area (Passages 7, 9, 12, 14, 16, pp. 17–23, 26–27), and Pliny mentions the importation of this material for construction of the lighthouse island at Portus (Passage 15, pp. 22–27).

The growing body of shipwreck excavation has also so far provided only meagre evidence that this important construction material ever left the Gulf of Naples region in bulk. Although the pumiceous volcanic ash occasionally noted at Roman shipwreck sites is usually identified as *pozzolana*, the techniques of analysis are seldom noted, and if they are, these are not comprehensive mineralogical and chemical studies. For example, one of the many Roman shipwrecks found at Pisa was reported as having carried "*pozzolana*" of Campanian origin stored in amphorae (Giachi and Pallecchi 2000: 350), but the material has recently been re-identified as possibly originating near Vulsini/Volsini (Marra and D'Ambrosio 2013a). Pumiceous volcanic pozzolan (interpreted as *pozzolana* from Puteoli) was used as both ballast and stabilizing element for the 6,000–7,000 amphorae found on the Madrague de Giens shipwreck of *c.* 75–60 BC (Liou and Pomey 1985: 562–63; Wilson 2011a: 38). More recently, the Chrétienne M shipwreck site near Marseilles is reported to include a 5 m × 6 m area covered with a thick layer of "le ciment à de la pouzzolane" (Joncheray and Joncheray 2002: 85). The shipwrecked material was probably deposited in the first century BC or AD. If other known shipwrecks contained pumiceous ash pozzolans, or tuff aggregate, any trace of their existence as cargo or ballast was either overlooked or has disappeared over the centuries. The volcanic ash could easily be scoured away by currents or storms or become so mixed with bottom sand and mud over the centuries that its presence would not be obvious. In addition, rubble rock of any kind intended for *caementa* might easily have been mistaken for ballast. Lacking conclusive *comparanda*, the volcanic ash of the Madrague shipwreck excavated between 1972 and 1982, might have been viewed only as worthless ballast, but given the ongoing recognition of pumiceous ash pozzolan in the harbour concretes (Jackson *et al.* 2012), it can now be seen as a nearly invisible trade item. Even Parker's enormous corpus of cargoes (1992a: 85) does not list *pozzolana* as a bulk cargo. Dubois (1902: 447–48, n. 1) was an early and lone voice in asserting that "*pouzzolane*" was exported from Puteoli "dans toute les parties du monde antique," citing a heap of the material found on the Aegean island of Delos. As is usually the case, he does not specify the method of identification. Excoffon and Dubar (2011) identify a pumiceous ash pozzolan used in marine concrete at the Roman harbours of Marseilles and Fréjus as "pouzzolane" from the Gulf of Naples region, but the methods of analysis are not decisive. The CTG Italcementi laboratory qualitatively identified the region around Vesuvius as the source of pumiceous ash pozzolan found in mortar from the fish-pond walls at Quarteira in Portugal (pp. 121–22). Although these identifications need further analytical verification, in combination with the record of ancient literary sources and the archaeological results of the ROMACONS project, the hypothesis of an extensive long-distance trade in volcanic ash pozzolans from the Gulf of Naples region during the first three centuries of the Roman Empire seems reasonable. Other pumiceous ash sources could have also been present in ancient maritime trade, however, and future analytical investigations may be able to identify the volcanic origins of these materials.

Recently, Lancaster (2011; Lancaster *et al.* 2010, 2011; *cf.* Davis 1981), through geological source analysis, has uncovered a related, but less extensive trade in lightweight volcanic aggregates for concrete construction during the Empire. In Cilicia in Southern Turkey the material was moved from regional quarries, apparently by land. In Italy *scoriae* and pumice from Somma-Vesuvius and pumice from the Campi Flegrei were transported to Rome, mainly by sea (Lancaster *et al.* 2011; Marra *et al.* 2013b). *Scoriae* were also exported by sea from Sardinia to Carthage, and pumice aggregate from the island of Pantelleria to Leptiminus and other sites on the North African coast (Lancaster *et al.* 2010). On both these trade routes the construction stone was accompanied by millstones from the same regions. Siddall (2000: 342–43) has proposed that potentially pozzolanic sand from the Aegean island of Melos was intentionally imported to the Roman port of Kenchreai, along with local volcanic rock rubble, to produce hydraulic concrete for terrestrial structures along the shoreline. There is no other evidence for this trade, and it would be useful to determine the precise material characteristics of the resulting concrete. There is at present no analytical evidence for a substantial trade prior to the modern period in Santorini ash erupted from the Thera volcano. Roman engineers seem not to have made use of Santorini ash intentionally as a pozzolan in the maritime concretes drilled by ROMACONS, but they did make intentional use of local volcanic deposits as pozzolans in mortars for architectural concretes around Pergamon (Özkaya and Böke 2009; Lancaster 2010), Sagalassos (Viaene *et al.* 1997; Degryse *et al.* 2002), and Cologne (Lamprecht 1996: 61, 75, 87).

In contrast, the compositions of the pumiceous volcanic ash pozzolan in the mortars of all the cores taken by ROMACONS throughout the Mediterranean are somewhat similar, in terms of the phenocryst mineral assemblages and trace element compositions of bulk pumice specimens (pp. 153–59). This similarity suggests that a widespread long distance trade could possibly have developed for this specialized construction material. The initial discovery of what was presumed to be Neapolitan *pozzolana* in the hydraulic concrete of Caesarea by Oleson and Branton (1992: 60) removed its cloak of anonymity as a raw building material transported in bulk over long distances. The following hypothesis has gained wide acceptance: the logistics of transporting *ca*. 20,000 tons of pumiceous volcanic ash 2,000 km from the Gulf of Naples to Caesarea could possibly have been accomplished if the large *annona* grain freighters sailed in ballast from Puteoli or a nearby port to Caesarea before heading on to Alexandria (Gianfrotta 1996: 74; 2007a: 17; 2009; Hohlfelder *et al.* 2007: 414; new information has shown that the estimated weight of pozzolana at 52,000 tons in this last paper is incorrect; Wilson *et al.* 2012: 367–70). This kind of direct, commissioned trade between two major harbours, with pumiceous ash pozzolan as the primary cargo but with the possible addition of piggyback cargo such as Campanian wine or ceramic bricks and tiles (Leitch 2013: 288–89), is easy to understand given the likely involvement of the Imperial house. The provision of this material could have been either Roman aid to a client king (Herod) or a regal purchase of the commodity. Marzano (2011: 185) notes the similar transport of Campanian wine to Egypt as ballast on otherwise empty freighters leaving from the Gulf of Naples to pick up grain. This arrangement could have been ideal for a merchant who owned or had leased an empty ship in Puteoli, for example, to bring grain back to Rome from Alexandria, since it provided profit for both legs of the round trip. Commercially valuable ballast could also accompany a cargo, for example the 120,000 *modii* of lentils that served as ballast on Caligula's enormous ship transporting an obelisk to Rome (above, p. 27, Passage 15).

A similar arrangement, but not involving a client king or an Imperial initiative such as grain shipment to Rome, may have occurred in Crete. Ships from Puteoli, possibly carrying *pozzolana* ballast, arrived in Crete to pick up amphorae of Cretan wine for delivery to Capua, a city that owned much of the territory around Knossos and was most probably the agency behind this trade pattern (Gianfrotta 2011a: 191–92). The ships making these runs probably were not as large as those involved in the transport of volcanic ash pozzolans to Caesarea, but they could easily have carried pumiceous ash as ballast and primary cargo along with other piggybacked items for sale. The identity of the merchants involved in this trade, and their specific relationship to Capua is unknown. Were they individual ship-owners, merchants who had leased a ship or ships for this trade, or *ad hoc* companies created for a single round trip or for more than one? However these questions might be answered, it does not alter that fact that point-to-point, commissioned transport most likely occurred frequently, although not on the same Imperial or regal scale as the transport of pumiceous volcanic ash to Caesarea.

How else might the pumiceous ash pozzolan required for maritime construction have been traded around the Mediterranean if not by point-to-point direct, commissioned trade? As knowledge of the efficacy of the marine concrete formulation became more widely known, its desirability as a building material would also have increased. Enterprising ship-owners and captains might quickly have seen the financial possibilities of opportunistic trading of saleable ballast no matter how large or small their merchant ships were.

In many respects pumiceous volcanic materials could have been an ideal secondary commodity for this type of trading. For ships from or berthing in the Gulf of Naples, the pumiceous ash and pyroclastic rock was readily available as malleable ballast that could stabilize amphorae or other types of fragile products to minimize shifting and breakage, and it could also be used to balance stowage of various types of cargo. The ash did not require any special handling, consideration, or modification of the hull or storage areas for the vessel in which it was carried. One factor that could have been considered, however, was a weight increase of about one-third if the porous pyroclastic rocks became saturated with water while in transit (p. 178). For a sea captain grappling with heavy seas the consequences could have been dire, even if his pumps were working to the maximum effect. Awareness of the potential hazard of this otherwise benign and potentially profitable ballast may have spread as rapidly as the knowledge of its desirable qualities as a building material, as described by both Vitruvius and Pliny. Before leaving port, shipmasters probably considered the possibility of increased weight when loading ballast and limited the quantity of pumiceous ash and tuff accordingly. Like their modern counterparts, ancient shipmasters had to be aware of the effect of cargoes on trim and draft in all conditions to be encountered (*e.g.* Aristotle, *Mete.* 2.3, 359a; Demosthenes, 34 *Phorm.* 10).

In fact, merchant captains may have been one factor behind the apparently rapid spread of the technology of using pumiceous pozzolan in marine concretes. It would have been easy for them to trumpet the desirability of pumiceous volcanic pozzolan to prospective customers at various ports of call. There was a long tradition of expertise with mortared construction in the Mediterranean basin, and substitution of volcanic ash for sedimentary sands would have been of real interest to those willing to experiment with the Roman formulation of maritime concrete. As awareness of the advantageous qualities of the pozzolanic concrete became more commonplace, the amount of practical and anecdotal information that sea captains could share with prospective new customers also probably increased. The spread of sub-literary technical manuals probably also played a role (see below), since there was significant local initiative for innovation in harbour design and construction (Blackmann 1988).

It seems possible that many ships sailing from the Gulf of Naples to near or distant points in the later Republic through the High Empire could have carried pyroclastic materials as ballast or as part of their ballast. Captains would have lost nothing by carrying volcanic ash, either in bulk in their hulls or in sacks, instead of beach sand. If lucky or sufficiently enterprising, they had potential for additional profit en route. If not successful on one trip, they could look to the next leg of their voyage for an opportunity to sell their ancillary product. Another possibility could have been the direct or point-to-point transport of large amounts of pumiceous ash from the Gulf of Naples to international emporia for short-term storage and subsequent redistribution to construction projects in maritime zones when the need and opportunity arose. This pattern of redistribution has been suggested for cargoes of marble (Russell 2011: 150). Such a speculative venture might appeal to a ship's owner or lessor if his vessel was sailing to pick up a commodity such as grain or marble with an essentially empty ship on its outbound leg. Note that there is, as yet, no rigorous analytical documentation for the transport of Latian *harenae fossiciae* beyond the immediate territory of Rome (Jackson *et al.* 2010).

In the absence of direct evidence, we can only speculate about how pumiceous ash pozzolans, and volcanic tuff aggregates were transported or traded throughout the Mediterranean. The archaeological evidence at Caesarea, Chersonesos, Pompeiopolis, Alexandria and the north African coast, where ROMACONS was unable to obtain permission to collect cores but where structures built of Roman marine concrete abound (Wilson 2011b: 256), clearly indicates an important and widespread trade in pyroclastic rock. Pumiceous tuff from the Gulf of Naples has been identified in the harbour concretes of the central Italian coast through mineralogical and chemical analyses (pp. 147–53), but this material appears to have been transported to a lesser extent beyond Italy. Small fragments of pumiceous yellowish-gray tuff occur in the concretes of the eastern Mediterranean harbour concretes drilled by ROMACONS (Figs. 7.8, A3.56–58, 62–64), and – based on visual examination alone – were possibly used as the common aggregate in marine concrete at Carthage. Builders at locations far distant from the Italian peninsula must have quickly learned that local carbonate rocks could be substituted for tuff without noticeable differences in the final product. At Egnazia, for example, constructed in first century BC, the principal *caementa* of the marine concrete are local limestone (pp. 148–53). The *caementa* formed a large proportion of the concrete mix, about 45 to 60 volume % (Table 7.1), so use of local limestones must have substantially minimized costs and reduced building time.

The thesis offered here is that pumiceous ash pozzolan, possibly from the Gulf of Naples area, could have been commonly used as ballast on ships, in addition to direct, commissioned point-to-point transport. As a commodity on many transport ships at sea at any one time, it could have been readily available as building material at many sites through the Mediterranean area. Short-term storage of the ash at major emporia or at lesser nodes of commerce would have made it available for redistribution by coastal traders or *caboteurs* to smaller maritime communities. For ash derived from the Gulf of Naples, a builder in a far distant port could certainly place a direct order for this commodity with a captain heading to Puteoli, or to a closer emporium where pyroclastic materials had been stored for regional distribution.

The paradigm of Imperial Roman maritime trading that is proposed here would have had numerous elements linked together in ways not yet fully understood. This includes long-distance, direct, or commissioned trade with secondary cargoes frequently piggy-backing on the major one; middle-distance coastal trading between designated markets; short-haul trading among small maritime communities as either the final leg of redistribution of cargoes previously imported into emporia, or the first leg of moving local products into these nodes of international commerce; and, finally, tramping (or less correctly, "cabotage"; *cf.* Arnaud 2011: 62) conducted by merchant captains who moved freely along the littoral looking for opportunistic trades or sales. Behind this proposed model was a complex, yet flexible, infrastructure to support trade that included a private financial system of bankers, bottomry and other types of maritime loans, scrupulous entrepreneurs and those without scruples, sea captains, *ad hoc* companies, the shadowy involvement of local and international aristocrats, and an enabling Imperial bureaucracy that selectively intervened in its operation, but never completely controlled it. It is possible that the large scale transport of pumiceous ash pozzolans and, occasionally, pumiceous tuff and other *caementa,* was firmly meshed into this paradigm, especially for the intensive 100-year period during which the Mediterranean harbour infrastructure was being created.

## 9.2. Mechanisms for the spread of innovation in Roman marine construction (J. P. Oleson)

The formulation by Roman builders of a pozzolanic mortar that could be hydrated with sea-water and remain intact and coherent for very long periods of time in the aggressive sea-water environment was an enormous breakthrough in the technology of maritime construction. It was the critical first step in the development of an extensive harbour infrastructure that made possible the economic and military expansion of Imperial Rome. Employment of such a mortar also greatly simplified the process of construction in the sea for structures of all sizes, and in situations that otherwise would have required the use of double-walled caissons that were drained of water before construction began. Observations of the concrete fabrics of Late Republican maritime structures, and Vitruvius' remarks concerning these topics (pp. 17–19, 21–23, Passages 7, 9) indicate that by the first century BC it had become evident to Roman builders that concrete produced with mortar incorporating pumiceous volcanic ash provided the greatest durability in the challenging marine environment. During the second century BC, the standardization of facings on concrete walls had speeded up and improved monumental construction in Rome and allowed reductions in the use of formwork (Wilson 2006). During the first century BC, new techniques for integrating dimension stone and concrete masonry were developed and, at the initiation of the Augustan era, innovations in the technology of architectural concretes in Rome became standardized in terms of their materials and mixing procedures (Jackson *et al.* 2010, 2011). Given the challenges of marine construction, the materials and formwork necessary for pozzolanic concretes must have been subject to special scrutiny, which perhaps explains why Vitruvius's handbook provides numerous details about the production and placement of marine concrete, but fewer about the methods for placing terrestrial concrete. The tradition of formwork design for marine construction revealed by the ROMACONS surveys around the Mediterranean is rich and varied (see Chapter 8), in contrast to the somewhat standardized formulae for marine concrete itself. Formwork for placing marine concrete naturally has to respond to local conditions and resources.

Unfortunately, there is no explicit ancient testimony concerning the channels by which these important engineering innovations spread from Central Italy to the rest of the Roman world. Vitruvius states that one of his motivations in writing the *De architectura* was the fact that previous Roman architects and engineers had not left behind organized, publicly available presentations of their techniques and accomplishments (*De arch.* 7, *praef.* 18; above, p. 14). With careful reading, the *De architectura* makes it clear that Vitruvius had a very nuanced understanding and informed opinions based on empirical experience regarding the geological materials that went into both terrestrial and submarine mortars (Jackson and Kosso 2013). Since one of his objectives in writing the handbook seems to have been the provision of a resource to the owners of villas and farms that would theoretically allow them to supervise their own construction projects (*De arch.* 6, *praef.* 6–7), Vitruvius apparently envisaged a wide circulation for his book. He writes: *sed tamen his voluminibus editis, ut spero, etiam posteris ero notus* ("But through the publication of these books I will be known, as I hope, even to posterity."). Vitruvius was correct, since the *De architectura* remained popular enough for 300 years to be epitomized by Faventinus, then to serve again a century later as an important source for portions of Palladius' handbook of agricultural management (above, p. 33). The book remained popular through the medieval and early modern periods.

***9.2.1. The role of Central Italian piscinae.*** Some of the best preserved early examples of marine concrete construction are the numerous elaborate fish-raising ponds (*piscinae*) fronting the seaside villas built by wealthy Romans along the west coast of Central Italy during the first century BC (Higginbotham 1997; Lafon 2001; Marzano 2013: 213–33, 318–24). Pliny (*HN* 9.170) attributes their invention to L. Licinius Murena early in the first century BC. Construction continued at a lesser pace in the first century AD, then died out as their prestige value faded, in favour of industrial fish farms of more practical scale and design, as seen at Cosa (McCann *et al.* 1987; Higginbotham 1997: 62–64). The early *piscinae* (also termed *vivarium, stagnum,* and *cetaria* or *cetarium*) show a uniformly high standard of design and construction. While privately owned fish-ponds are a relatively minor accomplishment in the field of Roman marine construction, they are important to our understanding of the spread of maritime concrete engineering because they appear earlier than the great Imperial harbours, and their social and technological contexts are better documented in contemporary written sources. The construction of submerged bridge footings in the Tiber began by at least 179 BC, when the censor M. Fulvius Nobilior let a contract to build *pilas pontis in Tiberi* ("bridge footings in the Tiber," Livy 40.51.4). The bridge seems to have had a timber superstructure, which was torn away by a flood in 156 BC and replaced with stone arches in 142 BC (Richardson 1992: 296). These *pilae*, and the supports for the nine later bridges of Rome, may have involved some use of mortars with pozzolanic volcanic ash, but there is at present no published information about the early history of this type of structure, which was not investigated by the ROMACONS Project (but *cf.* p. 220).

Varro (*Rust.* 3.3.2), writing in the mid-first century BC, makes an explicit connection between fish-pools and the aristocratic villa: *Similiter piscinas dico eas, quae in aqua dulci aut salsa inclusos habent pisces ad villam* ("Likewise, by *piscinae* I mean those ponds near the villa that keep fish confined in fresh or salt water."). According to Varro, inland fresh-water pools for fish were traditional around rural villas of the mid-Republic, but marine fish-pools were an extravagance that had appeared his own lifetime (*Rust.* 3.3.10): *Sic nostra aetas in quam luxuriam propagavit leporaria, hac piscinas protulit ad mare et in eas pelagios greges piscium revocavit*

("In the same way our generation has brought fish-pools to the same degree of luxury as rabbit warrens on land, built the ponds out into the sea and gathered into them schools of marine fish."). As noted above (pp. 23–24), Cicero labelled these wealthy Romans satirically as *piscinarii* (Cicero, *Att.*1.19.6, 1.20.3), "fish-pool fanciers" who had no interest in politics; Horace may also allude to their construction activities (p. 229). There were many such pools associated with villas along the coastline of modern Toscana, Lazio, and the Gulf of Naples (Higginbotham 1997; Lafon 2001), but the shoreline around Baiae had the most notorious patrons (D'Arms 1970; see the catalogue pp. 130–34, and Fig. 6.1).

Most of these pools, like that at Santa Liberata, were constructed of standardized, highly coherent marine concrete on a bedrock foundation, sometimes supplemented extensively with basins and channels cut in the bedrock. It is certainly possible that the pumiceous volcanic ash in the mortar, and the tuff *caementa*, for many of these fish-pools was sourced from the Gulf of Naples. The ash and tuff in the concrete of the *piscina* drilled at Santa Liberata, for example, have compositions that correlate well with Campi Flegrei pyroclastic deposits (pp. 147–59). Export from that region to sites along the west coast of Central Italy would have been easy for small ships carrying relatively modest amounts of volcanic ash and tuff. In his long section on fish-farming, Columella (*Rust.* 8.17.1–16, esp. 8.17.1) says the fish-pond should be built with *opus signinum*, a mix in which crushed potsherds take the place of volcanic ash pozzolan: *in litore construitur opere signino* ("or [the pool] is built on the shoreline with *opus signinum*"). This material, often referred to by its Italian term *cocciopesto*, was frequently used as a pavement, for lining cisterns, or for weatherproofing vaults, but it is an unlikely choice as a mortar for large structures (Blake 1947: 322–23; Lancaster 2005a: 58–59). Rustico (1999: 55, 62) reports the use of *cocciopesto* for lining small tanks associated with the La Saracca and Torre Valdaliga *piscinae*, but it does not appear to survive in the larger basins. Columella may have been referring only to the material used to finish portions of the fish-pool. In any case, no other surviving written source mentions the construction materials for *piscinae*.

Varro's handbook on farming, published in the mid-first century BC, provided advice concerning the location, proper design, and maintenance of fish-pools (*Rust.* 3.17.2–9). Vitruvius' *De architectura* was not published until about 30–22 BC, so the instructions it provides concerning the materials and placement of marine concrete cannot have influenced the builders of the early *piscinae*, which in any case he mentions only in passing. In the 70s AD, Columella's *De re rustica* (8.16–17) provided extensive advice concerning location, design, and stocking of fish-pools, but he says nothing about their actual construction other than the puzzling comment about *opus signinum* mortar. Lafon (1998: 579–80) attempts to date some *piscinae* approximately by reference to the use of *opus incertum* or *opus reticulatum* facing on their walls. This brings up once again the issue of how to apply this kind of facing to concrete placed in inundated forms (p. 85). Although it would not be particularly difficult to install facings on the concrete walls at these relatively shallow fish-pool sites, in fact the facings may not extend down much below ancient sea level. Published photographs seldom provide evidence for this issue, and in any case the wall surfaces are usually too eroded or encrusted to allow such details to be seen easily. Incremental forms were used to build large concrete walls at the Torre Valdaliga *piscina* (Rustico 1999: 64, fig. 13), and traces of more conventional Category 1 forms can be seen around the *piscina* at Santa Severa (Fig. 8.14; Oleson 1977: 304; Pellandra 1997: 24–25).

Roman aristocrats frequently brought their own design contributions to concrete construction on land and in the sea, and the tanks do in fact vary significantly in design and internal compartmentalization. Although based on the practical need to separate various sizes, ages, and species of fish (Varro, *Rust.* 3.17.2), the design of the internal compartments could also have a striking aesthetic effect when seen from above, from the associated villa. Varro's charming comparison (*Rust*. 3.17.4) of the compartments for varieties of fish with the compartments of an artist's paint box reflects this appeal to the eyes. The spectacular layout of Varro's country villa at Casino, inspired by that polymath's wide interests in the natural and earth sciences, contained elaborate water features and included displays of fish and birds (Varro, *Rust.* 3.5.9–17). In the 90s BC the enterprising C. Sergius Orata developed a new kind of heated bathing pool considered very luxurious, then went on to build numerous *pecularia…maria* ("personal seas") near Puteoli for raising fish and possibly oysters (Valerius Maximus 8.1.1; Pliny, *HN* 9.168; *cf.* Varro, *Rust.* 3.3.10; Columella, *Rust.* 8.16.5; D'Arms 1970: 18–20). Valerius reports that Orata overextended himself in building *cupidius publicae aquae* ("too greedily in public water") and was sued by his contractor (*publicanus*), Considius. Pliny (*HN* 9.170) states that Orata's contemporary Licinius Murena *reliquorum piscium vivaria invenit* ("…invented fish-ponds for all the other kinds of fish."). There are numerous other stories about the extravagant *piscinarii* of the first century BC, including L. Licinius Lucullus (Consul 74 BC), who cut a channel at enormous expense through a "mountain" near Naples to allow a flow of sea-water into his *piscina* (Varro, *Rust.* 3.17.9).

In all these stories it is clear that the patrons played a role in both design and execution, and that the fish-pool projects were large, expensive, and required engineering expertise. Varro regards saltwater *piscinae* as an expensive extravagance of the elite (*maritimae piscinae nobilium*, "maritime fish-pools of the elite"; *Rust.* 3.17.2–3), but about a century later (in the mid-first century AD), Columella (*Rust.* 8.16.7–17.16) indicates that they could generate a good income. The latter opinion is supported by recent research into the economic potential of this kind of Roman fish-farming (Kron 2008a: 206–13, 2008b; Marzano and Brizzi 2009) and indicates that the technology and methods of marketing had advanced over time. Columella provides explicit instructions on location and design to early

Imperial villa owners hoping to build a profitable fish-pool. It is interesting, however, that the custom of building elaborate fish-raising pools with marine concrete did not spread to the eastern Mediterranean. Instead, more utilitarian fish-pools were carved out of the low seaside shelves of limestone or calcium-cemented sandstone (Nicholaou and Flinder 1979; Flinder 1985; Francis 2010).

The relatively small social world of the Roman elite with seaside villas would have facilitated the transfer of information about successful and unsuccessful designs by word of mouth and through personal letters, since at least part of the reason for constructing a *piscina* was attaining social prestige (D'Arms 1970; Higginbotham 1997: 55–64). Nevertheless, it is unlikely that very many villa owners were enthusiastic or handy enough to design and build a *piscina* without some outside help. After some preliminary research concerning design and material among the neighbours and in polite literature, such as Varro's handbook, or later on in the handbooks of Vitruvius or Columella, most individuals probably were content to hire contractors (*conductores, redemptores, publicani*) with practical experience in the design and execution of marine structures, as Orata did and the proud villa owner mentioned by Horace (*Carm.* 3.1.33–37; pp. 23–24, Passage 10). These early work teams probably depended on individual expertise gained by apprenticeship training and practical experience. It is possible that sub-literary manuals incorporating the specialized technical information in written and graphic form moved with these engineers and contractors, or even independently from workshop to workshop by sale and purchase (see below, pp. 229–33).

Since the delivery of pumiceous volcanic pozzolans and tuff *caementa* would have been a conspicuous and expensive part of the construction process, along with the assembly of elaborate formwork for the walls and compartments (*e.g.* Rustico 1999: 64, fig. 13), the passion for villa *piscinae* could have played an important role in educating the elite of late Republican Rome in the materials and processes of construction with marine concrete. This instruction would have occurred at the very time when control of the sea had become crucial to the Roman socio-economic system, and the need for large, well protected harbours was becoming all too apparent. In fact, breakwaters were often associated with villa *piscinae*, to protect them from wave action. The famous orator Q. Hortensius Hortalus (Consul 69 BC) hired an architect at great expense to build *specus e piscinis in mare obiecta mole* (a tunnel from his fish-pools into the sea, with a breakwater set in front"; Varro, *Rust.* 3.17.9). Columella (*Rust.* 8.17.10–11) recommends the provision of *in gyrum moles* ("breakwaters all around") to protect a *piscina* from turbulence and the accumulation of sea-weed. The *pila* closest to the *piscina* of the Domitii at Santa Liberata may also have been intended to protect it from waves curving around the edge of the bay in which it was located (Figs. 4.17–18). Villas of this period without fish-pools might have private harbours with concrete breakwaters, for example, Pausilypon near Baiae (Figs. 6.53–54; Lafon 2001: 406–10). Finally, the constant emphasis in the literary sources on the crucial importance of ensuring the regular circulation of water through a fish-pool to provide the proper temperature and aeration (Varro, *Rust.* 3.17.8–9; Columella, *Rust.* 8.17.1–4) reflects on a small scale the concern of ancient harbour engineers with ensuring circulation of water in a harbour basin to prevent siltation. The problems were different, but the solutions were similar. For example, a rock-cut flushing channel survives at the base of the southern breakwater at Sebastos (Raban 2009: 123–25), and another by the North Bay at Dor (Raban and Galili 1985: 341–44). Rock-cut flushing channels (probably of the fourth-century BC) survived at Sidon until covered by modern concrete (Poidebard *et al.* 1951). These channels are similar in both appearance and function to those around both rock-cut and concrete *piscinae.* Furthermore, the harbour breakwater design consisting of concrete *pilae* connected by low concrete arches, typical of the west coast of Italy and best exemplified by the mole at Puteoli (Fig. 2.2), was developed to allow long-shore currents to purge the harbour basin of sand and silt. The causeway leading from shore to the Torre Astura *piscina* used just such an arcuated design, and the later breakwaters may have been arcuated as well (Lafon 2001: 364–68, fig. 93). The "Sarinola" fish-pool near Formia also seems to have had an arched approach bridge (Ciccone 1996: 19). The technologies involved in Late Republican fish-pool construction and those of Imperial harbour construction thus show many similarities. In fact, Seneca (*Ep.* 90.7–8) describes *piscinae* as "harbours for extravagance": *vivaria piscium…ut pelago saeviente haberet luxuria portus suos, in quibus distinctos piscium greges saginaret* ("[philosophy did not invent] fish pools…so that while the sea rages luxury might have its own harbours in which to fatten up carefully segregated schools of fish"). Tibullus (2.3.49–50) and Martial (10.30.19–21) echo this metaphor. The unifying factor in this complex of burgeoning engineering technologies was the knowledge among the Roman elite of the potential of marine concrete, codified early in the reign of Augustus in the detailed instructions in Vitruvius' handbook. These conditions set the stage for the ambitious Imperial harbour projects at Portus, Antium, Centum Cellae, elsewhere in Italy, and around the entire Mediterranean coastline – the *ora maritima* constituting Rome's enormous, interconnected *façade maritime* (Purcell 1996).

The evidence from throughout the Mediterranean world assembled in Chapter 8 reveals that Roman engineers developed a sophisticated knowledge of both stationary and floating forms for placing pozzolanic concrete in the marine environment. Unfortunately, archaeological evidence is still lacking for stationary cofferdams that could be pumped dry to allow the placement of non-hydraulic concretes below water level. The description in Vitruvius (above, pp. 22–23), however, is explicit and reasonable, and the technologies involved were well known to the Romans. This innovative combination of marine concrete with elaborate formwork designed to cope with particular problems apparently first evolved in Campania and Latium in the second or first century BC, exemplified particularly well by the fish-pools along these coastlines, so the Italian origin of these practices seen elsewhere in the Mediterranean world is clear.

***9.2.2. The role of technical handbooks in the spread of marine concrete.*** How did reliable information regarding the proper materials and techniques for marine construction move outside Central Italy to the entire Mediterranean world, from Rome and Puteoli to Alexandria and Caesarea Palaestinae on the east, and to the Atlantic coast of Portugal on the west? It was suggested above that sub-literary manuals incorporating the specialized technical information in written and graphic form moved with these engineers and contractors, or even independently from workshop to workshop by sale and purchase. The traces of manuals of this type (*commentarii*) have been discerned in the archaeological evidence for military and agricultural equipment, and for wooden pumps, and they certainly could have existed for the elements of concrete construction in the sea as well (Oleson 2004; Oleson and Jackson 2010).

Most historians of ancient technology now recognize that both the elite and the craftsmen of Greek and Roman society were aware of the benefits of technological innovation, and that what we would call "progress" took place in diverse technologies, even during the Roman Empire, which used to be characterized as a time of stagnation (Greene 2000; Wilson 2002, 2006; Cuomo 2007). It remains difficult, however, to define the intellectual and social milieu in which such development occurred, and to identify the means by which technological innovations relevant to daily life spread through Greek and Roman society. It is even more difficult to determine the identity and role of the solitary inventor, since innovations based on existing techniques or materials were much more common in antiquity, as today, than the discovery of something completely new. Roman marine concrete, for example, was not an invention, but rather an innovation based on techniques of lime calcination and hydration and the selection of specific pozzolanic aggregate mixtures that had evolved over several millennia (see pp. 2–4). Its development also relied on innovations in the techniques of concrete construction on land that Republican era builders implemented during the second and first century BC. How were developments in the production of marine concretes made known, and how did this knowledge spread throughout the Mediterranean world? Did technical literature play a part? Even the indefatigable Pliny the Elder was puzzled about how to reconstruct the process of information transfer (*HN* 14.3–4):

> No one knows the wealth of information handed down by writers of former times. The research of the men of long ago was so much more productive or their industry so much more fortunate when, a thousand years ago at the very beginnings of literacy, Hesiod began to publish his instructions to farmers and numerous others followed his line of research. For this reason our task is more difficult, since now we have to investigate not only what was found out later, but also the discoveries made by the pioneers, since a general disregard has brought about complete destruction of the record.

The identification of the specific inventor of a device or procedure is difficult, of course, since most technological advances are the result of the long accumulation of human experience and experiment. This problem is particularly pressing for ancient technological innovations, for which first-hand documentary records are rare (but *cf.* Oleson 1984: 146–47; Oleson 2000: 217–302, 289) and historical texts, where they exist, are usually ambiguous or tendentious. Pliny's dutiful citation of unconvincing lists of "inventors" in his *Natural History* is a typical example of the need felt by Greek and Roman writers to pin down the origins of particular devices and techniques (esp. 7.191–215): "It seems appropriate, before we leave the subject of human nature, to point out what has been invented, and by whom" (7.191). Pliny proceeds from divine or mythological inventors to a varied group of historically attested and unknown individuals, cultures, and towns to whom inventions are attributed. This ancient phenomenon of seeking inventors is discussed in detail by Kleingünther (1933). Occasionally, a plausible but unverifiable invention story appears, such as the depiction of the youthful accomplishments of the third-century BC Alexandrian inventor Ctesibius, preserved in Vitruvius (*De arch.* 9.8.2–4; Oleson 1984: 109–10; 2000: 290).

In any case, identification of specific individuals is far less relevant than an understanding of the historical and cultural context that spawned an invention or innovation and fostered its spread. In the Hellenistic world there is occasional mention of the royal patronage of "think-tanks" formed to study problems in military technology. The late first-century BC historian Diodorus of Sicily describes a research group set up by King Dionysius I of Syracuse (430–367 BC) that "invented" catapults. (*History* 14.41.3–4, 42.1; Kingsley 1995). Philo of Byzantium (*Belopoeika*, 50) reports a similar effort concerning catapult design in Hellenistic Alexandria, and similar positive results (Lewis 2000: 634). These sources tell us about the context of innovation in the Greek world, but not about the means by which the new information was transmitted, and to whom. Did the catapult engineers produce manuals for distribution to royal workshops? Were free or slave apprentices instructed in the new methods by expert craftsmen and sent out like animate handbooks to royal workshops? Some Hellenistic military engineering manuals, or their titles, survive, such as the *Mechanike Syntaxis* of Philo of Byzantium, the *Poliorketika* of Apollodorus of Damascus, and treatises by Biton. A striking example from this period for the intentional transfer of technical knowledge in written form is the translation into Latin of the Carthaginian Mago's Punic text on agriculture, written in the third-century BC and now lost (Columella, *Rust.* 1.1.13; Stoll 1993: 94–97). The growing self-awareness of harbour engineers in the mid-third century BC is symbolized by the composition of the *Limenopoiïka* (*Handbook of Harbour Construction*) by Philon of Byzantium, a lost book of the *Mechanike Syntaxis*, which unfortunately we know only by its title (Blackman 2008: 643).

As far as can be determined, the Hellenistic texts appear to have been intended for royal patrons and their engineers, and for gentlemen officers, so for the most part they involve theory and general specifications rather than details of materials, construction, and maintenance. The same focus on the upper-class, their interests and needs, and an implied or stated delegation of the actual manual labour to others can be seen in most of the surviving Latin technical manuals: to cite just a few examples, the agricultural "handbooks" of Cato, Varro, Columella, and Palladius, Vitruvius' treatise *de Architectura*, and Frontinus' report *De aquis urbis Romae*. A less literary, more utilitarian sort of handbook survives in Apicius' recipe book *De re coquinaria*, which lists the ingredients, pans, and preparation methods for a variety of dishes in enough detail to allow their replication today (Bode 1999). The high cost of some of the ingredients, however, indicates that many of the dishes were intended for elite households. Another unassuming utilitarian treatise, the *De munitionibus castrorum* (*On Fortifying Camps*) of Pseudo-Hyginus, dating to the early second century AD, describes in clear terms how to lay out on the ground a temporary or seasonal marching camp. This work, of which the author and original title are unknown, appears to have been written by a military engineer active in the East during Trajan's reign (Lenoir 1979: 113–33). Pliny essentially eliminates *machinalis scientia* from his *Natural History* because he felt that subject had already been sufficiently explained by Greek authors (*HN* 7.125), but few ordinary citizens in the Western provinces would have been able to read the Greek handbooks of Archimedes, Philo, or Ctesibius, or the other sources to which he was referring.

During the Roman Imperial period, how was precise technical information received, formulated, or circulated by the individuals who actually got their hands dirty doing the work, particularly in every-day occupations, as opposed to waging war or managing a country estate? We can see snippets of practical information here and there – for example, Vitruvius' instructions on how to construct a water-screw (*De arch.* 10.6.1–4), which Oleson followed without difficulty in building two full-scale examples for a BBC-TV film (Oleson 2004: 76–81), or the information he provides on the selection of materials and the recipe for mixing mortar for marine concrete (pp. 15–23, Passages 5–9). The tenth book of the *De architectura*, in which the descriptions of water-lifting devices appear, is the closest thing we have to a handbook of mechanical technology in Latin (Fleury 1996: 46). Nevertheless, in the introduction to this book Vitruvius states (*De arch.* 10.1.6) that he does not feel it necessary to discuss mechanical devices (*rationes machinationum*) that are in common use: *Non minus quae sunt innumerabili modo rationes machinationum, de quibus non necesse videtur disputare, quando sunt ad manum cotidianae, ut sunt molae, folles fabrorum, raedae, cisia, torni ceteraque, quae communes ad usum consuetudinibus habent opportunitates* ("Countless mechanical devices also exist about which it is not necessary to speak since they are at hand every day: mills, blacksmith's bellows, wagons, two-wheeled carts, lathes, and other things commonly suited to general use").

Upper-class Romans and intellectuals must have been aware of the need for the transmission of technical information to or among the working classes directly engaged in crafts, manufacturing, or the construction of fish-ponds, but we hear little about it. Was the news of innovations in every-day devices and procedures spread only by imitation or direct oral instruction, or were affordable manuals available to instruct non-elite Romans in the technical innovations that could make life easier or more pleasant, the ancient equivalent of the North American series of how-to-do-it manuals incorporating titles such as *Sewing for Dummies* or *Auto Repair for Dummies*. Books of Martial's poems were available at low cost in the Argiletum at Rome (Martial 1.2.7–8, 1.3.1, 1.117.9–12), so why not the Latin equivalent of *Plumbing for Dummies*, or *Water-mills for Dummies*? Among surviving "published" ancient texts, Apicius' recipe book comes closest to this sort of practical manual, but there is still an upper-class gloss to the ingredients and presentation, labour is not considered a factor, and machines are not involved. On the other hand, the *Periplus Maris Erythraei*, a first-century coastal guide for ship's pilots engaged in long-distance trade in the Indian Ocean (Casson 1989; Dunsch 2012), is a practical handbook closely focused on the specialized craft of navigation.

A particularly instructive comment that is unique in Latin technical literature appears in the introduction to Pliny's *Natural History*. After a conventional dedication to the emperor Titus, Pliny accords a back-handed complement to his readers when he states that he wrote *humili vulgo scripta sunt, agricolarum, opificum turbae, denique studiorum otiosis* ("for the common crowd: farmers, craftsmen – in short, those who have time for such pursuits"; *HN praef.* 1). The *Natural History* is an unwieldy, sprawling work, and most craftsmen would have found the information contained in it of little help in their day-to-day activities, but Pliny does concentrate on topics of immediate importance for human life (Healy 1999: 78). Pliny cites numerous sources of information and says he perused "about 2,000 books" to collect his "20,000 facts" from "100 authors" (*praef.* 17). Although the *Natural History* was not meant to be a handbook of crafts and industry along the lines of the eighteenth-century encyclopedia of Diderot, some of Pliny's sources may have been practical manuals concerned with every-day technical challenges such as building a concrete wall, a wagon, or a forge, laying out cog-wheels for a water-mill, or making a well pump. The titles in Pliny's lists sound very theoretical and academic, but he does not in fact cite all his sources (Healy 1999: 42–62).

Some crafts, such as ship design and construction, relied on such complex sets of information that – given the technical level of the Roman world – direct transmission of techniques and designs from master to apprentice seems the only solution. Nevertheless, the relatively high level of basic literacy in the Roman Empire, combined with the expanding population and economy of the first two centuries AD, may well have fostered the spread of some craft techniques and innovations in popular written form. Practical manuals with easily accessible technical information would have been particularly important in isolated frontier forts, or in sparsely populated areas of the European provinces, for example, in northern Gaul. Labour shortages, climate, and topography led to the development of a mechanical grain reaper in that region, the *vallus*. This device is mentioned only by Pliny (*HN* 18.296) in the mid-first century and Palladius (*Ag*. 7.2.2–4) in the late fourth, but four representations of it survive on second or third-century Roman reliefs in Luxembourg and Belgium (White 1967: 157–73). How did the knowledge of such a potentially useful innovation spread? Palladius may have had family connections with Gaul, but how did Pliny, who did not, find out about this device 300 years earlier? Inclusion of the design in some practical manual of mechanics or agriculture would explain the spread of the information beyond the range of verbal description and beyond the area where environmental and social conditions made it advantageous.

Art historians have long cited the influence of lost "cartoon books" to explain the rapid assimilation in Etruscan and Roman art of motifs that originated in Greek sculpture, painting, and mosaics (*e.g.* Oleson 1982: 97–101; Morgan 1996). The movement of artists and of plundered works of art cannot explain all the similarities. Some technological advances may have been communicated in the same way, in manuals with a straightforward text accompanied by illustrations or diagrams. These might have been similar to Hero's *Pneumatica*, but less extravagant, more practical, and focused on a single technology. Hero's chapters on water-lifting devices and the syringe could have been drawn from such a text (*Pneumatica* 1.10–11, 28, 2.18; Bliquez and Oleson 1995). On the basis of literary and epigraphic sources that mention experts in mechanical engineering, some scholars reconstruct a lost literature of practical handbooks written to advise Roman magistrates concerning various topics (Greene 1992: 103; Fleury 1996: 56; DeLaine 1996). Such *commentarii* were possibly the source of the nuggets of precise technical information that appear in the more general and literary works of Vitruvius, Caesar, Cato, Varro, and Columella. It is a reasonable hypothesis that technical texts were excerpted and transmitted by craftsmen, as well as elite administrators, and that their influence can be traced in some of the artefacts created by the individuals who read them.

The problem, however, is to find a coherent body of well-preserved archaeological remains of relatively complex mechanical devices from widely scattered sites, and to search this material for similarities that can only have resulted from the written transmission of designs. Vitruvius' list of commonplace devices and machines cited above is of little help, since the milling machinery, bellows, and wagons he mentions simply do not survive in sufficient numbers. Military equipment, which Vitruvius does not mention, is a more promising field. For example, striking similarities in the dimensions and patterns of the hob-nails on soldiers' boots from various European sites suggest the existence of standard pattern books or manufacturing instructions (Van Driel-Murray 1985: 54). The military, however, is always a special society, set somewhat apart from the civilian world and more organized. Equipment was sometimes produced in centralized workshops for distribution, and technical staff could easily be transferred from one post to another, carrying information in their heads (Bishop and Coulston 2006: 233–40). Nevertheless, written, sub-literary handbooks undoubtedly played a role, similar to the instructions by Pseudo-Hyginus on how to lay out a Roman marching camp. The *caementarius* L. Iulius Valens, serving with the fleet at Misenum in the first or second century, may well have had at his disposal a handbook on harbour construction with marine concrete of which parts originated with the *publicani* building fish-pools for the Roman elite a century earlier. As the discussion of Agrippa's construction of the Portus Iulius in the Bay of Puteoli has shown (pp. 81–82), the military, staffed by members of the elite, were involved early on with the construction of harbours.

Does physical evidence survive from non-military Roman contexts for the spread of precise technical information in written form? A close examination of the surviving Roman wood-block force-pumps suggests that this artefact can be cited as evidence for the existence of a lost, low-level technical literature in Latin. The striking similarities in design and dimensions that link many of the wood-block force-pumps used in rural wells in the Western Roman provinces can be best explained by the influence of a lost manual concerned with the techniques of domestic water supply – the Roman equivalent of *Well-Pumps for Dummies* (Oleson 2004, 2005).

While the initial spread of techniques for using marine concrete may have resulted from the circulation of rough handbooks among fish-pond builders, the great Imperial harbour projects involved high-level administrators, military engineers, and merchants involved in long-distance trade. For example, the core of the two enormous breakwaters sheltering the outer basin of the harbour *Sebastos* at Caesarea Palaestinae were built with approximately 35,000 cubic metres of hydraulic concrete. Pumiceous volcanic ash is the predominant pozzolan in all the mortars, and approximately 24,000 cubic metres weighing about 20,000 tons were required for the harbour structures. Compositional analyses of three pumice specimens from the harbour concretes, suggest an origin from the Gulf of Naples (pp. 153–59), the source recommended by Vitruvius (*De arch.* 2.6.1–6, pp. 17–18, Passage 7), a decade or so prior to the harbour installation at Caesarea. It seems likely that Herod the Great requested technical assistance from Rome for his enormous project, probably from his friend Agrippa, who had built the harbour of Portus Iulius near Puteoli (pp.

81–82). Like Agrippa, Herod named the city, the port, and some of the ancillary harbour structures after Augustus and the royal family. Agrippa most likely would have sent experienced harbour engineers out from Italy, possibly military engineers like the *caementarius* Valens (mentioned above, p. 36). These engineers, demonstrating the same practical expertise as their contemporary Vitruvius – himself a retired military engineer (*De arch.* 1, *praef.* 2) – evidently recommended the use of incorporated hydrated lime and pumiceous volcanic ash for a pozzolanic mortar, which was incorporated with local carbonate rock *caementa*. The fact that elaborate single-use barge forms identical to those documented at Caesarea appear in the construction of concrete structures in the harbour of Alexandria in the first century AD, suggests that some movement of expertise occurred between these two important ports during their construction (pp. 215–19). Military engineers are the most likely vector. Although archaeological confirmation is still lacking, it is possible to speculate that similar teams of engineers might have been dispatched at about the same time to the western Mediterranean to assist King Juba II with construction of his great harbour at Caesarea Mauretaniensis. As suggested above, merchant captains with a partial cargo of pumiceous volcanic ash may also have spread the knowledge of how this remarkable material could be used.

***9.2.3. Conclusion.*** Despite its enormous success, Roman marine concrete appears to have been a phenomenon restricted to the Mediterranean coastline. The only application so far documented of volcanic ash pozzolan possibly from the Gulf of Naples used in marine concrete outside the Mediterranean is that in the fish-pool at Quarteira (Portugal; pp. 123–24), which is nearly the same straight-line distance from the Gulf of Naples as Caesarea Palaestinae, just over 2,000 km, but outside the Straits of Gibraltar. As a relatively minor project, it was possibly the villa owner or an itinerant engineer who brought the expertise and raw material here, but this may not be an isolated structure. Will (in Begley 1996: 317–18) claims that she visually identified traces of "pozzolana" adhering to potsherds of Italian origin at Arikamedu in India. She suggests that the sherds had been used as an aggregate in concrete. Sidebotham (in Begley 1996: 110), however, also examined the material and concluded that it was a natural concretion. In the absence of any analytical proof, the unlikely suggestion that Roman engineers carried a bulky construction material all the way to India can be rejected. Will's suggestion is mentioned here only because it occasionally reappears in the literature concerning Roman concrete as a documented fact.

## 9.3. Conclusions: Society, trade, and technology in the Roman Mediterranean (J. P. Oleson)

The archaeological record and extant Roman texts suggest that the technology of maritime concrete construction penetrated deep into Roman society of the Late Republic and Empire. The maritime villas of the Roman elite may have been some of the early incubators for marine concrete, since the fish-pools that were often a part of such complexes made use of the same materials as the great Imperial harbours, along with some of the same procedures and formwork designs. Roman marine concrete was an innovation in marine construction, not a new invention. It was rapidly accepted because it solved urgent problems, while at the same time resembling in its procedures and materials the pyroclastic rock concrete that had been in use for at least a century on land. The earliest patrons may have been the Roman nobility who controlled the Republic in the first century BC. Late in the first century BC, Augustus, who was at the apex of the social pyramid of the early Empire, was well aware of the technologies and culture surrounding *piscina* construction. An anecdote preserved in Cassius Dio (54.23.1–6) puts him at a dinner given by his friend P. Vedius Pollio, a rich equestrian so addled by his enthusiasm for the eels raised in his *piscina* that he ordered a clumsy serving slave who had dropped a crystal goblet to be thrown into the pool (in Greek, δεξαμενή) as fish food. Augustus tried to dissuade his host, and, when he refused to relent, had all the expensive drinking vessels in the household brought in and smashed. The incident may have taken place at Vedius' villa of Pausilypon on the Gulf of Naples, which he bequeathed to Augustus upon his death in 15 BC (D'Arms 1970: 76–77, 229–30).

The knowledge of marine concrete, however, went farther down the social scale. Vitruvius, a former military engineer, incorporated in his handbook of architecture a remarkably full account of the materials and procedures for building in the sea with concrete, including details of formwork design. This valuable information may have been derived in part from sub-literary handbooks first developed by the contractors who built the fish-pools at the sea-side villas of the elite. In the context of the Roman military corps of engineers, such handbooks likely evolved into more formal documents that treated harbour engineering in a more comprehensive manner, including choice of location, alternatives for harbour and breakwater design, appropriate formwork for various situations, the sourcing, preparation, and stockpiling of materials, the pace and sequence of construction, and the selection of personnel. The general homogeneity of the fabric of the marine concrete drilled by ROMACONS across the central and eastern Roman Mediterranean world suggests an evolution over a relatively brief period of time in a restricted geographical area, the west coast of the central Italian peninsula. In particular, what appears to be a striking dependence throughout the Mediterranean on pumiceous volcanic ash sourced from the Gulf of Naples may be an artefact of the early history of marine concrete. As far as we know, engineers selected the traditional material despite the availability of similar pumiceous volcanic ash from other Mediterranean sources, such as Santorini, Melos, or the Lipari Islands.

This remarkable construction material and the techniques for placing it in the sea appeared at a crucial time for the Roman state. The administration of the enormous empire that had been gradually assembled since the mid-third century BC had become increasingly difficult, as had the supply of food to the city of Rome, probably the largest urban agglomeration in the ancient world (Robinson 1992: 1, 8–9). Rome lacked a proper harbour, so the crucial bulk foodstuffs were at least in part imported through Puteoli, 200 km to the south. Julius Caesar had thought of building a port at Ostia, but abandoned the idea because of the numerous difficulties involved. It was left to Claudius to start the project nearly a century later. Elsewhere, however, in the later first century BC Roman engineers set to work constructing great harbours with marine concrete to facilitate the commerce of the Imperial system: Sebastos at Caesarea Palaestinae in the East, for example, and at Caesarea Mauretaniensis in the West, but also at dozens of other locations (Chapter 6; Lehmann-Hartleben 1923; Blackman 1982, 2008). The coastline of North Africa, for example, previously difficult of access, had acquired between 30 and 40 new harbours by the later first century AD, many of them enormous in scale (Wilson 2011a: 49–51). This new type of construction required careful organization of finances, labour, and materials, all of which were areas of Roman skill. It is possible that volcanic ash from the Gulf of Naples may have been carried to Sebastos, for example, as a useful ballast in the holds of ships returning to Alexandria to load the grain crucial to feeding the enormous population of Rome. The carbonate rock *caementa* for the concrete, however, presumably was sourced locally, along with the limestone burned for lime, which may have been aged on site for several years prior to use, while the other necessary construction materials were gathered and the site prepared. A new type of single-use, floating barge form may have been developed specifically to meet the special challenges of this exposed construction site. Individual merchant trading on a smaller scale may also have carried the knowledge of *pulvis* and stocks of the material itself to minor harbour sites.

These harbours evidently fostered trade in a variety of materials, from building stone to fine textiles and were the underpinnings of the Roman economic system (Morley 2007; Wilson 2011a–b). By the early second century Juvenal (14.275–83) could claim that nearly everyone was involved in maritime trade:

> Look at our ports and the sea, crowded with great ships! The majority of the human race is now at sea. A fleet will go wherever the hope of profit calls, and it will fly across not just the Carpathian and Gaetulian seas [eastern and southern Mediterranean] but will also leave Calpe [Gibraltar] far behind and hear the setting sun hiss in the Herculean main [Atlantic Ocean]. It is well worth while, no doubt, to have seen the sea serpents and mermen of the ocean so that you can return home from there with a tightly packed wallet and boasting of your swollen purse.

Slightly later in the second century the orator Aelius Aristeides characterized Rome as the marketplace for the whole known world (*To Rome* 10–13):

> The sea is drawn like a sort of waistband across the middle of the inhabited world – the middle of your Empire, since they are one and the same. Far and wide around the sea lie vast continents, from each of which you are constantly filled with provisions. From every land and sea are brought the fruits of each season, whatever all the farms and rivers and lakes produce, by Greek or barbarian techniques. It follows that, if anyone wishes to behold all these things, he must travel the known world to gaze on them – or he must be in Rome. For whatever is grown or manufactured in each nation is inevitably found here always in abundance. Every hour, every harvest cycle sees so many merchant ships arriving here with cargoes from all parts that the city is like some communal production centre for the world. You can see so many shipments from India, if you like, or from Arabia Felix that you imagine that the trees there have been left perpetually bare for the inhabitants who, if they need anything, must journey here to Rome to beg for a share of their own produce. Clothes from Babylonia, too, and decorations from the barbarian world beyond arrive here in greater quantities and more easily than whatever cargoes had to be brought from Naxos or Kythnos to Athens. Your farmlands are Egypt, Sicily, and the cultivated parts of Africa… Everything converges here: commerce, seafaring, agriculture, metallurgy, all crafts present and past, everything that is produced and grown. Whatever one does not see in Rome is not to be counted among things that have existed or now exist.

When and why did this frantic pace of construction slow and stop? Once sufficient harbour space had been created to support the Imperial system, perhaps early in the third century, it is likely that construction was limited to improvements on existing structures. The new Imperial capital of Constantinople was an exception, and the emperor Julian is recorded to have built the *Portus Magnus* in 362, and at the end of this century Theodosius built a harbour named after himself (Mango 1985: 38–40; Müller-Wiener 1994: 6–11). Sometime between 527 and 555 the emperor Justinian built yet another harbour (Procopius, *Aed.* 1.11.18–20; above p. 35, Passage 30). The period of greatest trade activity on the sea, calculated from statistics on Roman shipwrecks carefully adjusted to remove distortions, was the second century BC through the first century AD (Wilson 2011a: 33–39), but with significant activity continuing into the third century. Most sources agree that there was a precipitous decline in sea trade in the Western Mediterranean in the sixth century, and a slower decline in the Eastern Mediterranean in the course of the seventh and eighth centuries (Wilson 2011a: 38–39). Overall, there was a general downward trend in sea trade across the Empire from the third through the seventh century (McCormick 2001: 42–63, 83–114).

It is not clear when the large-scale transport of pumiceous volcanic ash ceased to be important. Hohlfelder (1988) suggests that the formwork Procopius describes in use for Justinian may have been filled with pozzalanic concrete, but there is no firm evidence either for the concrete or the use in it of pumiceous volcanic ash. Concrete employing volcanic ash continued to be used on land at least into the fourth century, but the sources were generally local, as they had been for earlier concrete architecture on land (Chiari *et al.* 1992, 1996; Lancaster 2005a: 67). After the fourth century Byzantine engineers may have depended mainly on crushed potsherds or lime produced from argillaceous limestone to produce pozzalanic mortar that could set out of contact with the air, although some localized use of *pulvis* may have continued into the Early Byzantine era (Ousterhout 1999: 133–34). It is likely that the sophisticated Roman techniques of preparing marine concrete, along with the carefully constructed formwork in which to place it, died out along with the final cessation of major Imperial harbour construction in the later sixth century. When harbour construction commenced once again in the fourteenth or fifteenth centuries, the extraordinary Roman recipe based on the products of pyroclastic volcanism had been forgotten.

# Appendix 1

# Glossary of Technical Terms

### *M. D. Jackson and J. P. Oleson*

**aggregate**: In the Roman maritime concretes this is a decimetre-size fragment of rock, mainly volcanic tuff or limestone, that forms part of the clast-supported internal framework of the concrete. See also "*caementa*". In modern terminology "aggregate" usually indicates the relatively inert sand- or gravel-sized fraction of mortar or concrete, that mainly does not have pozzolanic properties.

**anion**: An ion or group of ions having a negative charge ($SO_4^{2-}$, $Cl^-$).

**air lime**: A pure lime that hardens slowly in air by reacting with atmospheric carbon dioxide. Air limes generally do not harden under water, as they have no innate hydraulic properties, which must be supplied by a pozzolanic additive.

**authigenic**: A mineral that crystallizes *in situ*. In a volcanic ash deposit, zeolite minerals commonly precipitate from pore fluids that are oversaturated in chemical constituents.

**beachrock**: A carbonate cemented sedimentary rock that forms along an active shoreline in warm marine waters, composed of local sand or gravel materials.

**bioclastic**: A rock formed wholly or in part by living organisms or biologic processes.

***caementa***: Singular: *caementum*. Latin term for the decimetre-sized chunks of rock incorporated with pozzolanic mortar to form ancient Roman concrete. The equivalent English term is "rubble aggregate."

**cation**: An ion or group of ions having a positive charge ($Na^+$, $Mg^+$, $Al^{3+}$, $Si^{4+}$, $K^+$, $Ca^{2+}$).

**cement**: A powder of aluminium, silica, lime, iron oxide and magnesium oxide derived from limestone and clay that is burned together in a kiln, finely pulverized, and hydrated to provide the cementing binder of modern mortars and concretes.

**chine beam**: A structural beam running along the junction between the bottom and side of a vessel, to which athwartships bottom planks are fastened.

**clastic**: A rock or sediment, such as sandstone, volcanic tuff or volcanic ash, composed of particles (clasts) broken from prexisting rocks.

***cocciopesto***: Italian term for "pounded potsherds"; ceramics of various sources, often bricks, reduced to fine gravel-sized and smaller fragments and mixed with lime to form a water-resistant mortar.

**concrete**: Cementitious construction material consisting of a mortar or cement matrix and sand- and gravel-sized aggregate that hardens to form a rock-like mass.

**day joint**: The seam left between two installations of concrete in a single block separated by a short time interval, probably most often representing the night time interval in work.

**diagenesis**: The physical, chemical, and biological alteration of sediments at relatively low pressures and temperatures over long periods of time to form rock.

**dimension stone**: Rock of a consistency firm enough to be cut into blocks for use in construction.

**exothermic**: A process or reaction that releases energy from a system, usually in the form of heat.

**furring strip**: Thin wooden planks used to sheath the exterior of a ship against wear or marine organisms.

***kurkar***: Arabic word for calcareous grainstone, or calcarenite, that occurs in large deposits formed from Pleistocene sand dunes along the shoreline of the eastern Mediterranean from Turkey to Egypt.

**lapilli**: A tephra (volcanic ash) particle that is 2 to 64 mm in diameter. An Italian term meaning "little stones". In the archaeological literature this generally indicates small, round pumice pebbles.

**limestone**: A sedimentary rock composed of carbonate minerals, mainly calcite and aragonite (calcium carbonate) and dolomite (calcium magnesium carbonate).

**lime**: A white, caustic, alkaline solid composed of calcium oxide and small amounts of silicon, magnesium, aluminium, and iron produced by the thermal decomposition of limestone (calcite) in a kiln. Quicklime, in principle, is the single compound calcium oxide (CaO). Lime forms the basis for most cements and concretes.

**mafic**: A silicate mineral or rock that is rich in magnesium and iron.

**mortar**: A cementitious material of lime and/or cement and mineral or rock particles used to bond brick or stones.

**palagonite**: Volcanic glass that is more or less altered and devitrified, becoming deep yellow or deep orange or brown in color. Palagonitized glass is commonly associated with the authigenic development of zeolite minerals.

**pebble lime**: Lime crushed to 6 mm to 6 cm particles, generally as quicklime in the modern industry.

***pila***: Plural: *pilae*. The Latin term employed by Roman authors to describe a large mass of concrete, generally square in plan, and often a cube or upright rectangular prism in shape. The term is used in this book to avoid both laborious periphrasis and the confusion that might arise from the English term "pier" in the context of maritime technology. *Pilae* were an important element in the construction of harbour installations or protection of shoreline structures.

***piscina***: Plural: *piscinae*. The Latin term employed by Roman authors to describe an artificial pond for breeding fish (*pisces*), usually a structure built out from the shoreline into the sea with marine concrete. In the eastern Mediterranean such structures were often cut into the surface of flat shoreline formations of soft bedrock.

**plaster**: A lime (or gypsum) based material used to provide a smooth surface to a wall. This term is generic and poorly defined in English.

***pozzolana**:* In Latin, *Puteolanus pulvis.* In the archaeological literature, a type of powdery, pumiceous, incoherent volcanic ash erupted, in principle, from the Campi Flegrei volcanic district around the Gulf of Pozzuoli at the northwest sector of the Bay of Naples.

**pumiceous ash pozzolan**: Pumiceous volcanic ash used with lime to produce mortar for marine concrete.

**pumiceous volcanic ash**: Loosely-consolidated pyroclastic ash and lapilli with a predominance of vitric (glassy) particles.

**pyroclastic rocks**: Clastic rocks, from the Greek (πῦρ) fire and (κλαστός) broken, are composed of glass, crystal, and rock fragments that are ejected from a volcanic vent during an explosive pyroclastic eruption. Ash particles are < 2 mm in diameter; lapilli particles are 2 to 64 mm in diameter; and a bomb is a hardened mass of molten rock (magma) > 64 mm in diameter.

**quicklime**: Calcium oxide (CaO), a highly reactive white crystalline powder that produces portlandite ($Ca(OH)_2$) when hydrated with water. Also known as "unslaked lime".

**scarfed**: Wood cut to form an overlapping joint between two planks without increasing their outside dimensions.

**slaked lime**: A slurry composed of portlandite crystals ($Ca(OH)_2$), produced by adding water to quicklime. Also known as "lime putty". Romans may have preferred aged slaked lime that matured in water away from carbon dioxide.

**tie beams**: Beams that run horizontally across a wooden form for concrete, bracing the walls against the load within; in Latin, *catenae*.

**tuff**: A deposit of volcanic ash formed of glass particles, crystals, and rock fragments that has consolidated and developed mineral cements to form rock. Tuff is the rock that forms from volcanic ash and lapilli through processes of lithification and the development of mineral cements or, in some cases, welding of volcanic glass.

**tufa**: A porous rock composed of calcium carbonate precipitated from water, generally around springs. In archaeological literature in English, the term is often incorrectly used to indicate tuff.

***tufo***: Italian term for the volcanic rock "tuff".

**volcanic ash**: Volcanic ash is composed of particles, sand-sized and smaller (<2 mm diameter), of glass and crystals derived from magma, or molten rock, as well as particles of rock, mainly lavas broken from the underground edifice of the volcano.

**zeolite**: Hydrated, porous aluminosilicate minerals containing potassium, sodium, and calcium with internal channels that have strong effects on absorption properties and industrial applications.

# Appendix 2

# Schedule of Samples Collected for Preliminary Study Prior to the ROMACONS Project

*C. J. Brandon and M. D. Jackson*

Prior to the formation of the ROMACONS project, Brandon, Hohlfelder, Oleson, R. Yorke (then of Cambridge University), R. L. Vann (University of Maryland) and E. K. Gazda (University of Michigan at Ann Arbor) collected small samples of Roman maritime concrete and related geological materials from sites throughout the entire Mediterranean area. The samples were taken over a long period of time, in connection with a variety of projects, and some sample portions were turned over to the ROMACONS team for analysis. Those from archaeological sites were taken with the kind permission of the archaeological authorities involved. Table A2.1 gives a brief summary of these samples. Many were sent to commercial laboratories for petrographic analysis (see note 1). Although pumiceous volcanic ash was recognized in many of these specimens, the resulting descriptions contain some errors and misleading identifications of minerals and cementitious fabrics, mainly because our protocols for testing were not yet sufficiently advanced in the early years of the project. Relevant geochemical analyses listed in Table A2.1 are reported in Table A4.2 and Table A4.3, and described in Chapter 7. The samples form an important archive for future ROMACONS investigations, and it seems appropriate to list them here for the sake of completeness. Most of the sites appear on the maps Figs. 3.2, 4.43, or 6.1. References to sample locations are given where posssible.

*Table A2.1 Samples taken prior to the ROMACONS project, or independently of the drill cores.*

| **Reference Number** | **Site and Samples** | **Date** | **Investigator** | **Lab** | **Analysis** |
|---|---|---|---|---|---|
| 4 | Area G, Caesarea, Israel (Fig. 6.72) | 1982 | Oleson and Branton | UVC | 3, 4 |
| K2-1 | Area K-2, Caesarea, Israel (Fig. 4.26) | 1992 | Hohlfelder | SCC | 1, 2, 3 |
| K5-1 to K5-5 | Five mortars, with pumiceous volcanic ash pozzolan; Area K-5, Caesarea, Israel (Fig. 4.26) | 1994 | Brandon | TUK | 1 |
| K3-1 to K3-4 | Four mortars, with pumiceous volcanic ash pozzolan and authigenic zeolites; Area K-3, Caesarea, Israel (Fig. 4.26) | 1999 | Brandon | UAS | 4, 5 |
| L1<br>L2<br>L3 | Three mortars, with pumiceous volcanic ash pozzolan, sedimentary sands, and ceramic fragments; L1, quay alongside canal leading into inner harbour of Lechion, Greece; L2–L3, from fill around wooden caissons outside harbour entrance | 1999 | Brandon | TUK | 1 |
| L5 | Mortar, with pumiceous volcanic ash pozzolan, sedimentary sands, and ceramic fragments; Top of the south-eastern jetty, Zire Island, Saïda/Sidon, Lebanon | 1999 | Brandon | TUK | 1 |
| P-02 | Mortar, with ceramic aggregate and relict lime clasts; Western side of the central harbour of Phaselis, Turkey | 1999 | Brandon | TUK | 1 |
| S-01<br>S-02 | Two mortars, S-01, with pumiceous volcanic ash pozzolan and ceramic fragments, from the western most block, and S-02, with pumiceous volcanic ash pozzolan, from shore line block on the concrete mole at Side, Turkey (Fig. 6.68) | 1999 | Brandon | TUK | 1 |

| **Reference Number** | **Site and Samples** | **Date** | **Investigator** | **Lab** | **Analysis** |
|---|---|---|---|---|---|
| ES-01 | Mortar, with light brown to buff coloured pumiceous volcanic rock pozzolan; Concrete platform on the south-eastern side of the entrance to the ancient harbour at Elaeusa-Sebaste, Turkey | 1999 | Brandon | TUK | 1 |
| C-01 | Mortar, with pumiceous volcanic ash pozzolan; End of the concrete rubble mole at Corycus, Turkey | 1999 | Brandon | TUK | 1 |
| SP-01<br>SP-02<br>SP-04<br>SP-08<br>SP-09 | Five mortars, with light brown to buff coloured pumiceous volcanic ash and vitric-crystal tuff pozzolan, and occasional ceramic fragments; Western and eastern moles at Pomeiopolis, Turkey (Figs. 4.43–44) | 1999 | Brandon | TUK | 1 |
| K-5 | Mortar, with light coloured pumiceous volcanic ash and vitric-crystal tuff pozzolan; Lowest level of block above caisson floor. Area K-5, Caesarea, Israel (Fig. 4.26) | 1999 | Brandon | TUK | 1 |
| L1 | Mortar, with buff coloured pumiceous volcanic ash pozzolan; Northwestern mole, Anzio, Italy (Fig. 4.8, w.2) | 2000 | ROMACONS | TUK | 1 |
| L2 | Mortar, with dark brown scoriacous ash and light coloured pumiceous volcanic ash pozzolan; Claudian harbour mole at Portus, Rome, Italy (Figs. 4.1, near POR.2002.02) | 2000 | ROMACONS | TUK | 1 |
| L3<br>L4 | Two samples, light coloured pumiceous tuff and pumiceous volcanic ash; Bacoli (near Baia), Italy | 2000 | ROMACONS | TUK | 1 |
| COSA-28,<br>PCO.SPRH.T1 | Tuff *caementa*; Spring House Platform, Cosa, Italy (Figs. 6.1, 8.29). Cf. Tables A4.2–3 (Figs. 7.10, 7.11) | 2002 | Stern | UCA | 7 |
| COSA-1 | Tuff *caementa*; Spring House platform, Cosa, Italy (Fig. 8.29). Cf. Table A4.3 | 2002 | Brandon | UCA | 6 |
| 34 | Volcanic tuff; near Pitigliano, Italy | 2002 | Stern | UCA | Not used |
| COSA-40 | Mortar; Outer harbour Pier 5, Cosa, Italy (Fig. 4.10). Cf. Table A4.3 (Fig. 7.14) | 2002 | Stern | UCA | 6 |
| ANZ-42 | Mortar; west breakwater, Anzio, Italy (Fig. 4.8, w.4). Cf. Table A4.3 (Fig. 7.14) | 2002 | ROMACONS | UCA | 6 |
| POZ-01.T1 | Tuff *caementa*; Portus Iulius, Pozzuoli, Italy (Fig. 4.32). Cf. Table A4.2 (Figs. 7.10, 7.11) | 2002 | ROMACONS | ACT | 7 |
| BAIAE-33 | Sample of volcanic ash/tuff from quarry; Baia, Italy | 2002 | ROMACONS | UCA | Not used |
| BAIAE-02.T1 | Tuff *caementa*; cliff above Baia, Italy. Cf. Table A4.2 (Figs. 7.10, 7.11) | 2002 | ROMACONS | UCA | 7 |
| BAI-38 | Mortar; “Tempio di Venere” Baia, Italy Cf. Table A4.3 (Fig. 7.14) | 2002 | ROMACONS | UCA | 6 |
| MISENO-21 | Mortar; Submerged pier on west side of bay, Agrippan harbour, Miseno, Italy. Cf. Table A4.3 | 2002 | ROMACONS | UCA | 6 |
| CUMAE-22 | Mortar; Podium of Temple of Jupiter, Cumae (near Baia), Italy. Cf. Table A4.3 | 2002 | Oleson | UCA | 6 |
| CAE-6 | Mortar; Area E block north of subsidiary breakwater, Caesarea, Israel (Fig. 4.23, near CAE.2005.02). Cf. Table A4.3, Fig. 7.14. | 2002 | Brandon | UCA | 6 |
| CAE-2.2 | Mortar, pumice separates; Lowest level of Block K5, Caesarea, Israel (Fig. 4.26) | 2002 | Brandon | UCA | Not used |
| CAE-B | Volcanic rock; Kerem Maharal, near Caesarea, Israel | 2002 | Oleson | UCA | Not used |
| CAE-A | Volcanic rock; ; Kerem Maharal, near Caesarea, Israel | 2002 | Oleson | UCA | Not used |
| SANT-1 | Pumice sample; Santorini, Greece | 2002 | Vann | UCA | Not used |
| CH-02 | Mortar, pumice separates; quay near CHR.2007.02, Chersonesos, Crete (Fig. 4.38). Cf. Table A4.3 | 2002 | Brandon | UCA | 6 |
| POM-07 | Mortar; Inner face of western mole, Pompeiopolis, Turkey (Figs. 4.43–44). Cf. Table A4.3 | 2002 | Brandon | UCA | 6 |

| Reference Number | Site and Samples | Date | Investigator | Lab | Analysis |
|---|---|---|---|---|---|
| Cadiz | Mortar, with pumiceous volcanic ash and tuff pozzolan, sedimentary sand and shell fragments; Cadiz, Spain (Fig. 6.4) | 2003 | Brandon | TUK | 1 |
| CH-1<br>CH-2<br>CH-5<br>CH-6<br>CH-7 | Five mortars, possibly with pumiceous volcanic ash pozzolan; harbour *pilae,* Cherchel, Algeria (Fig. 6.83) | 1968 | Yorke | ITC | 2 |
| Wall B<br>Wall D1<br>Wall D2 | Mortars, some with crushed ceramic pozzolan, walls; Carthage, Tunisia | 1973/75 | Yorke | ITC | 2 |
| 77QC8 | Wood and mortar; north end of wall C, Carthage, Tunisia (Fig. 6.77) | 1973/75 | Yorke | ITC | 2 |
| 6X | Concrete, with crushed ceramic pozzolan; Carthage, Tunisia | 1973/75 | Yorke | ITC | 2 |
| Fréjus | Mortar; large concrete block alongside Le Chemin des Horts, Fréjus, France | 2006 | Brandon | ITC | 2 |
| QS-1<br>QS-2 | Two mortars, with pumiceous volcanic ash pozzolan; Quarteira, Portugal (Fig. 6.3) | 2008 | Oleson | ITC | 2 |

## References to Table A2.1

### *Laboratory*

| | |
|---|---|
| UVC | University of Victoria, Canada |
| SCC | Schwein/Christensen, California, USA |
| TUK | Technotrade, United Kingdom |
| UCA | University of Colorado, USA |
| ITC | CTG Italcementi, Bergamo, Italy |
| ACT | Activation Laboratories, Canada |

### *Analytical Techniques*

| | |
|---|---|
| 1 | Petrographic analysis of polished thin section, includes visual estimates of relative proportions of light coloured pumiceous volcanic ash pozzolan, ceramic fragments, sedimentary sands, relict lime clasts, cementitious matrix, including alteration to calcite, and void fillings |
| 2 | Scanning Electron Microscope, Energy Dispersive Spectroscopic analyses (SEM-EDS), polished thin section in back-scattered electron mode |
| 3 | X-ray diffraction analysis, powdered specimen |
| 4 | Material properties, as specific gravity, water absorption, uniaxial compressive strength, and Young’s (elastic) modulus |
| 5 | Electron microprobe analysis of mortar specimen |
| 6 | X-ray fluorescence analysis, major element geochemistry, powdered specimen |
| 7 | ICP-MS, major and trace element geochemistry, fused glass bead of powdered specimen |

# Appendix 3

# Catalogue and Descriptions of Concretes Drilled from Marine Structures by ROMACONS

*J. P. Oleson, M. D. Jackson and G. Vola*

A summary of all the cores extracted from the Roman maritime structures is given in Table A3.1, arranged chronologically by date of sampling. The core diameters vary slightly depending on the bit used, and the characteristics of the concrete, but they are always close to 0.088 m. The macroscopic descriptions of the cores (Tables A3.2 to A3.37) are arranged geographically, beginning with the harbour sites in Tuscany, then going south along the central Italian coast to the Gulf of Naples, to Brindisi and Egnazia in southern Italy, and finally to the eastern Mediterranean sites at in Crete, Turkey, Israel and Egypt. The descriptions at each harbour site are introduced with a general outline of the character of the maritime structure or structures, their topographical and geological context, and the date of their construction. For full descriptions of the harbours, their history, and relevant bibliography see the entries in Chapter 4. The concrete fabrics are then described qualitatively in terms of their overall compaction, coherence, and consolidation, and material properties measured from testing experiments at ambient conditions in the laboratory are summarized. For further descriptions of the material properties of the concretes results see Chapter 7. Data tables with further mineralogical and geochemical analyses of the components of the concretes are given in Appendix 4. Munsell colours were described with the Geological Society of America Rock-Color Chart (1995), and with the Munsell Soil Color Charts (1994).

The Latin terms *caementa, pila/pilae,* and *piscina* have been used to avoid periphrasis and ambiguity; see the explanation of these and other terms in Appendix 1: Glossary. *Caementa* is the term used for decimeter-sized coarse aggregate. The term "compact" indicates a core or section of core in which the mortar is very hard (*i.e.* difficult to scratch or disaggregate with a stick or fingernail), and the *caementa* (coarse rubble aggregate) and sand or gravel-sized volcanic (or ceramic) pozzolans are well seated in the mortar. The term "coherent" indicates a core or section of core in which the mortar may be soft (*i.e.* somewhat easy to scratch or disaggregate with a stick or fingernail) but the *caementa* and sand or gravel-sized pozzolans are for the most part well seated in the mortar. The term "poorly consolidated" indicates a core or section of core in which the mortar is soft, and the aggregate *caementa* and sand or fine-gravel sized pozzolans are loosely bonded with the mortar. The scratch test is something the Roman engineers could have used on site to determine quality of the concrete or its degree of curing. Note that the concretes commonly show local variations as regards the hardness, porosity, and binding characteristics of the mortar and the overall coherence, and that systematic measurements of the macroscale void space (>1 to 2 cm) in the cores were not undertaken. The heterogeneous nature of the lime-volcanic rock mix, along with the variable density and porosity of the diverse components of the concrete fabrics make the results of evaluations using *in situ* geotechnical engineering techniques – such as a hardness pen or a rebound hammer – somewhat ambiguous, and *in situ* tests were not undertaken in this study.

## A3.1. *Domitiana positio*, modern Santa Liberata, 5 km west of Orbetello (Tuscany, Italy)

This site includes a Roman fish-breeding tank (*piscina)* built on limestone outcrops below a limestone ridge, and associated *pilae* that possibly were intended to break waves or to support a docking facility made of wood (pp. 69–72). The tank walls were initially built to *ca.* 0.50 m above ancient sea level in order to isolate and contain the fish, the *pilae* possibly to a slightly higher level depending on their function. At present, the upper surfaces are slightly above or below sea level depending on wind and tide. The rural character of the area in antiquity, and the existence of oak and pine forests today on the adjacent slopes of the Monte Argentario suggest that the local limestone could have been calcined near the construction site with local fuel. The marine structures probably belong to the villa on the promontory above, which traditionally and probably correctly has been attributed to the Domitii Ahenobarbi family (Gambogi 2008: 255). Given the political history of the family, the mid-first century BC makes the most sense as a construction date.

Table A3.1: Summary of core statistics, locations, and measurements. All dates AD unless marked BC.

| Cat. No. | Name | State | Site | Structure | GPS reing | Date taken | Water depth | Hole depth | Core Length | % Core Recovered | Percent aggregate | Percent Mortar | Mortar to Aggregate Ratio |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | |
| 01 | POR.2002.01. Portus Claudius (*ca.* 50) | Italy | Portus | N mole | 0271604, 4629777 | 2 Aug 02 | 1.35 asl | 1.38 | 0.11 | 8% | -- | -- | -- |
| 02 | POR.2002.02. Portus Claudius (*ca.* 50) | Italy | Portus | N mole | 0271508, 4629726 | 3 Aug 02 | 2.29 asl | 3.14 | 2.80 | 89% | 33.4% | 66.6% | 2.0 |
| 03 | POR.2002.03. Portus Claudius (*ca.* 50) | Italy | Portus | N mole | 0271688, 4629800 | 4 Aug 02 | 1.56 asl | 1.56 | 0.36 | 23% | -- | -- | -- |
| 04 | ANZ.2002.01 (*ca.* 65) | Italy | Anzio | E mole | 0302127, 4590670 | 6 Aug 02 | 0.20 asl | 3.10 | 3.10 | 100% | 32.3% | 67.7% | 2.1 |
| 05 | PTR.2002.01. Portus Trajani (*ca.* 115) | Italy | Portus Traiani | W mole | 0271623, 4628837 | 8 Aug 02 | 2.23 asl | 2.23 | 2.23 | 100% | -- | -- | -- |
| 06 | PTR.2002.02. Portus Trajani (*ca.* 115) | Italy | Portus Traiani | Quay | 0272140, 4628884 | 9 Aug 02 | 1.65 asl | 1.67 | 1.65 | 99% | 35.1% | 64.9% | 1.8 |
| 07 | SLI.2003.01 (mid-1C BC) | Italy | Santa Liberata | Piscina pila | 0688713, 4700418 | 5 Jun 03 | -0.1 | 2.28 | 1.50 | 66% | 27.3% | 72.7% | 2.7 |
| 08 | PCO.2003.01 (mid-1C BC) | Italy | Cosa | Pila 1 | 0688713, 4697618 | 7 Jun 03 | 2.11 asl | 2.23 | 1.65 | 74% | 31.0% | 69.0% | 2.2 |
| 09 | PCO.2003.02 (mid-1C BC) | Italy | Cosa | Pila 2 | 0688720, 4697597 | 9 Jun 03 | 2.51 asl | 3.50 | 1.60 | 48% | 43.0% | 57.0% | 1.3 |
| 10 | PCO.2003.03 (mid-1C BC) | Italy | Cosa | Pila 2 north | 0688720, 4697597 | 10 Jun 03 | 2.30 asl | 3.68 | 2.25 | 61% | 23.0% | 77.0% | 3.3 |
| 11 | PCO.2003.04 (mid-1C BC) | Italy | Cosa | Pila 1.5 | 0688720, 4697597 | 11 Jun 03 | -0.12 | 1.14 | 1.10 | 96% | 42.0% | 58.0% | 1.4 |
| 12 | PCO.2003.05 (mid-1C BC) | Italy | Cosa | Pila 5 | 0688826. 4697542 | 13 Jun 03 | -2.2 | 0.48 | 0.48 | 100% | -- | -- | -- |
| 13 | SLI.2004.01 (mid-1C BC) | Italy | Santa Liberata | Pila 2 | 0676991, 4700480 | 2 Oct 04 | -0.5 | 6.14 | 5.80 | 95% | 45.4% | 54.6% | 1.2 |
| 14 | BRI.2005.01 (2005) | Italy | Brindisi | Recon Pila | 0748275, 4503327 | 19 Mar 05 | 0.10 asl | 1.75 | 1.75 | 100% | 33.0% | 67.0% | 2.0 |
| 15 | CAE.2005.01. Herod (*ca.* 23–15 BC) | Israel | Caesarea, *Sebastos* | S BW, K5 | 0677287, 3598050 | 6 Oct 05 | -3.5 | 1.10 | 1.10 | 100% | 41.3% | 58.7% | 1.4 |
| 16 | CAE.2005.02. Herod (*ca.* 23–15 BC) | Israel | Caesarea, *Sebastos* | S BW | 0677285, 3597740 | 7 Oct 05 | -3.0 | 1.65 | 1.65 | 100% | 25.0% | 75.0% | 3.0 |
| 17 | CAE.2005.03. Herod (*ca.* 23–15 BC) | Israel | Caesarea, *Sebastos* | N BW, Area G | 0677369, 3598046 | 9 Oct 05 | -3.0 | 1.00 | 0.80 | 80% | -- | -- | -- |
| 18 | CAE.2005.04. Herod (*ca.* 23–15 BC) | Israel | Caesarea, *Sebastos* | S BW, Area CW.01 | 0677261, 3597965 | 10 Oct 05 | -3.0 | 2.35 | 2.10 | 91% | 17.0% | 83.0% | 4.9 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 19 | CAE.2005.05. Herod (*ca.* 23–15 BC) | Israel | Caesarea, *Sebastos* | S BW, Area CO.01 | 0677251, 3597893 | 11 Oct 05 | -2.5 | 2.00 | 1.95 | 98% | 32.6% | 67.4% | 2.1 |
| 20 | BRI.2005.02 (2005) | Italy | Brindisi | Recon Pila | 0748275, 4503327 | 17 Nov 05 | 0.10 asl | 1.65 | 1.65 | 100% | 24.3% | 75.7% | 3.1 |
| 21 | BAI.2006.01 (mid-1C BC) | Italy | Baiae | Port mole | 0422100, 4519004 | 6 Sep 06 | -5.1 | 2.30 | 2.15 | 93% | 28.4% | 71.6% | 2.5 |
| 22 | BAI.2006.02 (*ca.* 35 BC) | Italy | Portus Iulius | Port mole | 0423641, 4519891 | 7 Sep 06 | -3.9 | 1.60 | 1.20 | 75% | 33.4% | 66.6% | 2.0 |
| 23 | BAI.2006.03 (1C BC) | Italy | Secca Fumosa | Pila | 0423140, 4519491 | 8 Sep 06 | -3.45 | 3.15 | 2.90 | 92% | 36.0% | 64.0% | 1.8 |
| 24 | BAI.2006.04 (*ca.* 35 BC) | Italy | Portus Iulius | Port pila | 0423698, 4519821 | 9 Sep 06 | -3.50 | 1.63 | 1.63 | 100% | 39.3% | 60.7% | 1.5 |
| 25 | BAI.2006.05 (*ca.* 35 BC) | Italy | Portus Iulius | Starbord mole | 0423635, 4519992 | 11 Sep 06 | -3.0 | 1.50 | 1.10 | 69% | 39.8% | 60.2% | 1.5 |
| 26 | BRI.2006.01 (2005) | Italy | Brindisi | Recon Pila | 0748275, 4503327 | 22 Nov 06 | 0.10 asl | 1.00 | 0.80 | 80% | 22.9% | 77.1% | 3.4 |
| 27 | ALE.2007.01 (*ca.* 50) | Egypt | Alexandria | Antirhodos | 0776022, 3455981 | 8 May 07 | -4.0 | 0.76 | 0.75 | 99% | 44.5% | 55.5% | 1.2 |
| 28 | ALE.2007.02 (*ca.* 50) | Egypt | Alexandria | Antirhodos | 0776022, 3455981 | 8 May 07 | -4.0 | 1.10 | 1.03 | 94% | 43.4% | 56.6% | 1.3 |
| 29 | ALE.2007.03 (*ca.* 50) | Egypt | Alexandria | Ball Trap pila | 0775075, 3456696 | 9 May 07 | -2.0 | 3.10 | 3.05 | 98% | 46.4% | 53.6% | 1.1 |
| 30 | ALE.2007.04 (*ca.* 50) | Egypt | Alexandria | Royal Harbour | 0776548, 3456235 | 10 May 07 | -4.0 | 1.03 | 1.03 | 100% | 48.9% | 51.1% | 1.0 |
| 32 | CHR.2007.01 (1C BC or AD) | Greece | Chersonesos | E mole, tip | 0353943, 3909741 | 11 Sep 07 | -0.20 | 1.90 | 1.20 | 63% | -- | -- | -- |
| 32 | CHR.2007.02 (1C BC or AD) | Greece | Chersonesos | E mole, base | 0353835, 3909705 | 12 Sep 07 | 0.20 asl | 1.52 | 1.49 | 98% | 26.2% | 73.8% | 2.8 |
| 33 | BRI.2008.01 (2005) | Italy | Brindisi | Recon Pila | 0748275, 4503327 | 14 May 08 | 0.10 asl | 1.75 | 1.75 | 100% | 27.8% | 72.2% | 2.6 |
| 34 | EGN.2008.01 (2C or 1C BC) | Italy | Egnazia | N large Pila | 0701550, 4529339 | 15 May 08 | -3.20 | 2.60 | 2.60 | 100% | 44.5% | 55.2% | 1.2 |
| 35 | POM.2009.01 (*ca.* 150) | Turkey | Pompeiopolis | W mole | 0637607, 4066968 | 13 Aug 09 | 1.80 asl | 3.60 | 4.44 | 100% | 63.7% | 36.3% | 0.6 |
| 36 | POM.2009.02 (*ca.* 150) | Turkey | Pompeiopolis | W mole, base | 0637607, 4066974 | 14 Aug 09 | 0.49 asl | 0.90 | 0.80 | 89% | 53.7% | 46.3% | 0.9 |
| | | | | | | | | | | | | | |
| | | | | | | | Total | 73.47 | 63.55 | | | | |
| | | | | | | | Avg. | 2.04 | 1.77 | 85% | 36.2% | 63.8% | 2.0 |
| | | | | | | | StD | 1.10 | 1.12 | 22% | 10.4% | 10.4% | 0.9 |
| | | | | | | | Median | 1.75 | 1.65 | 96% | 34.3% | 65.8% | 1.9 |

*Table A3.2: SLI.2003.01 drill core summary.*

| Depth | Description |
|---|---|
| 0.0 to -0.10 m | Tuff and mortar fragments. |
| -0.10 to -0.20 m | Large, poorly calcined limestone clast. |
| -0.20 to -1.2 m | High proportion of tuff, -0.20 to -0.75 m, then a higher proportion of mortar to -1.10 m. |
| -0.78 m | An uneven, irregular mortar layer with especially fine-grained volcanic pozzolan may indicate a pause in laying the concrete. |
| -1.2 to -1.5 m | Mainly a mix of tuff fragments; the poorly consolidated mortar was ground away by the coring device. |

*Fig. A3.1: SLI.2003.01, Overview of core. Pumiceous mortar with abundant relict lime clasts and sea-water saturated pumiceous tuff* caementa*. Scale bar is 10 cm.*

*Fig. A3.2: SLI.2003.01, central section, -0.40 to -1.02 m. Pumiceous mortar with abundant relict lime clasts and sea-water saturated pumiceous tuff* caementa*. Scale bar is 10 cm.*

***SLI.2003.01.*** Taken 5 June 2003 from the centre of *Pila* 1, just off the northwest corner of the *piscina* (UTM 4700418; Figs. 4.71, A3.2). The core tube was drilled to a depth of 2.28 m below the upper surface (more or less at modern sea level), *ca.* 0.10 m into the original sand sea floor, yielding a core L 1.50 m (66% recovery).

*Description:* A compact, well-mixed concrete (Table A3.2). The mortar, greenish grey to dark greenish grey in colour overall (Gley 1 6/N to 5/10Y), includes particles of yellowish-grey to pale greyish-orange volcanic ash pozzolan, and common white inclusions (D ≤ 0.015 m) (Figs. A3.1–2). The *caementa* consist of large (D 0.10 m) irregular chunks of light yellow brown tuff (10YR 5/6 to 4/4) containing frequent light yellow brown pumice clasts and fine hard black volcanic glass fragments. The colour of the tuff fades to a greenish tinge near its contact with mortar. One very hard and fine-grained, light grey to pale yellow clast of limestone was visible at -0.10 to -0.20 m, and perhaps represents the source rock calcined for lime.

***SLI.2004.01.*** Taken 2 October 2004 from the centre of *Pila* 2, the largest *pila* associated with the *piscina* or villa, 10 m seaward of a possible Roman concrete quay, at the northwest edge of the promontory on which the villa was built (UTM 4700480; Figs. 4.17–18). The core tube was drilled to a depth of 6.14 m below the upper surface (more or less at modern sea level), *ca.* 0.20 m into the original sand sea floor, yielding a core L 5.80 m (95% recovery).

*Description:* A compact, well mixed concrete (Table A3.3; Figs. 7.6a, A3.3–8). The mortar is predominantly grey to greenish-grey (1 gley 3/1) overall, with many white inclusions that vary in size (D 0.002 m to 0.015 m). There are common dark grey lava lithic fragments, part of the pumiceous volcanic ash pozzolan, and very occasional fragments of red-brown ceramics (D 0.004 m to 0.012 m). The pumiceous tuff *caementa* are brown to greenish brown when wet, (10YR 6/6 to 1 gley 4/1) but light moderate yellowish-brown (10YR 6/4 to 10YR 7/6) when dry. Mineralogical and trace element studies suggest that the pumiceous volcanic ash and at least some of the moderate yellowish-brown tuff *caementa* originate from the Campi Flegrei volcanic district (Figs. 7.10–12, see pp. 147–59). The *caementa* are quite large, D >0.2 m, and they appear to be more closely spaced near the top and bottom of the pier. This is the longest core recovered, and it provides a clear sense of the compositional variations in the stratigraphy of the concrete in this large *pila.*

*Mortar to coarse rubble aggregate (*caementa*) ratio, as volume %:* SLI.03.01, 73/27 (2.7 to 1 ratio); SLI.04.01, 55/45 (1.2 to 1 ratio).

*Coarse rubble aggregate (*caementa*):* Yellowish-brown (about 10YR 7/6 to 6/6) pumiceous vitric-crystal tuff, up to

*Table A3.3: SLI.2004.01 drill core summary.*

| **Depth** | **Description** |
|---|---|
| 0.0 to -1.50 m | A high proportion of tuff *caementa* relative to mortar. |
| -1.50 to -1.60 m | The core fractured along an oblique surface, exposing a thin layer of beach sand, small shell fragments, mud or lime mud, and many fibres of Poseidonia grass. |
| -1.50 to -3.0 m | There seems to be a higher proportion of mortar in this section. The tuff *caementa* are brownish yellow (about 10YR 7/6 to 6/6), with numerous coarse yellow-brown pumice fragments (10YR 7/8); the tuff has less of a green tinge when dry than elsewhere in the core. Approximately 0.34 m of the core was lost, probably around -2.0 m to -3.0 m, where there are fewer *caementa* and the mortar is soft. The core jammed several times in this area, which resulted in loss of mortar and tuff through grinding. |
| -3.20 m | A section of fibrous wood or basketry with a circular cross section (D 0.011 m) was found in the mortar. |
| -3.44 m | Another section of fibrous wood or basketry with a circular cross section (D 6 mm) was found in the mortar. In this area there were grains of quartz beach sand. |
| -4.30 m | The core broke at this point, along the contacts of large inclusions of soft relict lime clasts (D up to 0.015 m). The surrounding mortar is compact, with fine-grained volcanic pozzolan. |
| -4.70 m | Lump of red-brown clay (D 0.01 m). |
| -5.10 m | Two lumps of grey-green clay at the contact between the tuff *caementa* and surrounding mortar (D 0.015 m). |
| -5.10–5.80 m | A high proportion of tuff *caementa*, relative to mortar. |
| -5.30 m | A fragment of reed or rope was recovered from the mortar. |
| -5.55 m | A long, thin fragment of fibrous material, probably a reed or withy fragment was found in the mortar (L 0.019 m). |

*Fig. A3.3: SLI.2004.01. Overview of core, the longest recovered by ROMACONS, 5.8 m. Scale bar is 10 cm.*

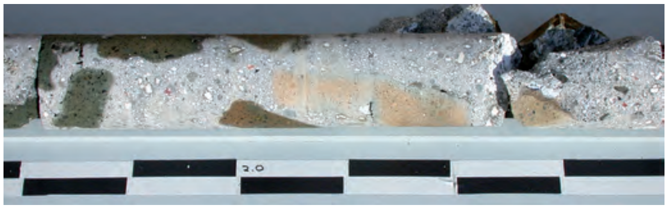

*Fig. A3.4: SLI.2004.01, detail, -1.80 to -2.40 m. Pumiceous tuff* caementa *and well-consolidated pumiceous mortar with abundant relict lime clasts. A possible trace of a relict lime putty-volcanic ash mixture occurs at the break in the core. Scale bar is 10 cm.*

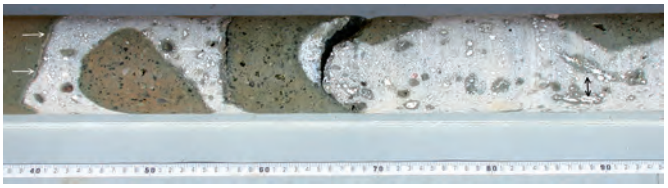

*Fig. A3.5: SLI.2004.01, detail, -3.38 to -3.65 m. Pumiceous tuff* caementa *and well-consolidated pumiceous mortar with abundant relict lime clasts. An* in situ *reaction rim occurs in the interfacial zone of the tuff* caementa *on left.*

*Fig. A3.6: SLI.2004.01, detail, -0.35 to -0.55 m. Mortar with abundant relict lime, particles of gravel-sized sea-water saturated volcanic glass and pumice clasts, and one ceramic fragment. The* caementa *are sea-water saturated pumiceous tuff on the right, and ceramic on the left.*

0.2 m, commonly has an earthy texture and local yellow-ochre to greenish-brown hues. The mineral assemblage and trace element signature suggests an origin from the Campi Flegrei volcanic district (Figs. 7.7a, 7.10–11; Tables A4.1, A4.2; specimen SLI.04.01.T1).

*Mortar pozzolan:* Fine-grained pumiceous yellowish-brown volcanic ash (about 10YR 7/6 to 6/6) with sanidine and clinopyroxene crystal fragments, and occasional plagioclase, iron-oxides, and analcite (Table A4.1); common dark grey 0.01 m glass shards with fine polygonal cracks; fine grained ceramic fragments, wood fragments, and benthonic foraminifera (Vola *et al.* 2011). Yellowish-orange (10YR 7/6) pumice from the SLI.04.01 core has a trace element signature that falls in the compositional field of pumice deposits in the Campi Flegrei volcanic district (Figs. 7.10–12; Table A4.2, specimen SLI.04.01C.P1).

*Lime/limestone source:* Upper Triassic limestone and dolomitic limestone from outcrops near the harbour sites (Pertusati *et al.* 2005) could have been calcined on site (Oleson *et al.* 2004).

*Mortar fabric:* A light grey cementitious matrix surrounds relict volcanic ash particles and partially-dissolved lime clasts. Poorly crystalline calcium-aluminium-silicate-hydrate (C-A-S-H), appears to be the principal binding component. The crystalline cementitious components of the mortar are calcite, gypsum, brucite, hydrocalumite, vaterite, aragonite as well as common phillipsite and chabazite. The bulk composition of one mortar specimen is similar to that of other harbours along the central Italian coast, with CaO/($Al_2O_3$+$SiO_2$)=0.23 and $Al_2O_3$+$SiO_2$=0.55 weight % (Table A4.3). MgO is relatively low, 2.5 weight %, suggesting a relatively pure limestone source (Fig. 7.16). Dull white inclusions are composed of Al-tobermorite and ettringite, and calcite (Vola *et al.* 2011). A complex mineral assemblage that includes calcite, (metastable) vaterite, brucite, hydrocalumite, phillipsite, chabazite, and aragonite in peripheral, sub-spherical microstructures occurs around the white inclusions. In the cementitious matrix, phillipsite crystallized *in situ* in relict voids (Vola *et al.* 2011).

*Concrete material properties:* The porosity, 45 to 48%, of the SLI.04.01 mortar falls within the range of most of the ancient sea-water mortars (Fig. 7.18) and the predominant void diameter, about 10 nm, appears to reflect the pore structure of the pumiceous volcanic ash pozzolan, (Fig. 7.19; Table 7.4). The SLI.04.01 concrete has a moderate unit weight, 1523 to 1550 Kg/m$^3$ but high compressive strength, 8 MPa, and Young's modulus, 6407 GPa, indicating relatively high resistance to strain, compared with other drill cores specimens (Fig. 7.18, Table 7.3). The mechanical tests and the microscopic observations of the mortar fabric indicate a relatively compact, cohesive, and well consolidated composite.

## A3.2. Portus Cosanus, modern Ansedonia, 7 km southeast of Ortebello (Tuscany, Italy)

The Cosa harbour complex consists of a marine harbour and associated intra-coastal lagoon regularized around 50 BC with concrete fish tanks, flow regulators, and a breakwater of concrete *pilae* founded on a rubble foundation (pp. 63–69; Fig. 4.10). The lagoon and harbour basin are bordered on the north and east by limestone ridges. Five *pilae* associated with the harbour breakwater survive in various degrees of preservation. For those closest to shore (nos 1 to 3; Fig. 4.11) the concrete in the upper part of the structure contains an abundance of sedimentary sand, while the lower part of the structure in contact with sea-water has tuffaceous coarse aggregate, and a greater proportion of pumiceous pozzolan relative to sedimentary sand. The contact between these different concrete compositions occurs close to modern sea level. The mole at Sapri also contains different concrete mixes above and below sea level (Scognamiglio 2008). Fluctuations in sea level seem to have been small during the last 2000 years (Lambeck *et al*. 2004), so the builders possibly intended the top of the *pilae* to protrude several metres above sea level. It seems likely that the lime was quarried and calcined locally, since the hill on which the city was built, and the hills adjacent to the harbour are underlain by limestone, and there was probably abundant forest cover (Brown 1951: 17, 1980: 6). The mortars of all the cores contain various proportions of the local beach sand, composed of quartz, feldspar, and iron-oxide crystals (Table A4.1). The addition of beach sand to the mortar of harbour concrete is not mentioned in ancient texts, and it does not occur in measurable amounts in any of the other sea-water concretes sampled.

***PCO.2003.01.*** Taken 7 June 2003 from the centre of the top surface of Pier 1 on the modern beach (2.11 m asl; UTM 4697618). The coring hole depth was 2.23 m, yielding a core of L 1.65 m (74% recovery). The pier appears to be the result of one sequence of construction. Although limestone coarse aggregate was used in the top 0.50 m of the *pila* and volcanic tuff in the lower section, the mortar appears rather uniform throughout. A fragment of charcoal (D 0.01 m) at 0.35 m below the top of the pier yielded a $^{14}$C date of 2020 ±40 BP, giving a range of 57 BC to AD 33 (TO-11233; Oleson *et al.* 2004: 225). The base of the recovered core is composed mainly of tuff crumbled during the coring process, and perhaps suggests that the concrete in the lower portion of the pier had a lower proportion of mortar. The top of this structure did not protrude above sea level.

*Description*: A uniform, compact concrete in a core that was recovered in several large sections (Table A3.4; Figs. A3.7–9). The light greenish grey to dark greenish grey (Gley 1 7/N to 7/10Y) mortar contains common particles of light yellowish-grey pumice, white inclusions, and relict lime clasts. These are generally small (D up to about 0.01 m, but mainly D < 0.005

*Table A3.4: PCO.2003.01 drill core summary.*

| Depth | Description |
|---|---|
| 0.0 to -0.50 m | Irregular, light grey (Gley 1 8/N to 7/N) limestone *caementa* (D ≤ 0.10 m) and mortar. This upper mortar may be slightly more granular than that below -0.50 m, but the difference is subtle. Where the two types of concrete meet, there is no obvious seam, but the lower mortar is slightly more yellow brown than the light greenish grey to dark greenish grey (Gley 1 7/N to 7/10Y) elsewhere in the core. |
| -0.50 to -1.65 m | Yellow brown (10YR 5/6 to 4/4) pumiceous tuff similar to the SLI.2003.01 and the other Cosa concretes, containing black glass fragments (Vola *et al.* 2011) and yellow brown pumice fragments. |
| -0.50 to -1.30 m | The proportion of tuff *caementa* seems quite low, perhaps about 10 volume %. |
| -1.30 to -1.65 m | The mortar contains large white inclusions, up to D 0.03 m, and there are irregular voids up to D 0.03 m. The core sample terminates with tuff crumbled during the sampling procedure. |

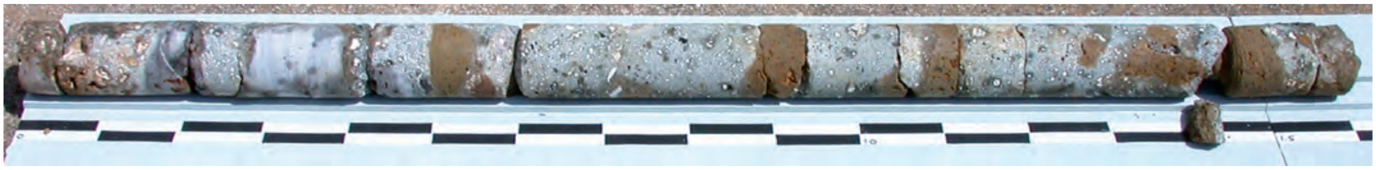

*Fig. A3.7: PCO.2003.01. Overview of core, pumiceous tuff* caementa *and one limestone fragment, and pumiceous mortar with abundant lime clasts. Scale bar is 10 cm.*

*Fig. A3.8: PCO.2003.01, detail, 0 to -0.58 m. Pumiceous tuff and gray limestone* caementa*, and mortar with relict lime clasts and possible clots of relict lime putty.*

*Fig. A3.9: PCO.2003.01, detail, -0.50 to -1.10 m. Pumiceous tuff* caementa *and pumiceous mortar with abundant lime clasts.*

m), and uniform in size and distribution. Pumice clasts removed from the mortar have a trace element signature that falls in the compositional field of pumice deposits in the Campi Flegrei volcanic district (Fig. 7.13, Table A4.2, specimen PCO.03.01.AC.P1). There are also common small tuff fragments in the mortar, occasional small fragments of ceramic, and small voids (D 0.003 to 0.02 m) indicating flaws in compaction at the macroscopic scale. The *caementa* are roughly trimmed limestone for the top 0.5 m, and then moderate yellowish-brown tuff below.

***PCO.2003.02.*** Taken 9 June 2003 from the south end of the top surface of Pier 2 just off the modern beach (2.51 m asl; UTM 4697597). The coring hole depth was 2.10 m to top of a beam hole, 2.38 m to bottom of beam hole, *ca.* 3.50 m to the bottom of the pier, yielding a core of L 1.60 m (48% recovery). The core tube passed through an empty beam hole from the wooden formwork, explaining the low recovery rate. The portion from -0.05 m to -0.50 m was intact, -0.50 m to -0.70 m was lost, and section -0.70 m to -1.60 m was broken but complete. It is likely that the lower portion of the core came from below the sea level water table.

*Description:* A rather compact concrete with a mortar that is light grey (1 Gley 7/N) overall, with abundant beach sand, as in PCO.2003.03, small tuff clasts, common white inclusions and relict lime clasts (D ≤ 0.01 m), and occasional small voids (Table A3.5; Figs. A3.10–12). A mortar with a greater proportion of pumiceous ash appears at *ca.* -0.95 m depth, but without any visible seam. The mortar contains occasional fragments of crushed ceramic throughout.

*Table A3.5: PCO.2003.02 drill core summary.*

| Depth | Description |
|---|---|
| 0.0 to -0.65 m | The *caementa* consist of amphora sherds, sandstone beachrock with natural carbonate cements, and grey limestone. The ceramic ware is hard, and sandy reddish yellow (5YR 6/8). There is a piece of beachrock at -0.70 to -0.80 m, and another at -1.50 to -1.60 m, but grey limestone predominates. |
| -0.65 to -0.75 m | Yellow-brown tuff *caementa*. |
| -0.75 to -1.45 m | Beachrock and limestone *caementa*; one potsherd. |
| -1.45 to -1.50 m | Mortar with pumiceous volcanic ash pozzolan. |
| -1.55 m | Tuff *caementa*. |

*Fig. A3.10: PCO.2003.02. Overview of core, with diverse* caementa*, ceramics, lava, and pumiceous tuff, and a relatively low proportion of mortar, with complex relict lime clasts. The red tint is caused by rust in the core tube.*

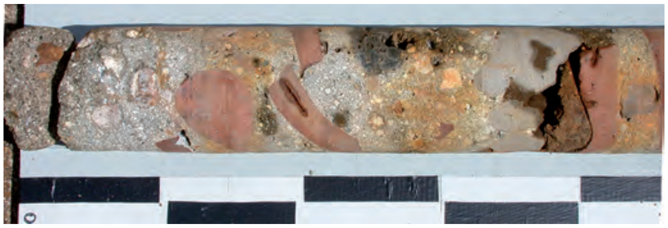

*Fig. A3.11: PCO.2003.02, detail 0 to -0.46 m. Ceramic and lava* caementa *in iron stained concrete, an artefact of the drilling process, and mortar with pale orange pumiceous pozzolan and complex relict lime clasts. Scale bar is 10 cm.*

*Fig. A3.12: PCO.2003.02, detail -1.25 to -1.35 m. Concrete with brown pyroclastic rock* caementa*, with carbonate rock lithic fragments. The origin of these rocks is not known.*

***PCO.2003.03.*** Taken 10 June 2003 from the northern end of the top surface of Pier 2, just off the modern beach (2.30 m asl; UTM 4697597). The top of the hole is 2.30 m above the modern high water mark, which is 1.38 m above the base of the pier. The coring hole depth was 3.68 m to the base of the pier, yielding a core of L 2.25 m (61% recovery).

*Description:* A compact, dense concrete (Table A3.6; Figs. A3.13–14). The mortar above -0.50 m is light grey overall, and there are many white inclusions, commonly as relict lime clasts (D ≤ 0.005 m), and occasional voids. The mortar below -0.50 m contains a greater proportion of pumiceous volcanic ash, and is slightly darker grey in colour and finer in texture, but there is no obvious seam with the upper section. It also contains beach sand, small tuff clasts, and frequent white inclusions, mainly as relict lime clasts (D ≤ 0.01 m). The *caementa* above -0.50 m are grey limestone; below -0.50 m, they are mainly yellow-grey tuff, fragments of limestone, and occasional fragments of ceramic.

***PCO.2003.04.*** Taken 11 June 2003 from middle area of Pier 1.5, a foundation block of sandy hydraulic concrete connecting Pier 1 and Pier 2, just off the modern beach (UTM 4697597). At this point the top of the core hole was 0.12 m below msl, and the pier was *ca.* 1.14 m thick. The core hole depth was 1.14 m, yielding a core of L 1.10 m (96% recovery).

*Description:* The core was saturated with sea-water to 0.15 m below the upper surface of the pier, 0.12 m below present sea level, but dry below that point (Table A3.7; Figs. A3.15–17). The compact light grey (1 Gley 7/N) to grey (1 Gley 6/N) mortar contains pumiceous volcanic ash pozzolan, beach sand (Table A4.1), and common white inclusions, mainly relict lime clasts, varying from D 0.01 to 0.15 m. There are common voids,

*Table A3.6: PCO.2003.03 drill core summary.*

| **Depth** | **Description** |
|---|---|
| 0.0 to -0.10 m | The *caementa* consist of hard, sandy light reddish brown (2.5 YR 6/4) amphora fragments; the mortar was largely ground up during drilling. |
| -0.10 to -0.50 m | Well consolidated, light grey mortar containing pumiceous volcanic pozzolan, beach sand, common white inclusions (D ≤ 0.005 m), and occasional small voids; grey limestone *caementa*. |
| -0.50 to -2.25 m | Hard, sandy, light grey mortar, with a small proportion of moderate yellow brown tuff *caementa*. Occasional small fragments of limestone and ceramic. |

*Table A3.7. PCO.2003.04 drill core summary.*

| **Depth** | **Description** |
|---|---|
| 0.0 to -0.15 m | Greenish grey tuff *caementa* and locally dark greenish grey mortar. |
| -0.15 to -1.14 m | Compact concrete with tuff *caementa.* |
| -0.40 m | Several irregular voids up to D 0.02 m. |
| -0.78 m | An uneven, irregular layer of mortar with more fine-grained volcanic ash may indicate a pause in laying the concrete. |
| -0.60 to -0.70 m | A thin layer of fine pozzolan particles, stratified perhaps through settling from sea-water. This stratum may indicate a pause in laying the concrete. |

*Fig. A3.14: PCO.2003.03, detail -0.98 to -1.10 m. Mortar with pale orange-gray pumice and relict lime clasts.*

particularly at -0.45 m, and a possible settling layer at -0.70 m. The mortar takes on a greenish tinge in proximity to pumiceous tuff *caementa*, which are greenish grey at the top of the core (Gley 1 4/1 10GY). Elsewhere, they are the typical yellow brown (10YR 6/6). Geochemical and mineralogical studies suggest the tuff originates from the Campi Flegrei volcanic district (Figs. 7.10–11; Table A4.2; specimen PCO.03.04A/B. T1). The tuff contains brownish yellow (10YR 6/6) pumice inclusions and dark grey lava lithic fragments. There are also occasional small chips of ceramic and one fragment of poorly calcined limestone (D *ca.* 0.03 m). The *caementa* seem to be uniformly distributed through the core.

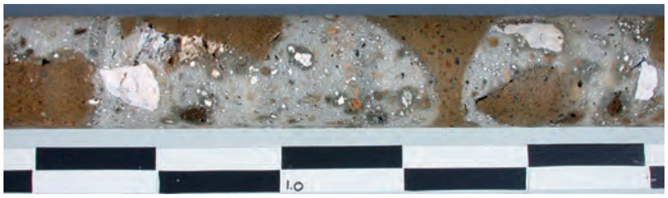

*Fig. A3.13: PCO.2003.03, detail -0.78 to -1.31 m. Pumiceous tuff* caementa *and pumiceous mortar with small relict lime clasts and larger fragments of poorly calcined limestone. Scale bar is 10 cm.*

***PCO.2003.05.*** Taken 13 June 2003 from southwest edge of Pier 5 (UTM 4697542). The top of the hole was 2.2 m below msl, and the pier approximately 1.5 m thick. Because of the porous and friable nature of the outer surface of the concrete, it was not possible to anchor securely the two front feet of the coring frame. As a result, the frame came loose after only 0.48 m of core had been secured, and coring was terminated.

*Description:* A relatively coherent concrete with a pozzolanic mortar that is somewhat soft, dark greenish grey (Gley 1 4/5GY) towards the surface of the block, a lighter greenish grey (Gley 1 7/10Y) and more compact towards the interior (Table A3.8; Fig. A3.18). The mortar contains common white inclusions, mainly as relict lime clasts (D ≤ 0.007 m), pumiceous volcanic ash pozzolan, and a substantial proportion of beach sand. Many of the *caementa* consist of dark greenish grey (Gley 1 3/1 10Y) tuff. There is a fragment of a hard, sandy, light red (2.5YR 6/6) ceramic ware (0.07 by 0.02 m) at -0.15 m, probably an amphora fragment, and one fragment of the local limestone.

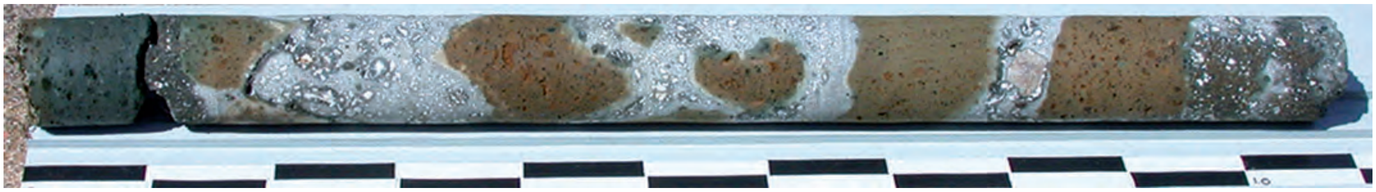

*Fig. A3.15: PCO.2003.04. Overview of core, with pumiceous tuff* caementa*, and mortar with abundant relict lime clasts. Scale bar is 10 cm.*

*Fig. A3.16: PCO.2003.04, detail -0.20 to -0.35 m. Mortar with complex relict lime fabrics and precipitation of carbonate textures on the surfaces of compaction flaws.*

*Mortar to coarse rubble aggregate (*caementa*) ratio, as volume %:* PCO.2003.01, 69/31 (2.2 to 1 ratio) overall; PCO.2003.02, upper section, limestone *caementa*, 55/45 (1.2 to 1 ratio), lower section, tuff *caementa*, 57/43 (1.4 to 1 ratio). PCO.2003.03, 77/23 (3.3 to 1 ratio) overall. PCO.2003.04, 58/42 (1.4 to 1 ratio) overall. PCO.2003.05, undetermined, crumbled concrete.

*Coarse rubble aggregate (*caementa*):* Yellowish-brown pumiceous vitric-crystal tuff, up to 0.2 m, has a trace element signature that falls in the compositional field of the Bacoli Tuff in the Campi Flegrei volcanic district (Figs. 7.10–11; Tables A4.1, A4.2; specimens PCO.03.04A/B.T1, PCO.SPRH.T1).

*Mortar pozzolan:* Beach sand gives most of the mortars a speckled, granular appearance, but all mortars also contain a substantial proportion of fine-grained, moderate yellowish-brown pumiceous volcanic ash with common sanidine and clinopyroxene crystal fragments, as well as occasional plagioclase, iron-oxides, and analcite (Table A4.1), common dark grey 0.01 m glass shards with fine polygonal cracks, fine grained ceramic fragments, wood fragments, and benthonic foraminifera. A moderate yellowish brown (10YR 5/4 to 6/4) pumice specimen from the PCO.2003.01 core has a trace element signature that falls in the range of pumice deposits in the Campi Flegrei volcanic district (Figs. 7.10–12; Table A4.2, specimen PCO.03.01.AC.P1).

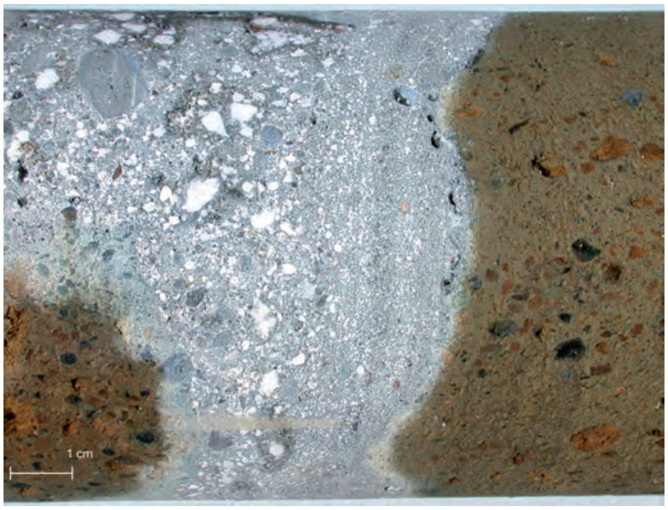

*Fig. A3.17: PCO.2003.04, detail -0.60 to -0.70 m. Stratified mortar with fine ash pozzolan at base (right) and coarse ash with gray pumice clasts coarsening upwards.*

*Table A3.8: PCO.2003.05 drill core summary.*

| Depth | Description |
|---|---|
| 0.0 to -0.15 m | Core is crumbled. |
| -0.15 m | Fragment of ceramic. |
| -0.15 to -0.50 m | High proportion of mortar relative to *caementa*. |
| -0.45 m | Fragment of limestone. |

*Fig. A3.18: PCO.2003.05. Overview of highly weathered concrete core, with pumiceous tuff* caementa *and mortar altered to dark green earthy fabrics. Iron staining is an artefact of the drilling process.*

*Lime/limestone source:* Upper Triassic limestone and dolomitic limestone from outcrops near the harbour sites (Pertusati *et al.* 2005) could have been calcined on site (Oleson *et al.* 2004). Some relict lime clasts have cracks, suggesting possible incorporation as quicklime (Fig. 7.15).

*Mortar fabric:* A light grey cementitious matrix includes quartz and iron oxide crystals from beach sand, relict volcanic ash particles and partially dissolved lime clasts. Poorly crystalline C-A-S-H appears to be the principal binding component; the principal crystalline cementitious components are Al-tobermorite and calcite, and traces of hydrotalcite and phillipsite. Dull white inclusions are composed of Al-tobermorite and calcite associated with a complex assemblage of strätlingite, wollastonite, ettringite, and vaterite, and traces of brucite, gypsum, and nordstrandite (Table A4.1). Wollastonite may have been produced during calcination of limestone. Some phillipsite crystallized *in situ* in relict voids in the cementitious matrix (Vola *et al.* 2011; Jackson *et al.* 2012), The bulk composition of some specimens of the mortar have low calcium, similar to other harbours along the central Italian coast, with relatively high $CaO/(Al_2O_3+SiO_2)=0.34$ to 0.42 and $Al_2O_3+SiO_2=0.46$ to 55 weight % (Fig. 7.16; Tables A4.2, A4.3). In some specimens MgO is relatively low, $\leq 1.6$ weight % for both the fine and coarse fractions of the mortar. One specimen has high MgO, 8 weight %, possibly suggesting a more dolomitic lime source, and/or other magnesium-rich aggregate components.

*Concrete material properties:* The porosity of the PCO.03.03 mortar, 45%, falls within the lower range of the sea-water mortars (Fig. 7.18; Table 7.4), and the predominant void diameter, 8 to 10 nm, may reflect the pore structure of the pumiceous volcanic ash pozzolan, likely from the Campi Flegrei volcanic district (Figs. 7.10–12; Table 7.4). The unit weights of the Portus Cosanus concretes vary from 1557 to 1652 Kg/m$^3$, with the exception of PCO.2002.02, subcore PCO02B, which has a rather high unit weight, 2163 Kg/m$^3$ (Fig. 7.18; Table 7.3). Compressive strengths vary from 5.1 to 9.4 MPa, but unit weight does not seem to be the single determining factor in strength gain.

## A3.3. Portus, modern Fiumicino, 24 km SW of Rome (Lazio, Italy)

The breakwater and other structures of the Claudian portion of the harbour at Portus are now all above sea level, although Pliny (*Nat.* 16.201–2), Suetonius (*Claud.* 20–3), and Dio Cassius (60.11.2–5) report that the breakwaters and lighthouse foundation were constructed in the sea (see pp. 55–61). Cassius Dio (60.11.2–5) notes that the quays were build on “dry land,” in fact, possibly a lagoonal swamp, and “the basin for anchoring the base of the concrete was excavated before the sea was let in.” Such a procedure might explain the low height of the long, narrow concrete wall that was cored for POR.2002.01 and POR.2002.03. This may be the footing for a masonry wall designed as a quay, or a retaining wall to hold backfill as the harbour basin was excavated; there is no surviving evidence for bollards to facilitate docking. The structure appears undermined and eroded at several points, and coarse sand underlies the wall at the POR.2002.03 core site. Core POR.2002.02, farther to the west, was taken from a much more substantial concrete wall, probably part of the principal breakwater in the sea.

The Portus harbour and commercial area were constructed about AD 42. The complex was largely out of use by the seventh century, and it was abandoned by the ninth century because it was gradually covered with silt and sand deposits during Tiber floods (Meiggs 1973: 168–71). The site was investigated piecemeal from the sixteenth century onwards, until the main harbour structures were exposed systematically during construction of Fiumicino Airport in the 1950s (Testaguzza 1970; Keay *et al*. 2005: 43–59).

The landscape around Portus consists of recent alluvium, with exposures of volcanic tuff farther inland. Lime would have been imported, perhaps from Terracina (DeLaine 1995, 2001), or from the Appennine foothills east of Rome (Lancaster 2005: 16–17). Likely sources would be the Monti Cornicolani, about 60 km up the Tiber and Aniene rivers from the coast, where limestone bedrock is currently used in cement production, and Monte Soratte, about 75 km up the Tiber river from the coast, whose limestone was described by Vitruvius (*De architectura* 2.5.1). The lime calcined from these sources has a very pure composition, containing about 95 weight % CaO (Jackson *et al.* 2007: 42–43).

***POR.2002.01.*** Taken 2 August 2002 from the top surface of the approximate midpoint of the exposed portion of the north breakwater, 7.5 m east of the bridge that carries the airport terminal access road over it (UTM 4629777). The top surface of the mole is 1.35 m asl at this point. The coring hole depth was 1.38 m, at which point drilling stopped because of increased vibration and because the core barrel had become slightly out of alignment with the drill rack. This was the first core taken by the ROMACONS team, and inexperience, combined with problems of water supply for the coring tube and the poor quality of the concrete, resulted unfortunately in the loss of most of the core to internal grinding in the tube.

*Table A3.9: POR.2002.01 drill core summary.*

| Depth | Description |
|---|---|
| *ca.* -0.50 m | Core is crumbled. Moderate brown (10YR 5/3, 7.5YR 4/6) Tufo Lionato tuff *caementa.* |
| *ca.* -1.0 m | Intact section of core has compact, off-white mortar with moderate yellowish-brown pumiceous volcanic ash, dark grey, brown, red, and volcanic sand, and occasional white inclusions, often as relict lime clasts; but the mortar on the whole is well mixed. |

*Description:* The core was retrieved in very broken condition, since much of the mortar had been ground up and washed away, along with some of the tuff aggregate (Table A3.9; Fig. A3.19). The final result was one core fragment L 0.11 m, taken from about -1.0 m, along with fragments from the above -1.0 m totalling L 0.15 m (11% recovery).

*Fig. A3.19: POR.2002.01, surviving fragment,* ca. *-1.0 m. Concrete with Tufo Lionato* caementa *from the Alban Hills volcanic district, and porous mortar with scoriaceous ash likely from the Alban Hills volcanic district, yellow-gray pumiceous ash from the Campi Flegrei volcanic district (Figs. 7.10–12), and ceramic fragments.*

***POR.2002.02.*** Taken 3 August 2002 from the top surface of a large concrete mass toward the seaward end of the north breakwater at 2.29 m asl (UTM 4629726), 14.27 m east of the road leading to the restricted military area. Testaguzza identified this mass of concrete as remains of the lighthouse foundation formed inside the great barge of Caligula (1970: 105–11). No wood from the hull was retrieved with the core, however, suggesting that this proposal is incorrect.

*Description:* The core hole depth was 3.14 m, yieldinga core of L 2.80 m (89% recovery) (Table A3.10; Figs. A3.20–22). Three solid core sections were retrieved: L 1.58 m from 0 to -1.58 m, L 0.40 m from -1.58 to -1.98 m, and L 0.82 m from *ca.* -2.32 to -3.14 m. The compact mortar has localized zones that are less coherent and poorly consolidated.

***POR.2002.03.*** Taken 4 August 2002 from the top surface of the eastern, landward end of the North Breakwater, a low section immediately north of the Museo delle Navi at 1.56 m asl (UTM 4629800) from the concrete surface to a depth of -1.56 m.

*Description:* The concrete is porous, poorly consolidated, and easily damaged, and most of the mortar was ground up during the coring process and discharged along with the flushing water (Table A3.11; Fig. A3.23). The original depth of the remaining solid core, L 0.36 m, could not be determined, but to judge from the milky colour of the flushing water discharged during the latter part of the coring, it should originate from the upper part of the block. It is not clear whether any part of the surviving core was originally below sea level.

*Mortar to coarse rubble aggregate (*caementa*) ratio, as volume %:* POR.2002.01, lower subcore, *ca.* 70/30 (2.3 to 1

*Table A3.10: POR.2002.02 drill core summary.*

| **Depth** | **Description** |
|---|---|
| 0.0 to -0.40 m | Compact, light-colored (N8) mortar, containing sub-rounded moderate yellow-brown pumice clasts and small fragments of pumiceous tuff, and numerous white inclusions, commonly relict lime clasts of various sizes. This is a very heterogeneous fabric. Light yellowish brown (10YR 6/4) tuff *caementa* at -0.40 to -0.73, with palagonitic glass fragments, are the Tufo Lionato tuff from nearby Alban Hills volcano. |
| -0.40 to -0.73 m | Compact, light grey (2.5Y 7/1, or Gley 1 7/N) mortar, containing sub-rounded yellow-brown pumice fragments and yellowish-gray tuff fragments, and white inclusions often as relict lime clasts (D 0.001 m to 0.015 m). Tufo Lionato tuff *caementa*. |
| -0.73 to -0.86 m | Coherent mortar, with white inclusions, often as relict lime clasts, and sub-rounded pumiceous clasts. |
| -0.86 to -1.38 m | Coherent concrete, the mix is *ca.* 80 volume % mortar, 20 volume % Tufo Lionato tuff *caementa*. Occasional fragments of charcoal, and rope, basketry, or reeds. |
| -1.38 to -1.98 m | Coherent concrete with Tufo Lionato tuff (10YR 5/3) *caementa*, and about 50 volume % mortar, 50 volume % *caementa*. The mortar contains a few large fragments of charcoal (up to D 0.015 m), and one carbonized fragment of a reed or stick. The lower 0.15 m of this sample consists almost entirely of mortar. There is a single fragment of hard, light brown (10YR 8/2) limestone. |
| -1.98 to -2.32 m | A stratum of porous, poorly consolidated mortar with a high proportion of relict lime that washed away during coring. |
| -2.32 to -3.14 m | Porous, poorly consolidated mortar with a high proportion of relict lime. Light yellowish brown (10YR 6/4) tuff *caementa*, possibly Flegrean tuff. The original lagoon (?) floor was possibly reached at -3.14 m; there is very fine, grey brown sea sand with black iron oxide particles. |

*Fig. A3.20: POR.2002.02, lower sections, -1.58 to -1.98 m, and* ca. *-2.32 to 3.14 m. Tufo Lionato* caementa, *and mortar with relict lime clasts.*

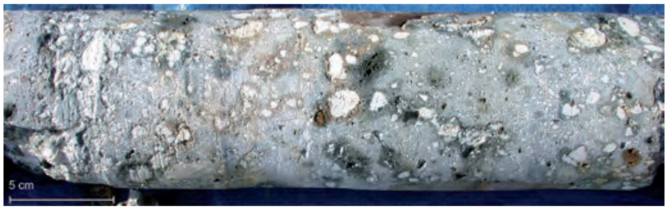

*Fig. A3.21: POR.2002.02, detail -1.06 to -1.38 m. Mortar with abundant lime, partly as relict putty clasts.*

*Fig. A3.22: POR.2002.02, detail -2.42 to -2.48 m. Tufo Lionato* caementa *with palagonitic glass and natural zeolite cements, and mortar with abundant relict lime.*

*Table A3.11: POR.2002.03 drill core summary.*

| Depth | Description |
|---|---|
| 0 to -1.56 m | Crumbly, light brownish grey (2.5Y 6/2) mortar with fragments of hard, brown (7.5YR 5.6) Tufo Lionato tuff *caementa* (D up to 0.008 m). Sub-rounded particles of pumiceous sand, but very few white inclusions, and little relict lime in the mortar mix. It is likely that the soft portions of the mixture were ground up during the coring process. |
| -1.56 m | Light colored (N8) sea sand; coarse grained, with black iron oxide particles. |

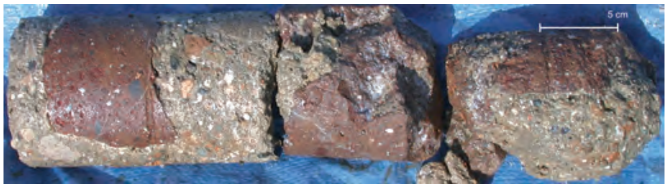

*Fig. A3.23: POR.2002.03. Surviving fragment of sea-water saturated concrete with pumiceous mortar and Tufo Lionato* caementa.

ratio). POR.2002.02, 67/33 (2 to 1 ratio). POR.2002.03, not determined, crumbled concrete.

*Coarse rubble aggregate (*caementa*):* The tawny brown (10YR 6/4) vitric-lithic-crystal tuff with abundant leucite crystals and altered palagonitic glass matrix is Tufo Lionato tuff, a ubiquitous building stone in Rome that erupted from nearby Alban Hills volcano (Jackson *et al.* 2005, 2009), and was also used as *caementa* in the Portus Traiani concretes, constructed about 60 years later.

*Mortar pozzolan:* All mortars contain fine-grained pumiceous yellowish-brown volcanic ash with common sanidine and clinopyroxene crystal fragments. A pale greyish-orange (10YR 8/4) pumice specimen has a mineral assemblage and trace element signature is similar to pumice deposits of the Campi Flegrei volcanic district, suggesting an origin from the Bay of Pozzuoli (Figs. 7.10, 12; Tables A4.1, A4.2; specimen POR.2002.PO2C.P1). There is also a small amount of scoriaceous volcanic sand incorporated in the mortar.

*Lime/limestone source:* Possibly transported from calcination sites for Mesozoic-Cenozoic limestone in the Appenine foothills near Tivoli, similar to the nearly pure CaO lime in the mortars of the monuments of Rome or, alternatively, from coastal calcination sites such as Terracina.

*Mortar fabric:* A light grey cementitious matrix surrounds relict volcanic ash particles and relict lime clasts (Fig. 7.6b). Poorly crystalline calcium-aluminium-silicate-hydrate (C-A-S-H) is the principal binding component. The principal crystalline cementitious components are calcite, tobermorite, hydrcalumite, ettringite, and phillipsite (Jackson *et al.* 2012: 56–59). Dull white inclusions are composed of Al-tobermorite, calcite, and vaterite, and associated hydrocalumite, ettringite, aragonite, afwillite, gypsum, and phillipsite (Table A4.1). The bulk composition of the fine fractions of the mortar has CaO/

($Al_2O_3$+$SiO_2$)=0.19 to 0.21 and $Al_2O_3$+$SiO_2$=0.55 weight % (Fig. 7.16; Table A4.3). MgO is 2.3 to 2.5 weight %, suggesting a relatively pure limestone source. Textures in the mortar suggest complex lime-volcanic ash mixtures (Fig. 7.16)

*Concrete material properties:* The porosity of the mortar, 44% to 51%, falls within the average range of the sea-water mortars (Fig. 7.18; Table 7.4) and the predominant void diameter, mainly about 10 nm, apparently reflects the pore structure of pumiceous volcanic ash pozzolan. The unit weight of the POR.02.PO2 subcore is 1583 Kg/m$^3$, and the compressive strength is 7.8 MPa (Fig. 7.18; Table 7.3). These relatively high values may reflect the higher unit weight of the Tufo Lionato tuff *caementa*, about 1530 Kg/m$^3$, relative to the Neapolitan Yellow Tuff, about 1300 Kg/m$^3$ (Jackson *et al.* 2005, Papakonstantinou *et al.* 2012).

## A3.4. Portus Traiani, modern Fiumicino, 24 km SW of Rome (Lazio, Italy)

The construction chronology of the boat passage, *darsena* (narrow docking basin), and hexagonal inner basin for anchoring and docking (pp. 54–61; Fig. 4.1) remains disputed. Although traditionally attributed to Trajan as an improvement on the poorly protected outer, Claudian basin, this complex may have been part of the original Claudian plan. Construction of the *darsena* and hexagonal basin may have commenced long before Trajan came to power, although he seems to have brought the enormous project to fruition (Keay *et al.* 2005: 271–82). The very high quality of the mortars in the drill cores suggests that these concretes may be Trajanic in age. The Late Roman to early medieval history of the area is similar to that of the Claudian basin. The harbour structures are now exposed subaerially, but their lower levels are currently saturated within the present brackish groundwater table, which was visible in the excavation in front of the structure from which core PTR 2002.02 was taken.

***PTR.2002.01***. Taken 8 August 2002 from the mole protecting the west side of the entrance channel from the Claudian to the Trajanic basin, at 40 m south of the north termination and 2 m inwards from the east face of the mole (upper surface 2.23 m asl; UTM 4628837). The core hole was drilled to a depth of 2.43 m, 0.2 m into the sandy sea floor beneath the mole, yielding a core L 2.23 m (100% recovery).

*Description:* A coherent and well-consolidated concrete, consisting of a compact, cohesive pumiceous mortar with a nearly white (10YR 8/1) cementitious matrix and uniformly sized and regularly spaced Tufo Lionato tuff *caementa* (Table A3.12; Figs. 7.5–6c, A3.24–25). A pale greyish-orange (10YR 8/4) pumice specimen has a mineral assemblage and trace element signature similar to those of pumice deposits in the Flegrean Fields volcanic district (Figs. 7.6c, 7.12; Table A4.2, specimen PTR.2002.01.P1). There are occasional brick fragments, and one possible "levelling course" of brick at -1.15 m. The block was founded on fine sand, possibly a lagoonal deposit.

***PTR.2002.02.*** Taken 9 August 2002 near the west edge of the north-south quay wall in front of the "Severan warehouses," just north of the entrance to hexagonal Trajanic basin, in a modern excavation pit surrounded by a wooden fence (1.65 m asl; UTM 4628884). The core tube was drilled to depth of 1.67 m below the upper surface, *ca.* 0.1 m into the underlying sand deposits, yielding a core L 1.65 m (100% recovery). It is not clear how much of the concrete originally was below sea level.

*Description:* A coherent and well consolidated concrete consisting of a compact, cohesive pumiceous mortar with a nearly white (10YR 8/1) cementitious matrix and uniformly-sized and regularly-spaced chunks of Tufo Lionato tuff

*Table A3.12: PTR.2002.01 drill core summary.*

| Depth | Description |
|---|---|
| -0.0 to -0.21 m | Reddish brown mortar, speckled with red, yellow, green, and grey sub-rounded volcaniclastic sand particles (to D 0.005 m), and few white inclusions, mainly as relict lime clasts. Mortar appears weathered and less coherent than that deeper in the block. Several brick fragments. Section -0.07 to -0.10 was returned to the drill hole as a plug once coring was complete. |
| -0.21 to -0.27 m | Very hard, brown (10YR 5/4) Tufo Lionato tuff *caementa*. |
| -0.27 to -1.10 m | Uniform deposit of compact, well-mixed, off-white (10YR 8/1) mortar with a substantial proportion of subrounded volcaniclastic sand particles and occasional white inclusions, as relict lime clasts. Fragments of light red brown (2.5YR 6/3) and very pale brown or light yellow (10YR 7/3) brick (Th 0.022 m, 0.035 m). Light grey (2.5Y 7/2) to dark brown (10YR 4.3) Tufo Lionato tuff *caementa*. |
| -1.10 to -1.12 m | A 0.02 m thick section of light red brown (2.5YR 6/3) brick occupies the entire core. This brick course can be seen on the face of the concrete mole. |
| -1.12 to -2.0 m | Same concrete mix as above. |
| -2.0 to -2.23 m. | Mortar is the same as above, but somewhat softer. Two large sherds of terracotta, possibly from amphorae, form the *caementa* at the base of the mole. |
| -2.23 m to -2.43. | The core tube penetrated the base of the mole at -2.23 m and recovered a very fine sand, perhaps lagoonal sediment. |

*Fig. A3.24: PTR.2002.01, detail -0.42 to -1.16 m. Tufo Lionato and ceramic* caementa*, and a well-consolidated mortar with gray pumiceous ash pozzolan.*

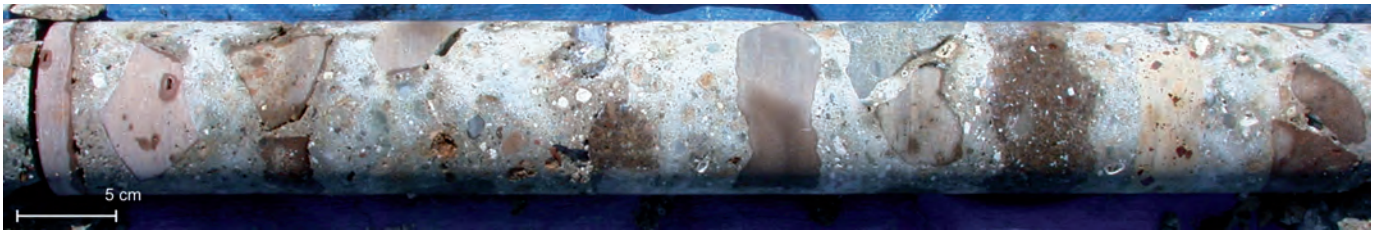

*Fig. A3.25: PTR.2002.01, detail -1.10 to -1.81 m. Well-consolidated mortar with pale orangish-gray pumiceous ash pozzolan, lava lithic fragments and scoriaceous ash, and relatively few coarse relict lime clasts. Sea-water saturated ceramics and Tufo Lionato* caementa*.*

*Table A3.13: PTR.2002.02 drill core summary.*

| **Depth** | **Description** |
|---|---|
| -0.0 to -0.20 m | Light yellowish brown (*c*.2.5Y 6/3) mortar with pale grayish-orange (10YR 8/4) pumice clasts and occasional relict lime clasts. The mortar near the sub-aerially exposed surface of the concrete appears weathered, and less compact than that deeper in the block. The tawny brown (5YR 4/6) tuff *caementa* are Tufo Lionato. |
| -0.20 to -1.40 m | Mortar as above, but fresh greyish white (10YR 8/1, 9/), with pale grayish-orange (10YR 8/4) pumice clasts and dark grey sub-rounded volcaniclastic sand (D 0.005 m), and Tufo Lionato tuff *caementa*. |
| -1.40 to -1.65 m | A layer of chalky, light greenish-grey (Gley 1 8/10Y) lime (Th 0.05 m) above light greenish grey (Gley 1 7/1) volcanic pozzolan, with dense lava particles underlying the pumice particles. Two pieces of Tufo Lionato tuff *caementa* at the bottom of the installation. |
| -1.65 to -1.85 m | The core tube penetrated the base of the mole at -1.67 m and recovered coarse, dark grey volcaniclastic sand from beneath the structure. |

*Fig. A3.26: PTR.2002.02, detail -0.60 to -0.80 m. Well-consolidated mortar with abundant sand- to gravel-sized particles of scoriaceous volcanic ash and Tufo Lionato* caementa*.*

*Fig. A3.27: PTR.2002.02, detail -1.35 to -1.50 m. A layer of white to light greenish-grey lime (to left) overlies light greenish grey volcanic pozzolan, and Tufo Lionato* caementa *on right.*

*caementa*, similar to that of PTR.2002.01 (Table A3.13; Figs. A3.26–27). The mineral assemblage and trace element signature of a specimen of the tuff (PTR.2002.02.TL1) is nearly identical to Tufo Lionato from the Salone quarry (Jackson *et al.* 2005) (Figs. 7.10–11; Table A4.2). There are few coarse relict lime clasts, compared to other harbour concretes. The lowermost portion of the quay was apparently laid in an inundated form on coarse sand.

*Mortar to coarse rubble aggregate (*caementa*) ratio, as volume %:* PTR.2002.01, 50/50 (1 to 1 ratio). PTR.2002.02, 65/35 (1.8 to 1 ratio).

*Coarse rubble aggregate (*caementa*):* The tawny brown (10YR 6/4) vitric-lithic-crystal tuff with abundant leucite crystals and altered palagonitic glass matrix is Tufo Lionato, an ubiquitous building stone in Rome that erupted from nearby Alban Hills volcano (Jackson *et al.* 2005), and was also used in the Claudian age concrete at Portus. Geochemical studies of the tuff *caementa* (specimen PTR.2002.02.TL1) and Tufo Lionato from an Aniene River quarry northeast of Rome (specimen 97.11B.TL) show nearly identical compositions (Figs. 7.6c, 7.10–11; Table A4.2).

*Mortar pozzolan:* All the mortars contain fine-grained pumiceous yellowish-brown (10YR 5/4 to 6/4) volcanic ash. The PTR.2002.01 pumices contain biotite, albite, and clinopyroxene crystal fragments, and numerous authigenic alteration products: chabazite and phillipsite, calcite, kaolinite and halloysite (Table A4.1). A pale orangish-grey pumice has a trace element signature that falls in the range of pumice deposits in the Campi Flegrei volcanic district (Fig. 7.12; Table A4.2). Dark-colored, sand-sized scoria and palagonitic glass particles have a mineral assemblage that suggests an origin from the Alban Hills and Monti Sabatini volcanic districts: there are sanidine, biotite, and leucite crystal fragments, and chabazite, kaolinite, and phillipsite produced through alteration of volcanic glass (Jackson *et al.* 2010).

*Lime/limestone source:* Possibly transported from calcination sites for Mesozoic-Cenozoic limestone in the Appenine foothills near Tivoli, similar to the nearly pure CaO lime in the mortars of the monuments of Rome or, alternatively, from coastal calcination sites such as Terracina.

*Mortar fabric:* A nearly white (10YR 8/1) cementitious matrix binds fine relict volcanic ash particles and relict lime clasts that are nearly wholly dissolved. A point count of a thin section of the PTR.2002.02 mortar indicates that cementitious binder composed mainly of poorly crystalline C-A-S-H, but also containing calcite and chabazite, forms about 47 volume % of the mortar; sand-sized, moderate yellowish-brown pumice clasts with sanidine crystals form 39 volume %; volcanic crystals, 6 volume %; lava, sub-rounded scoriae, and ceramic particles 5 volume %, and open space, about 4 volume %. The binder to pozzolanic aggregate ratio is about 0.9. The bulk composition of the mortar is quite similar to that of other harbours along the central Italian coast with $CaO/(Al_2O_3+SiO_2)=0.27$ to 0.55 and $Al_2O_3+SiO_2=44$ to 56 weight % (Fig. 7.16; Table A4.2). MgO is low, and ranges from 1.6 weight % in the cementitious matrix to 2.57 weight % in the bulk mortar. The lime may come from a nearly pure limestone source, such as from Monte Soratte or Monti Cornicolani, but incorporation of scoriaceous ash from Alban Hills deposits may elevate MgO. For example, Pozzolane Rosse scoriaceous ash contains about 45.5 weight % MgO while the Flegrean ash from Bacoli quarry contains about 0.8 weight % (Jackson *et al.* 2010; Fedele *et al.* 2011). Dull white inclusions are composed of calcite and Al-tobermorite, associated with wollastonite, ettringite, nordstrandite, vaterite, fluorite, and hydrocalumite (Table A4.1). The Tufo Lionato tuff *caementa* possibly developed *in situ* phillipsite cements in the sea-water concrete environment (Fig. 7.4).

*Concrete material properties:* The mortar porosity ranges from 44 to 53%, and falls within the average range of the sea-water mortars (Fig. 7.18; Table 7.4). The predominant void diameter ranges from 10 to 30 nm, and may reflect the pore structures of the pumiceous volcanic ash pozzolan and/or scoriaceous sands. The relatively high unit weight of the PTR.02.PT02-C subcore, 1665 Kg/m$^3$, likely reflects Tufo Lionato tuff *caementa* with unit weight, about 1530 Kg/m$^3$ (Jackson *et al.* 2005). The single measurement of compressive strength gives a relatively low value, 4.9 MPa, that does not reflect the compact, coherent, and well consolidated fabric of the concrete (Fig. 7.18).

## A3.5. Portus Neronis, ancient Antium, modern Anzio (Lazio, Italy)

The harbour of Antium was built by the emperor Nero (54–68) "at great expense" (Suetonius, *Ner.* 9), in an exposed bay framed on the north and south by low promontories. The northwest breakwater, of which little can be seen above the seabed, was 850 m long; the southern breakwater, 700 m long, had a lighthouse at its tip, next to the 68 m wide harbour entrance (pp. 61–63; Felici 1993, 1995, 2002). The shoreward portions of the breakwaters, at least, were constructed of concrete. The Romacons team was not given permission to sample the submerged portions of the southern breakwater but, instead, a core sample was obtained from the well-preserved block adjacent to the present shoreline.

***ANZ.2002.01.*** Taken 6 August 2002 from a point near the present base of the southeast breakwater (E1), 10 m seaward of the adjacent parking lot (UTM 4590670). The original landward end of the mole is now covered by modern fill. In this area the mole is a 4.75 m wide concrete wall with a level upper surface that protrudes just above present sea level. Westward of this 15 m long single block, the breakwater becomes a series of *pilae*. The core tube was drilled to *ca.* 3.10 m below the top of the mole. The first stage of coring was taken to -2.55 m, at which point the water stopped flowing through the tube because of the build-up of sea sand. The core material was removed, and drilling continued to

*Table A3.14: ANZ.2002.01 drill core summary.*

| **Depth** | **Description** |
|---|---|
| -0.0 to -0.27 m | Olive brown (moist, 2.5Y 4/4), light yellowish-brown (dry, 2.5Y 6/4), glassy pumiceous tuff *caementa* set in a light olive brown (2.5Y 5/4) mortar. The mortar has a granular aspect and common yellow (2.5Y 7/6) tuff and pumice fragments (D 0.001 m to 0.04 m). There are infrequent relict lime clasts. Of this core, 0.00 to -0.07 m was returned to the hole as a plug. |
| -0.27 to -1.90 m | At -0.27, an abrupt change to a light grey (10YR 7/1) mortar with numerous chunks of light yellowish-brown tuff *caementa,* as above. The concrete mix is very uniform, and the mortar contains very light gray (N8) and pale grayish orange (10YR 8/4) pumice clasts (up to D 0.04 m), along with common white inclusions (D 0.003 m to 0.01 m). There are two porous areas (-0.90 m, -1.80 m), but the general impression is that of a very carefully mixed and well-laid material. |
| 1.90 to -1.94 m | The tuff *caementa* are absent from the mixture below -1.90 m. The builders apparently packed a mix of lime and pumiceous volcanic pozzolan into the formwork, which was at least partially filled with water. The lowermost section from -1.90 m to -1.94 m consists of a stratified varve-like deposit composed of fine relict lime, light greyish white in colour, and fine pumiceous ash. A distinct upper boundary separates it from the more typical mortar mix above. |
| -1.94 to -1.99 m | The mortar has a fine greenish-grey volcanic pozzolan. |
| -1.99 to -2.04 m | Coarse greenish-grey volcanic pozzolan, with much lime in mortar mix. |
| -2.04 to *ca.* -2.25 m. | Loose mix of greenish grey (Gley 1 5/10Y) volcanic pozzolan and lime, retrieved from the tube in crushed form. |
| -2.25 to -3.10 m | The core tube penetrated the base of the mole at -2.25 m and recovered a coarse, greenish-grey volcaniclastic sand deposit on the harbour floor. |

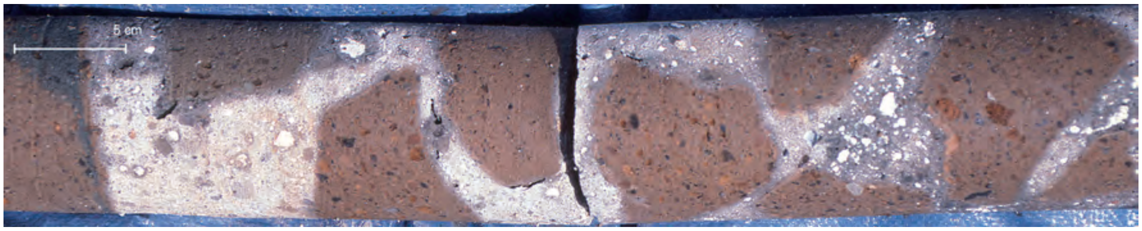

*Fig. A3.28: ANZ.2002.01, detail -1.20 to -1.70 m. Pumiceous tuff* caementa *and mortar with pumice and relict lime clasts.*

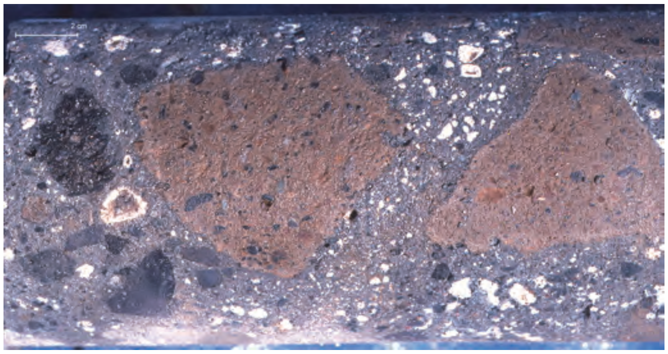

*Fig. A3.29: ANZ.2002.01, detail -1.65 to -1.80 m. Sea-water saturated pumiceous tuff* caementa *and mortar with abundant relict lime and lava lithic fragments.*

*Fig. A3.30: ANZ.2002.01, detail -1.76 to -2.01 m. Stratified deposit of fine relict light greyish white lime and fine pumiceous ash.*

-3.10 m. It is likely that approximately 0.25 m of loosely consolidated mortar at the bottom of the core was lost to the drilling activity. The core was thus L 2.25 m (90% recovery). The lowermost 0.60 m consisted of grey-greenish sea sand. The sediment deposit apparently is quite compact, since the hole remained accessible to a tape measure even after the coring tube was withdrawn, despite being filled with water by the flushing system.

*Description:* The concrete appears to have been placed in the formwork in three stages (Table A3.14; Figs. A3.28–30). The first was a concentrated lime mix with a small proportion of pumiceous volcanic pozzolan, apparently dumped in the formwork without tuff *caementa*, directly on the sandy sea floor (-1.90 m to -2.25 m). Much of this layer was apparently sorted by mass in the water and has poorly defined strata, with the slighty coarser fractions underlying the very fine fractions. The second installation was laid in a relatively massive layer 1.63 m thick (-0.27 m to -1.90 m); the mortar is light grey (N7) and has a more typical lime-volcanic pozzolan ratio. It appears carefully prepared, with few coarse relict lime clasts. In the third installation, above -0.27 m, the mortar has a greenish-brown to light yellow-brown colour, possibly resulting from subaerial weathering. This uppermost installation likely followed immediately upon the second, given the rather seamless contact.

*Mortar to coarse rubble aggregate (*caementa*) ratio, as volume %:* ANZ.2002.01, lower 1.90 m of core, 68/32 (2.1 ratio).

*Coarse rubble aggregate (*caementa*):* Rare light yellowish brown pumiceous tuff *caementa* in the upper 1.90 m of the core have a mineral assemblage with sanidine and clinopyroxene crystals in a fine-grained, altered vitric matrix, and a trace element signature (ANZ.02.01.T1) that falls in the range of tuff compositions in the Campi Flegrei volcanic district (Figs. 7.10–11; Tables A4.1, A4.2).

*Mortar pozzolan:* Pumice and tuff clasts up to 0.03 m diameter occur in the mortar (Fig. 7.6d). These have sanidine and clinopyroxene crystal fragments (Table A4.1). A greyish-orange (10YR 8/4) pumice specimen (ANZ.2002.01.P1) and a pale greenish grey (5Y 6/1) pumice specimen (ANZ.2002.01.P2) have trace element compositions that fall in the compositional range of pumice deposits in the Campi Flegrei volcanic district (Fig. 7.12; Table A4.2).

*Lime/limestone source:* The rather high MgO content of the mortar (see below) may suggest a dolomitic source for the lime, perhaps from deposits along the central Italian coast, as from Terracina.

*Mortar fabric and cementitious matrix:* A porous light grey (N8) cementitious matrix has fine-grained lime clasts (Fig. 7.15b) that are partially dissolved and relict volcanic ash particles. Poorly crystalline C-A-S-H appears to be the principal binding component (Fig. 7.20b). The bulk composition of the mortar has low $CaO/(Al_2O_3+SiO_2)=0.09$, high MgO, 5.4 to 7.8 weight %, and high $Al_2O_3+SiO_2=0.58$ weight % (Fig. 7.16; Tables A4.2, A4.3). The high MgO in the mortar may suggest a dolomitic source for lime, and brucite, $Mg(OH)_2$, occurs in the mortar (Table A4.1). Dull white inclusions occur as partially dissolved relict lime clasts (Figs. 7.15b, 7.20b), and are composed of Al-tobermorite, calcite with associated ettringite, vaterite, brucite, hydrocalumite, and aragonite (Table A4.1). Wollastonite possibly formed during calcination of limestone.

*Concrete material properties:* The mortar porosity falls within the average of central Italian coast concretes, 44% to 49% (Fig. 7.18, Table 7.4). The predominant void diameter, 10 to 30 nm, may reflect the pore structure of the pumiceous volcanic ash pozzolan. The unit weight, 1549 Kg/m$^3$, and compressive strength, 6.3 MPa, also fall within the range of the sea-water concretes from harbours along central Italian coast (Table 7.3). These indicate a relatively coherent and well consolidated composite.

## A3.6. Baianus Lacus, harbour of ancient Baiae, modern Baia (Campania, Italy)

The coring sites at Baianus Lacus, Baianus Sinus at Secca Fumosa, and Portus Iulius in the Bay of Pozzuoli are in close geographical proximity (pp. 81–85; Fig. 4.32). The concrete cores are described in Sections A3.6–8, and the summaries of their chemical, mineralogical and physical characteristics appear together as a single entry after the description of the Portus Iulius cores, in Section A3.8.

The harbour of Baiae, or Baianus Lacus, was built around a natural lagoon that follows the contour of the central caldera of the Campi Flegrei volcanic district produced by the voluminous pyroclastic eruptions of the Campanian Ignimbrite and Neapolitan Yellow Tuff, about 30,000 and 15,000 years ago, respectively (Orsi *et al.* 1996). The concrete harbour structures were possibly built during the first florescence of the resort town in the early first century BC (Brandon *et al.* 2008). Two concrete moles define the entrance channel: the northern or starboard mole (on entering the channel from the southwest) is 209 m long, and the southern or port mole is 232 m long. The moles are approximately 9.5 m wide and define a channel 32 m wide (Scognamiglio 2002: 48). It is likely that the moles were originally designed to project at least one metre above ancient sea level, but their upper surfaces now rest at 5.10 m below sea level. The isostatic topographical changes within the Campi Flegrei caldera submerged the structures at some point after the Late Roman period (Dvorak and Mastrolorenzo 1991). Volcanic deposits surround the Bay of Pozzuoli, so limestone and/or calcined lime must have been imported to the harbour site.

***BAI.2006.01.*** Taken 6 September 2006 from the approximate midpoint of the visible portion of the southern mole at Baiae, which stands *ca.* 1 m above the seabed at 5.1 m bsl (UTM 4519004). The concrete is at least as thick as the depth of the core hole, 2.3 m, and core recovered was L 2.15 m (94% recovery).

*Description:* A relatively coherent and well consolidated concrete, consisting of a pumiceous mortar with a nearly white (10YR 8/1) cementitious matrix and uniformly sized and regularly spaced pumiceous tuff *caementa* (Table A3.15; Figs. A3.31–33). See section A3.8 for a summary of material characteristics.

Table A3.15: BAI.2006.01 drill core summary.

| Depth | Description |
|---|---|
| 0.0 to -1.76 m | A nearly complete concrete core, with a small gap from -1.76 to -1.80 m. |
| 0.0 to -1.0 m | A compact concrete with a fine-grained light grey (N8) mortar, with pale greyish-orange (10YR 7/4) pumiceous volcanic pozzolan that includes many lava lithic fragments (up to D 0.010 m). White inclusions, mainly as relict lime clasts (up to D 0.050 m) occur throughout. The *caementa* appear to be the pale yellow (2.5Y 7/3, dry) pumiceous Flegrean tuff, in rather small fragments (D 0.05 m to 0.12 m). Towards the top of core the tuff becomes a dark greenish-blue or greenish brown (5Y 5/6). |
| -1.0 to -2.05 m | A poorly consolidated concrete, with significant erosion of the mortar during coring. |
| -2.05 to -2.15 m | Fragmentation of the concrete during coring. |

*Fig. A3.31: BAI.2006.01. Overview of core, with pumiceous tuff* caementa *and mortar with relict lime clasts. Scale bar is 10 cm.*

*Fig. A3.32: BAI.2006.01, detail -1.60 to -1.75 m. Mortar with pale yellowish-gray glass and pumice clasts, and a large clot of relict lime.*

*Fig. A3.33: BAI.2006.01, detail -1.85 to -2.0 m. Stratified mortar with fine ash pozzolan and relict lime at base (right), and overlain by mortar with coarse yellowish-gray pumice clasts.*

### A3.7. Baianus Sinus, Secca Fumosa (Smoking Shoals), ancient name unknown, Bay of Pozzuoli, 1.3 km E of Baia (Campania, Italy)

Twenty-eight large concrete *pilae* cluster in an area 75 m by 155 m in the centre of the Bay of Pozzuoli, ancient Baianus Sinus, about 400 m seaward from the modern beach, approximately in the centre of a straight southwest to northeast transect between the entrance to Portus Baianus and Portus Iulius (Brandon *et al.* 2008). The modern name for this area is Secca Fumosa, or "Smoking Shoals", since numerous *fumaroli* associated with geothermal activity of the Flegrean Fields volcanic system discharge cool gases and vapor near several of the *pilae* that are submerged approximately 1.5 m to 4.0 m below present sea level. The surfaces of the *pilae* are commonly faced with *opus reticulatum*, composed of small prismoidal blocks of volcanic tuff that form a regular net-like pattern (Fig. 8.2). This cluster of piers was apparently intended to stand *ca*. 1.0 m above sea level at the time of their construction, but now they are at least 1.5–4 m below present sea level. Gianfrotta (2010) has argued that at least some of the *pilae* supported a wooden platform just above ancient sea level that held baths "constructed in the sea" by M. Licinius Crassus Frugi in the first century (Pliny, *HN* 31.5; Pausanias 8.7.3).

It is puzzling that some *pilae* here and elsewhere in the Bay of Naples region have facings finished with *opus reticulatum* and *opus testaceum* (brickwork), even when they were apparently constructed underwater as at Secca Fumosa and Nisida (Gianfrotta, 1996:71; Scognamiglio, 2002: 54), the *pilae* at Puteoli (at least down to sealevel; Döring 2003: fig. 11), and the mole at Ponza (Gianfrotta, 2002: 71–3, figs. 5, 7). It is likely that this facing, invisible beneath the waves, was an attempt to protect the internal conglomeratic concrete core from erosion, but how the Romans laid the masonry in regular patterns underwater is not clear. Gianfrotta suggests

*Table A3.16: BAI.2006.03 drill core summary.*

| Depth | Description |
|---|---|
| 0.0 to -2.90 m | A very uniform, compact, complete concrete core. The mortar contains abundant relict lime clasts varying in size (D 0.003 m to D 0.008 m), and one atypical specimen (D 0.014 m by 0.026 m). There are common light grey (N6) and pale orangish-grey (10YR 8/4) pumice fragments (D 0.0005 m to 0.03 m) and common lava lithic fragments, a component of Flegrean volcanic ash. The *caementa* are pale yellow (2.5Y 7/3, dry), pumiceous Flegrean tuff, in rather small chunks (0.05 m to 0.14 m). Towards the top of core the tuff becomes a dark greenish-blue or greenish brown (2.5Y 6/6). |
| 2.90 to -3.15 m | Fragmentation of the concrete during coring. |

*Fig. A3.34: BAI.2006.03. Overview of sea-water saturated core, with pumiceous tuff* caementa *and mortar with relict lime clasts. Scale bar is 10 cm.*

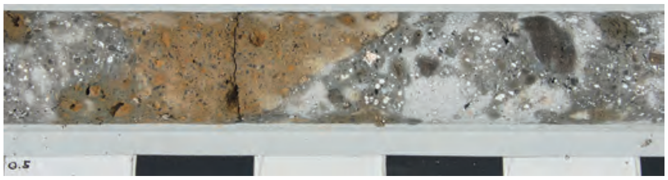

*Fig. A3.35: BAI.2006.03. detail -0.50 to -1.02 m. Pumiceous tuff, and mortar with relict lime clasts.*

*Fig. A3.36: BAI.2006.03. detail -1.90 to -1.98 m. Mortar with yellowish-gray and moderate gray pumice and glass fragments, and relict lime clasts.*

that the *pilae* with such facing were cast within a double walled cofferdam that had been pumped dry, but the practical difficulties of achieving this to a depth of 6 m in the open sea with the pumps then available seem insuperable. See the discussion on pp. 20–23, 208.

***BAI.2006.03.*** Taken 8 September 2006 from the top surface of a well-preserved *pila* toward the centre of the Secca Fumosa group (UTM 4519491). The top surface of the *pila* was at 3.45 m bsl, and it stood 5.7 m high on the seabed. The *pila* was approximately square in plan, with sides 9.9 m, 10 m, 10.4 m, and 10.3 m wide (Figs. 4.33–34). There was clear evidence of an *opus reticulatum* finish on the southern face at a depth of 6 m (Fig. 8.2). The *pila* was cast in the sea, but it is unclear to what height the water originally reached. The depth of the core hole was 3.15 m, and core recovered was L 2.90 m (92% recovery). There were no gaps in the core recovered, but loss occurred through grinding at the bottom. The coring had to be terminated because of equipment problems before reaching the base of the pier.

*Description:* A coherent and well consolidated concrete, consisting of a pumiceous mortar with a nearly white (10YR 8/1) cementitious matrix (Table A3.16; Figs. A3.34–36). The uniformly sized and regularly spaced pumiceous tuff *caementa* are shown to be Flegrean in origin through geochemical studies, and the pumiceous volcanic ash is also likely Flegrean in origin. See pp. 254–65 for a summary of material characteristics.

## A3.8. Portus Iulius, modern Porto di Giulio, Bay of Pozzuoli, 2.2 km W of Pozzuoli (Campania, Italy)

The concrete moles defining the entrance channel leading into the harbour basins of *Portus Iulius* are similar in design to those at Baiae, although much larger. Agrippa built the harbour facilities around 37 BC (Brandon *et al.* 2008). They are more than 220 m long, between 20 m and 30 m wide, and define a channel width of 40 m (Fig. 4.34). The ends of the moles are defined by a series of large *pilae*, six on the port side (as one enters the harbour) and one on the starboard (Figs. 6.47–49). Concrete samples come from both entrance channel moles and the outer *pila* on the port side. The concrete surfaces had been greatly eroded and the structure fractured. At the site of BAI.2006.02 on the port side mole and the site of BAI.2006.05 on the starboard side mole, the concrete was only 1.5 to

1.6 m thick. In contrast, the outer *pila* cored as BAI.2006.04 has lateral dimensions of 10 m, 10 m, 11.1 m, and 9.6 m and an overall height of over 6 m; the upper surface is at a depth of 3.8 m bsl. A 1.5 m long sample, BAI.2006.04, was extracted from the top, inset section.

***BAI.2006.02.*** Taken 7 September 2006 from a point halfway along the exposed portion of the port side mole of Portus Iulius (UTM 4519891). The top surface of the mole was at 3.9 m bsl, and it stood 1.6 m above the present seabed. Given the function of the mole to provide a calm entrance to the harbour basin, it is very likely to have been constructed in the sea, and the upper surface probably stood about 1.0 m above ancient sea level. The depth of the core hole was 1.6 m, and core recovered was L 1.2 m (75% recovery). There were several gaps in the core, but the portion from -0.40 to -1.10 m was intact.

*Description:* A relatively coherent and consolidated concrete, consisting of a pumiceous mortar with a light brownish white (5YR 7/1) cementitious matrix and regularly spaced pumiceous Flegrean tuff *caementa* (Table A3.17; Fig. A3.37). See pp. 264–65 for a summary of material characteristics.

***BAI.2006.04.*** Taken 9 September 2006 from a *pila* off the termination of the solid portion of the port side mole at Portus Iulius (UTM 4519821). The top surface of the mole was at 3.5 m bsl, and it stood 1.0 m above the present seabed. Given

*Table A3.17: BAI.2006.02 drill core summary.*

| **Depth** | **Description** |
|---|---|
| 0.0 to -0.40 m | The *caementa* are pale yellow (2.5Y 7/3, dry), presumably pumiceous Flegrean tuff, in rather small chunks (D 0.05 m to 0.10 m), but the surrounding mortar was lost through grinding. |
| -0.40 to -1.10 m | Very porous concrete with a light brownish-white mortar that appears somewhat poor in lime overall. There are only occasional relict lime clasts. The volcanic pozzolan has a granular aspect (D 0.02 m to 0.04 m). Large *caementa* of presumably Flegrean tuff vary in colour from pale yellow to dark olive grey (2.5Y 7/3 to 5Y 5/2). |
| -0.70 and -1.0 m | Twigs or basketry fragments (D 0.004 m to 0.005 m). |

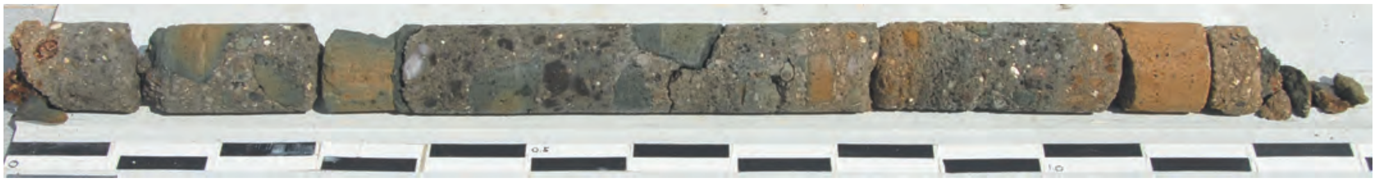

*Fig. A3.37: BAI.2006.02. Overview of sea-water saturated core with abundant weathered pumiceous tuff* caementa*. Scale bar is 10 cm.*

*Table A3.18: BAI.2006.04 drill core summary.*

| **Depth** | **Description** |
|---|---|
| 0.0 to -1.63 m | A porous concrete. The light grey (5YR 7/1) to nearly white (N8 to N9) mortar in the upper part of the core appears to have washed away, exposing the volcanic pozzolan with common light greenish grey (5GY 6/1) pumice fragments. There are occasional relict lime clasts, irregular in size (D 0.002 m to 0.02 m). Very large, irregular *caementa* (L 0.10 m, 0.50 m, 0.70 m) of pale yellow (2.5Y 7/3, dry) pumiceous presumably Flegrean tuff, with a fine grained altered vitric matrix. The *caementa* in the upper part of core have turned greenish grey (Gley Chart 1, 6/10GY), and one piece at depth has a blue green perimeter and pale yellow interior. |
| -0.80 m | Fragment of twig or basket.. |
| -1.50 to -1.63 m | Tuff *caementa* at the base of the recovered core have a bluish-green colour. Fragment of twig or basket. |
| -1.63 to 2.83 m | This portion of the core was cut but not recovered; the texture was too loose to allow the core-grabber to hold it. |

*Fig. A3.38: BAI.2006.04. Overview of sea-water saturated core with abundant weathered pumiceous tuff* caementa*.*

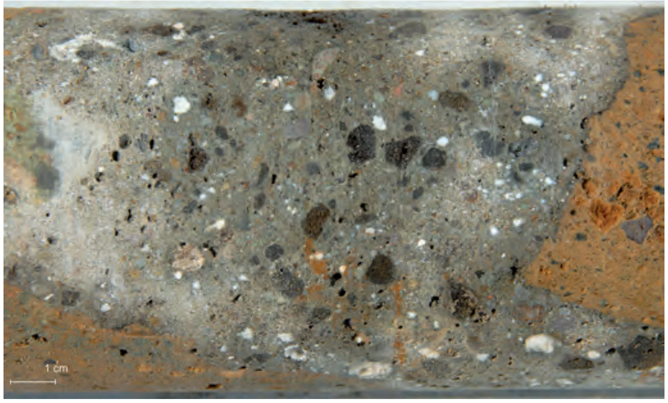

*Fig. A3.39: BAI.2006.04, detail -1.20 to -1.35 m. Sea-water saturated mortar and pumiceous tuff* caementa.

*Fig. A3.40: BAI.2006.05, detail -0.40 to -0.50 m. Sea-water saturated mortar and pumiceous tuff* caementa *with blue-green alteration in interfacial zones.*

its function, the mole was most likely constructed in the sea, with the crest probably standing 1.0 m above the water. The depth of the core hole was 2.83 m, and the core recovered was L 1.63 (58% recovery). The core bit worked its way through the *pila* very quickly, because the concrete was quite porous and poorly consolidated. As a consequence of its loose texture, the lowermost 1.2 m of core disaggregated and slipped out of the core-catcher's grasp, and was not recovered. It is possible that there was a beam hole nearby, allowing ingress of sea-water into the concrete, and this contributed to the erosion and disaggregation of the adjacent concrete. A fragment of wood from the formwork in which this *pila* was laid yielded a $^{14}$C date of 2060 ± 40 (Calendric Age of BC 87 ± 58), a date congruent with the historical evidence of 37 BC for the beginning of the construction of the port facilities (Suetonius, *Aug.* 16).

*Description:* A porous and poorly consolidated concrete, consisting of a partially disaggregated pumiceous mortar with a light grey to nearly white cementitious matrix, and regularly spaced pumiceous tuff *caementa* (Table A3.18; Fig. A3.39). See below for a summary of material characteristics.

***BAI.2006.05***. Taken 10 September 2006 from a relatively well preserved section of the starboard mole of Portus Iulius (UTM 4519992). The top surface of the mole was at 4.0 m bsl, 1.0 m above the seabed. Given the function of the mole to provide a calm entrance into the harbour basin, it is very likely to have been constructed in the sea, and the upper surface probably stood about 1.0 m above ancient sea level. The depth of the core hole was 1.50 m, and the core recovered was L 1.10 (69 % recovery), in several discontinuous fragments.

*Description:* A somewhat porous but well consolidated concrete, consisting of a coherent pumiceous mortar with a light olive grey to olive grey (5Y 6/2 to 5/2) cementitious matrix and regularly spaced pumiceous tuff *caementa* (Table A3.19; Fig. A3.40). See below for a summary of material characteristics.

*Summary of material characteristics of Pozzuoli Bay harbour structures.*

*Mortar to coarse rubble aggregate (caementa) ratio, as volume %:* BAI.2006.01, 72/28 (2.5 to 1 ratio). BAI.2006.02, 67/33 (2 to 1 ratio). BAI.2006.03, 64/36 (1.8 to 1 ratio). BAI.2006.04, 61/39 (1.6 to 1 ratio). BAI.2006.05, 60/40 (1.5 to 1 ratio).

*Coarse rubble aggregate (caementa):* Mineralogical and geochemical analyses (Tables A4.1, A4.2) suggest that the light yellowish brown vitric-crystal tuff *caementa* originate from the Flegrean Fields volcanic district. The primary volcanic crystal fragments are sanidine and analcite. Alteration phases – clay mineral (illite), and zeolites (phillipsite, chabazite) – likely developed in the geologic deposit, but hydrotalcite possibly developed in the concrete (Vola *et al.* 2010a). The results of trace element analyses for the tuff in the BAI.06.03 core (BAI.06.03.T1) suggest a Flegrean origin, possibly from the Bacoli Tuff (Figs. 7.10–11).

*Mortar pozzolan:* Yellowish grey and pale greyish orange pumiceous volcanic ash with common sanidine and clinopyroxene crystal fragments occurs as mortar pozzolan in all five concrete cores. Tuff clasts up to 0.03 m diameter are also distributed through the mortars. Three pale greyish-orange (10YR 8/4 to 7/4) pumice specimens (BAI.2006.01.P1, BAI.06.03.P2, BAI.06.05B.P1), and a light medium grey (N6) glassy pumice specimen (BAI.2006.03.P3) fall in the compositional range of pumice deposits in the Campi Flegrei volcanic district (Fig. 7.12; Table A4.3). A light medium grey to olive grey (N6 to 5Y 6/1) pumice specimen (BAI.2006.05.P2) has a mineralogical assemblage and trace element ratios that fall in the range of Vesuvian pumice compositions, but cannot be identified with any specific eruptive unit (Fig. 7.13).

*Lime/limestone source:* The low MgO content of the mortar and relict lime clasts (Figs. 7.15, 7.16) suggests lime calcined from a nearly pure limestone source was transported to the Bay of Pozzuoli, perhaps from the limestone bedrock of the

*Table A3.19: BAI.2006.05 drill core summary.*

| Depth | Description |
|---|---|
| 0.0 to -0.8 m | A somewhat porous concrete. The mortar in section 0.0 to -0.5 appears to have a low proportion of lime; there are small vitric tuff clasts (up to D 0.05 m) and common light olive grey (5GY 6/1) pumice fragments (D 0.01 m). White inclusions occur mainly as uniform, sub-rounded relict lime clasts (D *ca.* 0.003 to 0.005 m) except for one large particle (D 0.02 by 0.03 m). The mortar is greenish grey to dark greenish grey (Gley 1 6/10Y to 5/10Y) in the uppermost 0.02 m and the lowermost 0.03 m of the core, and light olive grey to olive grey (5Y 6/2 to 5Y 5/2) in center of the core. The mortar coheres well with the presumably Flegrean tuff *caementa*, and light olive brown (2.5Y 5/3 to 5/4) and olive yellow pumice fragments (2.5Y 6/6). In the uppermost and lowermost sections the tuff has turned dark greenish grey (about Gley 1, 4/1 10Y). |
| -0.5 to -0.75 m | One large chunk of tuff *caementa* occupied the entire diameter of the core. |
| -0.75 to -1.10 m | The mortar was lost to grinding, but chunks of tuff with grinding marks survive. |

Sorrento Peninsula about 35 km to the south (Fig. 7.2), or alternatively from the central Italian coast.

*Mortar fabric:* A porous light grey to nearly white cementitious matrix includes fine relict volcanic ash particles and lime clasts that are nearly wholly dissolved. Poorly crystalline calcium-aluminium-silicate-hydrate (C-A-S-H), appears to be the principal binding component. The bulk compositions of the mortars from all three harbour sites, Portus Baianus, Baianus Sinus, and Portus Iulius, are similar to those of other harbours along the central Italian coast with $CaO/(Al_2O_3+SiO_2)$=0.26 and 0.31, respectively, and $Al_2O_3+SiO_2$=0.0.56 and 0.60 weight % (Fig. 7.16; Tables A4.2–A4.3). The very low MgO content, 0.93 and 1.78 weight % suggests a nearly pure limestone source for lime. Tuff and pumice particles form 21 to 29 volume % of the mortars, based on point counts of thin sections (Vola *et al.* 2010a, Rispoli 2011). A cementitious matrix containing sparry calcite and C-A-S-H forms about 69 to 76 volume % of the mortars. Dull white inclusions of partially dissolved relict lime clasts, composed of calcite and Al-tobermorite, with associated vaterite, brucite, hydrocalumite (Table A4.1), form about 3 volume % of the mortar. The ratio of the relicts of pycroclastic pozzolanic particles to the cementitious binder is 2.4 for the BAI.06.01 specimen and 3.5 for the BAI.2006.05 specimen (Rispoli 2011).

*Concrete material properties:* The porosity ranges from 43 to 45% for the BAI.06.02 and BAI.03.03 mortars, 47% for the BAI.06.01 mortar, and 56 to 57% for the BAI.06.04 and BAI.06.05 mortars (Fig. 7.18; Table 7.4). The predominant void diameter ranges from 7 to 60 nm, seems to reflect the pore structure of the Flegrean pumiceous ash pozzolan. The unit weight of the BAI.06.03 concrete is 1494 $Kg/m^3$. The compressive strength, 7.4 MPa, falls within the upper range of strengths of the sea-water concretes from harbours along central Italian coast (Fig. 7.15; Table 7.3). These values and the relatively low porosity indicate a relatively compact, cohesive and well consolidated concrete.

## A3.9. Egnatia harbour, modern Torre Egnazia, 54 km Northwest of Brindisi (Puglia, Italy)

The harbour consisted of a shallow bay protected on the north and south by short concrete walls and *pilae* that appear to have been constructed on the local limestone and sandstone bedrock (pp. 93–94; Fig 4.40). The outer *pilae* are now all submerged well below sea level, but at the time of construction their upper surfaces presumably projected approximately 1.0 m above ancient sea level. The local fossiliferous wackestone from the Calcarenite di Gravina formation may be unsuitable for preparing lime. Perhaps the lime was calcined from Cretaceous marine limestones and dolomites a few kilometres inland. Although not well documented historically, the construction date could fall in the second or first centuries BC; the $^{14}C$ date noted below accords with this range.

***EGN.2008.01.*** Taken 15 May 2008 from the centre of the tallest *pila* near the north side of the ancient harbour (UTM 4529339). The top surface of the mole was at 3.5 m bsl, and it stood 2.0 m above the present seabed. Given the function of the mole to protect the otherwise exposed harbour basin, it is very likely to have been constructed in the sea. The depth of the core hole was 2.60 m, and the core recovered was L 2.60 m (100% recovery). Because of equipment problems, coring was stopped before the base of the block was reached.

*Description:* A somewhat well consolidated concrete with a coherent, porous, dark greenish grey mortar (Table A3.20; Figs. A3.41–42). The pale yellow limestone *caementa* vary greatly in size (D 0.035 to 0.60 m) and appear to have been placed at irregular intervals. The wood sample at -0.55 m was dated by Beta Analytic (no. 329099): 2120 ± 30 year BP, calibrated age 200 to 50 BC. The date range fits with the likely historical context of the later second to mid-first century BC, depending on the site of the wood chip in the growth rings of the tree and the time that elapsed between harvesting the tree and its incorporation in the concrete structure. Unlike several other Roman concrete structures in the harbour, this *pila* does

*Table A3.20: EGN.2008.01 drill core summary.*

| **Depth** | **Description** |
|---|---|
| 0.00 to -0.40 m | A somewhat well consolidated concrete with a coherent, porous mortar that is dark greenish grey, wet (Gley 1, 4/10Y); dry, light grey (Gley 1, 7/N). The pale yellow (wet: 2.5Y 8/2) limestone *caementa* vary greatly in size (D 0.035 to 0.60 m) and appear to have been placed at irregular intervals. There are pale yellowish-brown (10YR 6/3) and pale orangish-grey (10YR 8/4 to 7/4) pumice clasts, frequent relict lime clasts (up to D 0.015 but mainly D 0.005 m), and greenish black (Gley 1, 2.5/10Y) lava lithic fragments (up to D 0.044 m), and occasional orange to red potsherd fragments (D *ca.* 0.003 m) in the mortar. |
| -0.40 to -0.95 m | At -0.55 m, a wide sliver of wood traverses the whole core; two pieces were taken for $^{14}$C testing. |
| -0.95 to -1.45 m | One limestone *caementa* chunk occupies nearly the entire core for 0.5 m. |
| -1.45 to -2.20 m | Concrete with mortar and *caementa* as in uppermost core. |
| -2.20 to -2.40 m | Another large limestone *caementa* chunk, surrounded by mortar, occupies the core. |
| -2.40 to-2.60 m | Mortar alone, with no *caementa*. |

*Fig. A3.41: EGN.2008.01. Overview of sea-water saturated core, with calcareous sandstone* caementa*. Scale bar is 10 cm.*

*Fig. A3.42: EGN.2008.01, -1.91 to -2.18 m. Sea-water saturated calcareous sandstone* caementa *and pumiceous mortar with relict lime clasts.*

not have *opus reticulatum* facing, but consists entirely of conglomeratic concrete.

*Mortar to coarse rubble aggregate (*caementa*) ratio, as volume %:* EGN.2008.01 55/45 (1.2 to 1 ratio).

*Coarse rubble aggregate (*caementa*):* The *caementa* are large chunks of very pale yellow, porous fossiliferous wackestone, the local Pliocene-Pleistocene "Calcarenite di Gravina" formation, which was used as building stone throughout the city (Cassano 2009; Calia *et al.* 2011). These are mainly composed of calcite, with traces of aragonite, halite, and ettringite (Table A4.1), suggesting that crystallization of salts occurred in pores of the rock while submerged in sea-water.

*Mortar pozzolan:* Pale yellowish-brown pumiceous volcanic ash with sanidine crystal fragments is the predominant pozzolan; ceramic fragments are also present. A few specimens contain small amounts of quartz sand. Pumice clasts have sanidine crystals, and authigenic illite, phillipsite and chabazite; nontronite likely formed in the sea-water concrete environment (Table A4.1). A pale orangish-grey (10YR 8/4 to 7/4) powdered pumice specimen (EGN.2008.01.P1) and a pale yellowish-grey (10YR 6/3) powdered pumice specimen (EGN.2008.02.P2) have a nearly identical mineral assemblage and trace element composition that fall within the general range of Somma-Vesuvius compositions, but cannot be identified with a specific eruptive unit (Figs. 7.12–13; Table A4.2).

*Lime/limestone source:* Lime for the mortar preparation was possibly calcined from the succession of Cretaceous carbonate rocks, composed of limestones and dolomites, the "Calcare di Bari" (Calia *et al.* 2011), that crop out a few kilometres inland from the ancient harbour site. Seven mortar specimens have bulk compositions with very low MgO, about 1 weight %, suggesting lime calcined from a nearly pure limestone source. (Fig. 7.16; Tables A4.2, A4.3) Three specimens, however, have higher MgO, about 4 to 6 weight %. This could possibly derive from the presence of ceramic fragments or, alternatively, a more dolomitic limestone source.

*Mortar fabric:* The porous mortar has a granular aspect and is strongly enriched in volcanic pozzolan, about 31 to 32 volume % based on a point count of a thin section (Table 7.1), consisting of pumiceous ash, vitric tuff with pumiceous glass fragments, sanidine crystal fragments, and authigenic analcite, illite, and phillipsite and chabazite (Vola *et al.* 2010a, Stanislao 2011). Poorly crystalline calcium-aluminium-silicate-hydrate (C-A-S-H) is the principal binding component. Alteration to microcrystalline sparry calcite forms 10 to 11 volume % of the mortar, and local carbonate rock fragments and rare dull grains of relict lime each form about 1%. X-ray diffraction analyses of the mortar (Table A4.1) indicate that the crystalline components of the cementitious matrix are Al-tobermorite and ettringite, and lesser amounts of gypsum, halite, and bassanite,

*Table A3.21: BRI.2005.01 drill core summary.*

| **Depth** | **Description** |
|---|---|
| 0.0 to -0.06 m | Paving stone. |
| -0.06 to -1.75 m | Compact concrete; homogeneous mortar that is greenish grey when wet (Gley 1, 6/10Y), and off-white when dry (Gley 1, 8/N). The mix has a uniform appearance with common yellow orange (10YR 7/6) pumice fragments, occasional small lime putty inclusions (D 0.02 to 0.03 m), and very few voids. The pumiceous tuff *caementa* from Bacoli quarry are olive coloured when wet (5Y 5.3), light olive brown when dry (2.5Y 5/3 to 2.5Y 5/4) and have olive yellow pumice fragments (2.5Y 6/8). |
| 0.0 to -0.45 m | Two *caementa* occupy nearly the whole core. |
| -0.45 to -0.95 m | The core is composed almost entirely of mortar. |
| -0.95 to -1.10 m | Two *caementa* occupy nearly the entire core. |
| -1.10 to -1.75 | The core is composed almost entirely of mortar. |

*Fig. A3.43: BRI.2005.01. Overview of core, experimental concrete reproduction after six months hydration in sea-water. Scale bar is 10 cm.*

a hydrated calcium sulfate mineral. There is a relatively low cementitious binder to pozzolanic aggregate ratio, 1.7. The millimetre-scale porosity is very high, 5 to 7%, and, overall, there seems to a higher level of sulfate crystallization in both the mortar and the porous limestone *caementa*, than in any of the other concretes (Stanislao *et al.* 2011). The bulk composition of the mortar has CaO/($Al_2O_3$+$SiO_2$)=0.27 and $Al_2O_3$+$SiO_2$=0.47 weight %, similar to the concretes of the central Italian coast (Fig. 7.16). The pumiceous pozzolan may possibly derive from the Gulf of Naples volcanic district, based on the mineralogical assemblage and trace element ratios of pumice clasts (Figs. 7.11–13; Tables A4.2, A4.3).

*Concrete fabric and material properties:* The mortar porosity was not measured. The concrete has the lowest unit weight, 1263 Kg/m³ and 1348 Kg/m³, and compressive strength, 2.4 MPa and 2.7 MPa, of any of the ancient specimens (Fig. 7.18; Table 7.3). One specimen has higher unit weight and strength, 1497 Kg/m³ and 7.1 MPa.

## A3.10. Seno di Ponente, harbour of Brindisi, reproduction *pila*, Brindisi (Puglia, Italy)

The ROMACONS team built a *pila* according to Vitruvian specifications for materials and formwork in the harbour of Brindisi between 13 and 21 September 2004 (see Chapter 5). The *pila* was located near the marine testing station of the CTG Italcementi Group, at the Brindisi branch of the Lega Navale, an Italian yachting association, in the Sino de Ponente of the harbour (UTM 4503327; Fig. 5.1). The depth of the water was *ca.* 1.65 m at this point, and the upper surface of the *pila* stood at 0.10 m asl. Cores were taken on five subsequent occasions by the same method used for the ancient concrete structures: 19 March 2005, 17 November 2005, 22 November 2006, 14 May 2008, and sometime in November 2009. No signs of day joints were observed in any of the cores, even though the concrete was placed over a period seven days, with a hiatus every night.

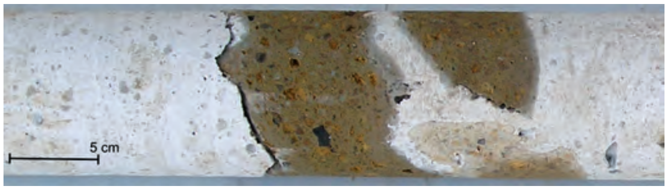

*Fig. A3.44: BRI.2005.01, detail -0.80 to -1.15 m. Pumiceous Bacoli Tuff and experimental mortar reproduction after six months hydration in sea-water.*

***BRI.2005.01.*** Taken 19 March 2005 near the western edge of the *pila* (UTM 4503327; Table A3.21; Figs. A3.43–44. The depth of the core hole was 1.75 m, and the core recovered was L 1.75 m (100% recovery).

***BRI.2005.02.*** Taken 17 November 2005 close to the centre of the *pila* (UTM 4503327; Table A3.22; Figs. A3.45–46). The depth of the core hole was 1.65 m, and the core recovered was L 1.65 m (100% recovery).

***BRI.2006.01.*** Taken 22 November 2006 from the northeastern corner of the *pila* (UTM 4503327; Table A3.23; Fig. A3.47). The depth of the core hole was 1.0 m, and the core recovered was L 0.80 m (80% recovery).

*Table A3.22: BRI.2005.02, drill core summary.*

| Depth | Description |
|---|---|
| 0.0 to -0.06 m | Paving stone. |
| -0.06 to -1.65 m | A compact concrete with a homogeneous light grey mortar. There are common pumice fragments, occasional small lime inclusions (D 0.02 to 0.03 m), and occasional voids up to D 0.010 m. The pumiceous tuff *caementa* from Bacoli appear similar to BRI.2005.01, with little macroscopic alteration. |

*Fig. A3.45: BRI.2005.02. Overview of core, experimental concrete reproduction after twelve months hydration in sea-water. Scale bar is 10 cm.*

*Table A3.23: BRI.2006.01 drill core summary.*

| Depth | Description |
|---|---|
| 0.0 to -0.06 m | Paving stone. |
| -0.06 to -0.80 m | A compact concrete with a homogeneous light grey mortar. There are common pumice fragments, occasional small lime inclusions (D 0.02 to 0.03 m), and occasional voids up to D 0.010 m. The pumiceous tuff *caementa* from Bacoli appear similar to BRI.2005.01, with little macroscopic alteration. |

*Fig. A3.46: BRI.2005.02, detail -1.27 to -1.53 m. Experimental concrete reproduction at 12 months hydration in sea-water, showing compaction flaws and a single relict lime clast in the hydrated lime putty – Bacoli volcanic ash mortar.*

*Fig. A3.47: BRI.2006.01. Overview of core, sea-water-soaked experimental concrete reproduction after twenty-four months hydration in sea-water.*

***BRI.2008.01.*** Taken 14 May 2008 0.50 m in from the east side of the *pila* (UTM 4503327; Table A3.24; Figs. A3.48–50). The depth of the core hole was 1.75 m, and the core recovered was L 1.75 m (100% recovery). The mortar was very compact, but the sample seems light in aggregate.

***BRI.2009.01.*** Taken during November 2009. There are few records of this coring session, which was carried out in the absence of the ROMACONS team by local staff at the nearby CTG Italcementi warehouse. The depth of the core hole was 1.0 m, and the core recovered was L 1.0 m (100% recovery). The macroscopic appearance of this core is quite similar to the four earlier Brindisi cores (Fig. 7.6f). The core was subjected to analysis at the CTG Italcementi Laboratory in Bergamo, and the results have been incorporated into the data concerning the other Brindisi cores (see Chapter 7).

*Mortar to coarse rubble aggregate (*caementa*) ratio, as volume %:* BRI.2005.01, 67/33 (2 to 1 ratio). BRI.2005.02, 76/24 (3.1 to 1 ratio). BRI.2006.01, 77/23 (3.3 to 1 ratio). BRI.2008.01, 72/28 (2.6 to 1 ratio). BRI.2009.01, undetermined.

*Coarse rubble aggregate (*caementa*):* The mineral assemblage of the Bacoli Tuff used in the Brindisi concrete reproduction has primary volcanic sanidine crystals, and authigenic analcite, illite, phillipsite and chabazite (Table A4.1). The major and trace element compositions of two powdered pumice specimens of the Bacoli Tuff, taken at 6 months and 12 months hydration, respectively (BRI.2005.02.T1, BAI.2006.01.T1) are nearly identical (Figs. 7.10–11; Table A4.2) and provide a reference for the volcanic provenance of the tuff *caementa* in the ancient maritime concretes.

*Mortar pozzolan:* The volcanic pozzolan supplied for the *pila* experiment in Brindisi comes from poorly consolidated deposits of pumiceous ash near Bacoli; this is the "pozzolana" used in the classic experiments of Sersale and Orsini (1969) and Massazza and Costa (1974). The ash has the same

Table A3.24: BRI.2008.01 drill core summary.

| Depth | Description |
|---|---|
| 0.0 to -0.06 m | Paving stone. |
| -0.06 to -0.13 m | Pumiceous tuff *caementa* from Bacoli, appear similar to BRI.2005.01, with little macroscopic alteration. |
| -0.13 to -0.70 m | A compact, homogeneous mortar that is greenish grey when wet (Gley 1, 6/10Y), and off-white when dry (Gley 1, 8/N), with a few small (D 0.03 m) particles of tuff near the top. The mix is very uniform, with a few lime inclusions here and there (D 0.02 to 0.03 m). The absence of *caementa* indicates irregular placement during construction. |
| -0.70 to -0.86 m | A compact concrete, but with deep voids at -0.70 to -0.75 m (D 0.004 m, 0.005 m, 0.006 m, 0.017 m); other such voids appear at -1.10 to -1.20 m. |
| -0.86 to -1.08 m | Mortar with infrequent tuff *caementa*. |
| -1.08 to -1.60 m | Compact concrete as above. A few voids are visible in the mortar at -1.10 to -1.20 m. |
| -1.60 to -1.76 m | Mortar with foundation sand adhering to bottom surface. |

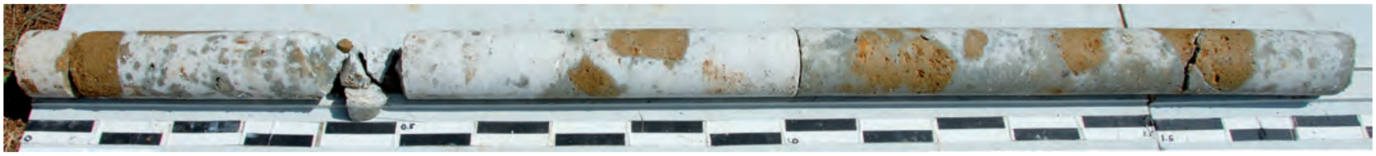

*Fig. A3.48: BRI.2008.01. Overview, experimental concrete reproduction after forty-eight months hydration in sea-water. Scale bar is 10 cm.*

mineralogical composition as the tuff, with sanidine crystal fragments. Larger pumice fragments floated to the surface of the water in the form during placement of the mortar.

*Mortar fabric and cementitious matrix:* The mortar shows discrete centimetre-scale zones of lime putty with variable proportions of volcanic ash pozzolan. The agglomerations are separated by selvages composed of vitric ash particles that became progressively more altered and opaque over time (Fig. 7.14). The principal cementitious binder of the young mortars is poorly crystalline C-A-S-H, similar to the ancient mortars, but no Al-tobermorite has been detected in the young reproduction (Table A4.1). The 2008 specimens, taken at four years hydration, show crystallization of zeolite, detected petrographically and with X-ray diffraction analyses (Table A4.1). This seems to reflect dissolution of the highly potassic volcanic glass and *in situ* crystallization of phillipsite in micropores of the concrete. The bulk compositions of mortar specimens as CaO+MgO vs. $Al_2O_3$+$SiO_2$ show a range of compositions, suggesting heterogenous cementitious processes in both time and space within the 2 m$^3$ *pila* (Fig. 7.17).

*Concrete fabric and material properties:* The porosity of the reproduction mortar decreases over two years of hydration in the pila (Fig. 7.18; Table 7.4). It ranges from 63% and 57% in specimens from the base and top of the BRI.2005.01 concrete at six months hydration, to 51% and 57% at the base and top of the BRI.2005.02 concrete at one year hydration, and 53% in the BRI.2006.01 concrete at two years hydration. The porosity of the BRI.2008.01and BRI.2009.01 concretes, cored at four and five years hydration, was not measured.

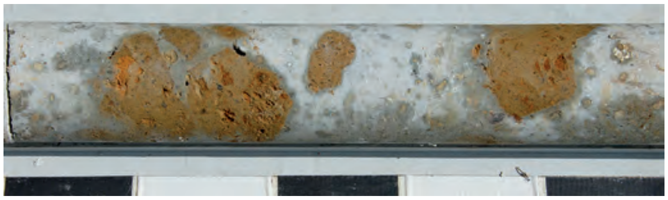

*Fig. A3.49: BRI.2008.01, detail -0.65 to -0.83 m. Pumiceous Bacoli tuff and experimental mortar reproduction after forty-eight months hydration in sea-water.*

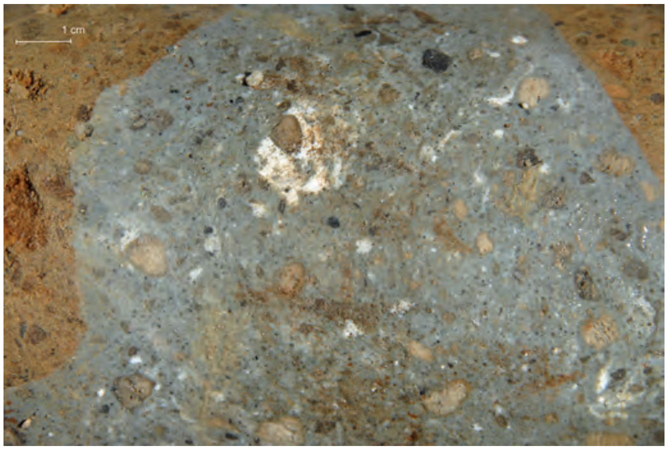

*Fig. A3.50: BRI.2008.01, detail -1.48 to -1.53 m. Experimental concrete reproduction at forty-eight months hydration in sea-water shows yellowish-gray Bacoli ash pumiceous pozzolan, and a clot of lime putty mixed with pumiceous ash.*

The unit weights of the BRI.2005.01 mortars at six months hydration range from 1390 Kg/m$^3$ in the mid-section of the core, 1415 Kg/m$^3$ at the base, and 1530 Kg/m$^3$ at the top, and compressive strengths range, respectively, from 3.9 MPa, to 3.5 MPa, and 7.0 MPa (Fig. 7.18, Table 7.3). It is not clear why the specimen at the top of the core has such high strength. At one year hydration, the unit weight and compressive strength of specimens from the base and the top of the BRI.2005.02 core are relatively uniform, 1398 Kg/m$^3$ and 5.6 MPa, and 1369 Kg/m$^3$ and 4.5 MPa, respectively. At 24 months hydration, the BRI.2006.01 concrete has similar unit weight and strength, 1343 Kg/m$^3$ and 6.2 MPa. Curiously, the BRI.2008.01 core obtained at four years hydration has far lower average unit weight and strength, 1043 Kg/m$^3$ and 3.35 MPa. The BRI.2009.01 core has equivalent unit weight and compressive strength relative to the 2006 values: 1314 to 1377 Kg/m$^3$ and 4.0 to 6.8 MPa.

## A3.11. Chersonesos harbour, modern Limenas Chersonisou, 25 km E of Heraklion (Crete, Greece)

The natural harbour basin on the north coast of Crete is poorly protected by a natural limestone ridge on the southwest, and was improved during the first century BC or first century AD with a concrete mole and *pilae* on the east (pp. 89–93; Fig. 4.38). Toward the shore the mole was founded on limestone bedrock; seaward it appears to be founded on boulders. The lower sections of the concrete structures were most likely constructed below sea level, while the upper surfaces were intended to project slightly above sea level. The local bedrock is a complex sequence of recent limestone deposits, and the island of Crete is known to have been well forested in antiquity (Strabo 10.4.4), so lime could have been prepared locally.

***CHR.2007.01.*** Taken 11 September 2007 from the second to last *pila* at the tip of the mole (UTM 3909741). The top of the pier was 0.20 m bsl. The depth of the core hole was 1.90 m, and the core recovered was L 1.20 m, but very fragmented, with much loss of mortar (63% recovery), making it impossible to provide a detailed visual analysis.

*Description:* A porous, poorly consolidated mortar with *caementa* consisting of fragments of the pale yellow local limestone (Table A3.25). The fragments were mostly *caementa*, and less than D 0.12 m. There is poor adhesion between mortar and *caementa*, and the longest intact mortar section is L 0.10 m.

***CHR.2007.02.*** Taken 12 September 2007 from a platform of concrete at the base of the mole, adjacent to the present shoreline, 0.20 m asl (UTM 3909705). The depth of the core hole was 1.52 m, and the core recovered was L 1.49 m (98% recovery).

*Description:* Very porous, poorly consolidated mortar (Table A3.26; Figs. A3.51–51). The local limestone *caementa* are very irregular in size, shape, and distribution.

*Mortar to coarse rubble aggregate (*caementa*) ratio, as volume %:* CHR.2007.01 (undetermined, poor core recovery). CHR.2007.02 74/26 (2.8 to 1 ratio).

*Coarse rubble aggregate (*caementa*):* Although there are occasional *caementa* of yellowish-grey pumiceous tuff, the predominant coarse aggregate seems to be hard Miocene-Pliocene carbonate rocks of the Chersonesos stratigraphic succession (Frydas and Bellas 2009). The porous, fossiliferous wackestone *caementa* are composed of both calcite and dolomite, and contain abundant halite, and lesser amounts of brucite and philipsite. These minerals indicate crystallization of salt in the porous limestone, possible magnesium attack to form brucite and, perhaps, migration of potassium to form phillipsite.

*Lime/limestone source:* The earthy character of the Chersonesos mortar suggests that the marly limestone deposits that crop out near the harbour site could have been calcined to produce an argillaceous lime, or that this is simply a poorly calcined, less cohesive lime. Nodules of poorly calcined limestone and lignite particles (Vola *et al.* 2010, 2011c; Stanislao 2011) may also derive from these deposits.

*Mortar pozzolan:* The pumiceous ash pozzolan has primary sanidine crystal fragments, and authigenic illlite, phillipsite and chabazite; nontronite likely formed in the sea-water concrete environment (Table A4.1). This is the same mineral assemblage as the pumiceous pozzolan at Egnazia and Pomepeiopolis, and there are geochemical similarities, as well. A pale yellow orange (10YR 7/6) powdered pumice specimen (CHR.2007.02.P2) and a medium yellowish orange (10YR 6/6 to 10YR 7/6) powdered pumice specimen (CHR.07.02.P2) have mineral assemblage and trace element compositions that fall within the range of Somma-Vesuvius compositions, but cannot be identified with a specific eruptive unit (Fig. 7.13; Table A4.2).

*Mortar fabric:* The porous mortar is poorly cohesive and, in some specimens, easily disaggregates into granules of rock, ceramic, and crystals. A point count of a thin section (Table 7.1) indicates the mortar has a low relative proportion of pumiceous ash pozzolan, and that this contains sanidine crystal fragments and tuff clasts with relict zeolite textures, 15 to 17 volume % (Vola *et al.* 2010a, Stanislao 2011). There are reddened fragments of *cocciopesto*, up to 4 volume %, and small carbonate rock fragments, some with dolomitic compositions (Table A4.1). A complex cementitious matrix forms 71 to 73 volume % of the mortar; the mortar has about 48 to 59 volume % C-A-S-H binder and 14 to 22 volume % sparry calcite cement. There are rare dull grains of relict reacted lime, about 1 volume %. Al-tobermorite occurs as a crystalline cementitious phase in some specimens (Table A4.1). The mortar has high porosity at the millimetre scale, 5 to 8 volume %, and a high binder/aggregate ratio, 3.4%. The bulk composition of the mortar has wide ranging values of $Al_2O_3$+$SiO_2$, 19.7 to 50.5 weight %, and CaO+MgO, 19.16 to 39.33 weight %. CaO/($Al_2O_3$+$SiO_2$) also shows wide variability, 0.19 to 1.26, perhaps reflecting local concentrations of poorly calcined carbonate rock particles (Fig 7.16, Tables A4.2, A4.3)

*Table A3.25: CHR.2007.01 drill core summary.*

| **Depth** | **Description** |
|---|---|
| 0.0 to -1.20 m | A porous, poorly consolidated mortar that appears quite low in lime, either because of the original mix or loss through chemical action or erosion. There are clusters of white inclusions as relict lime clasts (D 0.002-0.004 m), fragments of reddish yellow (7.5 YR 6/6) tuff (up to D 0.028 m), occasional yellow (7.5 YR 7/8) pumice fragments, and common large voids (D 0.014 m, 0.016 m) where a crumbly black lignite has fallen out. The *caementa* are fragments of the pale yellow (10YR 8/6) local limestone. |
| -0.70 to -0.80 | Some mortar fragments are dark grey (N2), with small relict lime clasts. |

*Table A3.26: CHR.2007.02 drill core summary.*

| **Depth** | **Description** |
|---|---|
| 0.0 to -1.49 m | Very porous, poorly consolidated mortar, ranging from pink (7.5YR 8/4) near 0.0, to light yellowish brown (10YR 6/4) at -0.60 m, to light brownish grey (10YR 6/2) at the base. Contains common sub-angular reddish-yellow (7.5YR 6/8) tuff or pumiceous pozzolan (D 0.004 to 0.020 m). Many white inclusions, as relict lime clasts (up to D 0.02 m). Mortar on the surface of the core was roughened by grinding and loss of soft surface material. The local limestone *caementa* are very irregular in size (D 0.05 to 0.18 m), shape, and distribution. |
| 0 to -0.10 m | Infrequent *caementa.* |
| -0.30 to -0.60 m | Mortar contains sub-rounded black sand particles. Limestone *caementa* are very pale brown (10YR 8/3). |
| -0.60 to -1.05 m | Infrequent *caementa*. |
| -1.38 m | A distinct seam separates the poorly consolidated mortar above from a mass of dark crystalline rocks below. The core is composed of light greenish grey (Gley, 7/5BG) rounded pebbles, bound together by thin layers of a reddish yellow (7.5YR 8/6) carbonate material. It is not clear whether this is the cobble-rich natural substrate of a layer of pebbles stabilized by mortar. |

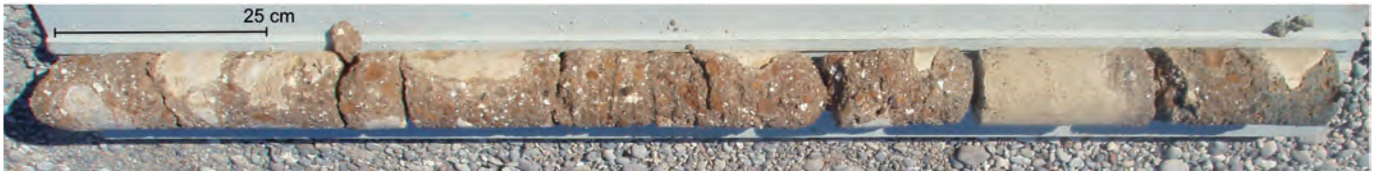

*Fig. A3.51: CHR.2007.02. Overview of core, limestone* caementa *and porous, earthy mortar with abundant pale orange pumiceous ash and tuff pozzolan.-0.40 to -0.65 m. Scale bar is 10 cm.*

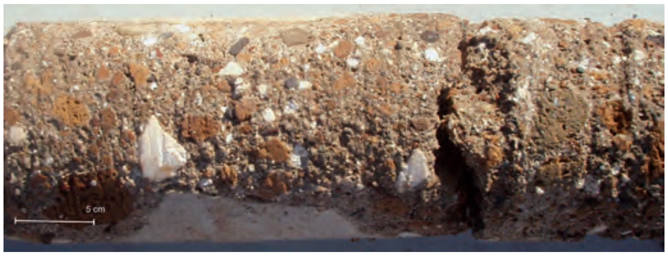

*Fig. A3.52: CHR.2007.02, -0.40 to -0.65 m. Porous mortar with a high proportion of pale orange pumiceous pozzolan, and angular fragments of poorly calcined limestone.*

MgO concentrations are the highest of all the concretes, 6.30 to 14.51 weight %, possibly the result of dolomitic lime, which is also recorded by X-ray diffraction studies (Table A4.1).

*Concrete fabric and material properties:* The measured porosity of the CHR.2007.02 mortar is 56% (Fig. 7.18; Table 7.4). Mechanical properties show wide variations (Fig. 7.18; Table 7.3). The top of the CHR.2007.02 core, which perhaps hydrated in sub-aerial conditions, has relatively high unit weight but low compressive strength, 1688 Kg/m$^3$ and 3.3 MPa. The mid-section of the core has higher unit weight and moderately high compressive strength, 1957 Kg/m$^3$

and 6.8 MPa. The basal section of the core, which hydrated continuously in sea-water, has very high unit weight, 2025 Kg/m$^3$, and the highest compressive strength, 11.9 MPa, of any of the ancient specimens. The high unit weight is likely the result of the contribution of the carbonate rock *caementa*.

## A3.12. Pompeiopolis harbour, modern Mezitli, 12 km SW of Icel, Turkey

The artificial harbour basin was most likely formed by bracketing the mouth of a small river with long, curving breakwaters to the east and west (pp. 95–105; Figs. 4.44, 4.53). Based on historical and numismatic evidence, the breakwaters that remain visible at present probably were constructed by Antoninus Pius (137 to 160) (Brandon *et al.* 2010a–b). The $^{14}$C analysis of wood taken from the POM.2009.02 core indicates a date of AD 147 ± 48, and supports this chronology. The cores were taken from the top surface of the western concrete breakwater (POM.2009.01), and from the lower layer of concrete exposed on the western edge of the western breakwater that were exposed by erosion of the upper layer (POM.2009.02). The mole was founded on the local argillaceous carbonate bedrock, which is visible as a low reef at the present seaward termination of the breakwater. Where preserved, the original upper surface of the mole is *ca.* 1.80 m asl, which is approximately its original relation to sea level. Where the carbonate rock reef was exposed subaerially, the mole was constructed of concrete with poorly consolidated mortar and smooth cobbles as *caementa*. It was installed in rectangular forms constructed of large blocks of the argillaeous limestone bedrock (Fig. 4.47). Where the reef was submerged below sealevel, a similar concrete was also installed in the argillaeceous limestone forms, but on top of a concrete base with a more typical lime-volcanic ash mortar and volcanic tuff *caementa*. This lowermost 0.50 m of the mole was presumably installed below sea level and has most likely remained inundated since construction. The river cobbles visible at the top surface of the structure and its exposed sides clearly were laid in place by hand, in orderly rows forming uniform layers. Where the conglomeratic concrete core is exposed subaerially, the poorly consolidated mortar has eroded from around the smooth cobbles, ultimately allowing them to dislodge from the concrete. Stanislao *et al.* (2011) describe the mineralogy and material characteristics of the concretes.

***POM.2009.01.*** Taken 13 August 2009 from a point 5 m from the seaward end of the exposed portion of the wide western breakwater, toward the west edge (UTM 4066968). The depth of the core hole was 4.44 m, and the core recovered was L 4.44 m (100% recovery).

*Description:* Compact concrete with a high proportion of closely packed smooth river cobbles as *caementa* (Table A3.27; Figs. A3.53–55).

***POM.2009.02.*** Taken 14 August 2009 from the western edge of the western breakwater at its approximate midpoint, in an area where the upper layer of cobble-rich concrete has been eroded away (UTM 4066974). The core site is at the top of a flat concrete surface 0.49 m asl, that lies within the argillaceous limestone blocks framing the upper part of the mole.

*Table A3.27: POM.2009.01 drill core summary.*

| **Depth** | **Description** |
|---|---|
| -0.0 to -0.75 m | The compact concrete consists of a smaller proportion of mortar, and a higher proportion of closely packed smooth river cobbles of stony coral and amphibolite as *caementa*. The mortar is with very pale brown (10YR 8/4) and fairly soft, brownish yellow (10YR 6/6) volcanic tuff and pumice fragments, clinopyroxene crystals, white relict lime clasts (D 0.04 to 0.08 m), travertine particles, and occasional ceramic fragments. There is a stratified layer across the core at -0.15 m. |
| -0.75 to -0.95 m | The mortar was mostly ground away by the coring at this point. Several hard *caementa* cobbles remain, and several pumice fragments (D 0.02 to 0.03 m). |
| -0.95 to -1.40 m | The mortar is a very light grey to white with common pumice fragments, and stony coral and amphibolite cobbles as *caementa*. The mortar pozzolan is similar to the upper section of the core. |
| -1.35 m | A sub-rounded fragment of light greenish brown (10YR 7/6) volcanic tuff, with yellow brown (2.5Y 7/4) pumice. Similar material occurs in POM 2009.02, There are common relict lime clasts (D < 0.08 m). |
| -1.40 to -2.20 m | The mortar is similar to the uppermost section, but poorly compacted with voids (D < 0.01 m). Nevertheless it is quite hard. It varies in colour from white to light green. There are common coarse relict lime and pumice clasts, and clinopyroxene crystals associated with the volcanic ash pozzolan (Stanislao *et al.* 2011). |
| -2.20-4.40 m | Yellowish-red to yellowish-pink argillaceous carbonate bedrock. There are no joints indicative of dimension stone, and the bedding layers dip at a low angle across the core. Very fine mud overlying the bedrock infiltrated the core hole each time the casings were removed.The mud partly filled the hole when the core tubes were removed the last time, so that the measured depth is less than the length of the core. |

*Fig. A3.53: POM.2009.01. Overview of core, pumiceous mortar and diverse* caementa *to the left (upper portion), and argillaceous carbonate bedrock on right. Scale bar is 10 cm.*

*Fig. A3.54: POM.2009.01, detail -1.47 to -2.0 m. Pumiceous mortar and diverse* caementa*: coral and amphibolite river cobbles and local travertine.*

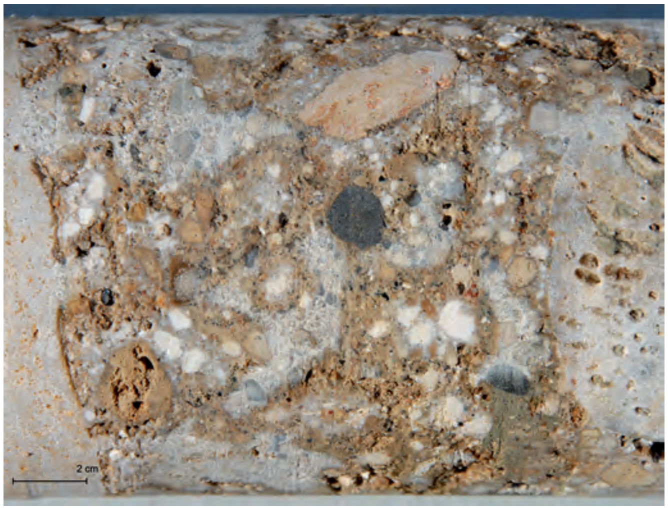

*Fig. A3.55: POM.2009.01, detail -1.55 to -1.65 m. Porous mortar with pale orangish-gray pumiceous ash pozzolan and relict lime clasts.*

*Description:* Compact concrete with a moderately well consolidated mortar containing abundant pumiceous volcanic pozzolan (Table A3.28; Figs. A3.56–57). The *caementa* include rounded limestone cobbles, and fewer pumiceous tuff fragments. The depth of the core hole in the concrete was 0.80 m, and the core recovered was L 0.80 m (100% recovery). The core tube penetrated another metre into what may have been a rubble foundation beneath the concrete. $^{14}$C analysis of a small fragment of wood and a reed or twig at -0.75 m depth provided a date of 1864 ± 28 BP, and a calibrated calendrical date of AD 147 ± 48 (OxA Sample no. 21197).

*Mortar to coarse rubble aggregate (*caementa*) ratio, as volume %:* POM.2009.01 36/64 (1.8 to 1 ratio). POM.2009.02 54/46 (1.2 to 1 ratio).

*Coarse rubble aggregate (*caementa*):* In the POM.2009.01 core, these are hard, closely-packed rounded river cobbles up to 0.2 m diameter composed of dark amphibolite and stony corals. In the POM.09.02 core, there are angular fragments of travertine from local quarries and decimetre-sized rubble of what appears to be the Neapolitan Yellow Tuff (Stanislao *et al.* 2011), with a fine-grained vitric ash matrix that incorporates pumice, lava lithic fragments, and sanidine and clinopyroxene crystal fragments.

*Lime/limestone source:* Modern quarries for Plio-Pleistocene travertine deposits occur several km north of Mersin. These rocks occur in the concretes as *caementa* and as pale yellow gravel-sized particles in the mortars, and they seem to have been calcined for lime, as well (Stanislao *et al.* 2011). The calcination of limestone was not always taken to completion, however, and there are common residual limestone particles, poorly reacted lime clusters, and poorly calcined local travertine particles in the mortar fabric.

*Mortar pozzolan:* In the POM.2009.01 core, the mortar contains particles of travertine and volcanic tuff fragments (D 0.004 to 0.018 m), and pale yellow, yellowish-brown, and light olive grey pumice particles. A light olive grey pumice specimen (POM.09.02/A.P1) has a mineralogical assemblage and trace element composition nearly identical to those of the yellowish-grey and pale-orange pumice specimens from the EGN.2008.01 core (Fig. 7.13; Table A4.2). These fall in the range of Vesuvian pumice compositions, but cannot be identified with any specific eruptive unit. In the POM.2009.02 the mortar contains the same pumiceous ash pozzolan, as well as particles of local travertine, stony corals, amphibolite rock, and pale yellow volcanic tuff.

*Mortar fabric and cementitious matrix:* In the POM.2009.01 core, the light brown mortar contains common white inclusions, and pale yellow to yellowish brown pumiceous particles

*Table A3.28: POM.2009.02 drill core summary.*

| **Depth** | **Description** |
|---|---|
| 0.0 to -0.80 m | A compact concrete with a moderately well consolidated mortar containing abundant pumiceous volcanic pozzolan. The upper portion is yellowish brown (10YR 5/6), drying to a very pale brown (10YR 7/4). There are common pumice fragments (D 0.011 to 0.018 m), angular relict lime clasts (D 0.002 to 0.01 m), some poorly calcined, and small spherical voids (D 0.001 to 0.003 m). The *caementa* include rounded limestone cobbles, and fewer pumiceous tuff fragments (D 0.023 to 0.053 m). Wet, the tuff is greenish blue, like the mortar, and dry it is light yellow brown (2.5Y 6/4). |
| -0.33 to -0.70 m | There is a abrupt change in colour of the mortar, to bluish green or greenish grey (Gley 1 6/5GY), drying to a light greenish grey (Gley 1 7/10Y). At -0.70 m the mortar returns to yellowish brown (10YR 5/6). |
| -0.65 to -0.75 m | A small fragment of a fibrous material, possibly a reed or twig (D 0.006 m), was embedded in the mortar. At -0.75 m a small fragment of wood was embedded in the perimetral surface of the core. Both were recovered for $^{14}$C analysis. |
| -0.80 to -1.80 m | A piece of limestone at the bottom of the core appears weathered, and does not show traces of mortar; this may represent the bottom of this concrete installation. The core tube went approximately a metre beyond this point, going through layers of hard and soft material, and jamming frequently. Nothing was recovered from this horizon, which may have been a rubble footing. |

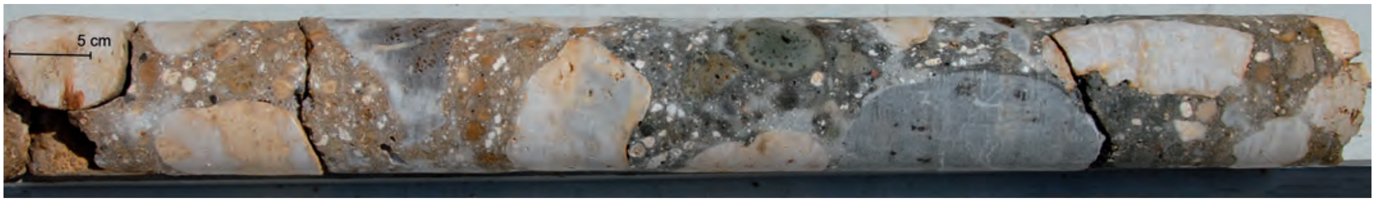

*Fig. A3.56: POM.2009.02. Overview of core,* caementa *composed of river cobbles and altered pumiceous tuff, and mortar with pale-orangish gray pumiceous ash (on left) and light olive gray pumiceous ash (on right).*

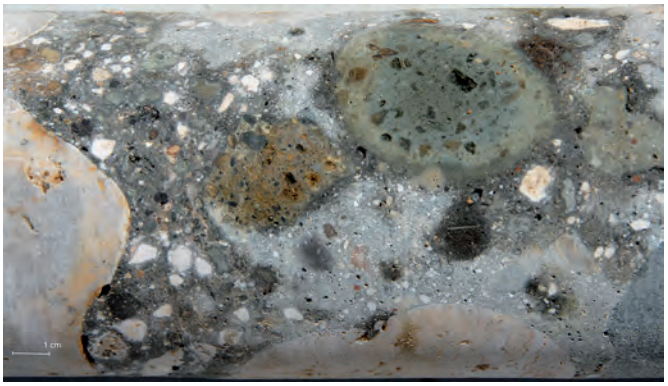

*Fig. A3.57: POM.2009.02, detail -0.35 to -0.50 m. Pumiceous mortar with relict lime clasts surrounds three subrounded clasts of pumiceous tuff.*

(Fig. 7.8g, h). Close to sea level the mortar transitions from white to pale green, and the porosity, white inclusions, and pumiceous particles increase (Stanislao *et al*. 2011: 475). In the upper section of the POM.2009.02 core, the brownish yellow mortar contains common pumiceous particles, pale yellow (2.5Y 7/3) Flegrean tuff, angular fragments of relict lime clasts, calcareous limestone clasts, and travertine clasts. Precipitation of dendritic gypsum, fibrous ettringite, and halite crusts occurred within both mortars, along with hydrocalumite, hydrotalcite, and brucite (Vola *et al*. 2010a). A point count of a thin section of the POM.2009.02 mortar indicates that fine particles of tuff aggregate, including pumiceous glass fragments, sanidine and augite crystal fragments and altered vitric ash matrix, form 13 to 19 volume %, microcrystalline sparry calcite forms 40 to 61 volume %, poorly crystalline C-A-S-H forms 9 to 31 volume %, and carbonate rock and red brick or ceramic particles form a few %. There are abundant dull white grains of reacted lime, about 3 to 9 volume %, composed of calcite and Al-tobermorite (Table A4.1). The millimetre-sized porosity is rather high, 3 to 6 volume %, and the ratio of the cementitious binder to aggregate particles, at 4.5, is the highest of the ancient specimens. The bulk composition of two specimens has somewhat average CaO/($Al_2O_3$+$SiO_2$)=0.32 and 0.56, $Al_2O_3$+$SiO_2$=41 to 55 weight %, and low MgO=0.94 to 1.14 weight %. However, one POM.2002.02 specimen has low CaO/($Al_2O_3$+$SiO_2$)=0.09, high $Al_2O_3$+$SiO_2$=60 weight %, and high MgO=6.92 weight % (Fig.7.16; Tables A4.2, A4.3).

*Concrete fabric and material properties:* There are no measurements of porosity or mechanical properties.

## A3.13. Limēn Sebastos, harbour of ancient Caesarea, modern Kaysaria, 45 km N of Tel Aviv (Israel)

The harbour Sebastos was completed in one phase of massive construction by Herod the Great between about 23 to 15 BC (Hohlfelder *et al.* 2007), for the most part as a series of concrete *pilae* and rectangular blocks on a foundation of imported river stones or on unconsolidated sea floor sands, and surrounded by rubble of the local *kurkar* bedrock (pp. 72–81; Figs. 4.23–24). *Kurkar* is the Arabic term used to indicate aeolian quartz sandstone with carbonate cement, formed by Pleistocene sand dunes. Paving, splash walls, and other dimension stone constructions were built on top of the concrete blocks to finish off the port facilities. It is likely that all the concrete blocks were installed below sea level, or at most were awash at the surface. The entire outer harbour structure is now, however, submerged 5 to 10 m below sea level and traversed by fractures. Archaeological and geological studies suggest that the Caesarea region has been tectonically stable over the past 2000 years (Galili and Sharvit 1998: 156–58). A recent theory suggests that a local tsumani associated with an earthquake near Antioch in 115 and another tsumani in 551 caused a great deal of destruction to the concrete structures (Reinhardt *et al.* 2006). The impact of the tsunami bore may have shifted the mole's foundation and undermined its shoreward edge, causing the offset of the underlying caissons. It also may have loaded the underlying sediments to the point of liquefaction, causing additional foundering and subsidence of the structure (Reinhardt *et al.* 2006). Further erosion and scour during the mid-6th century tsunami lowered the top levels of the structures and a high-energy wave environment developed with progressive destruction of the harbour by the 7th century. It is also possible that the subsidence of the harbour area was the result of construction in the open sea on poorly consolidated sediments. The weight of the concrete combined with marine erosion of the underlying substrate undermined the foundations of the structures and they eventually settled into the sediments, causing large-scale subsidence of the western sector of the harbour installations.

A focused effort was made to take cores from *pilae* and thinner rectangular concrete masses at points distributed along both breakwaters, and from concrete masses that were cast in a variety of forms. Cores CAE.2005.01, 02, 04 and 05 resemble each other closely in macroscale composition and appearance. Core CAE.2005.03, from a large, relatively thin concrete mass laid on sand, is less cohesive. Relict lime clasts are more abundant in this core, suggesting variations in preparation of the concrete materials. Numerous cracks that developed during settling over 2000 years, apparently produced accelerated weathering through the mass concrete.

***CAE.2005.01.*** Taken 6 October 2005 from Block K5 on the South Breakwater (UTM 3598050). The core site is on the flat upper surface of the large (L 14, W 7 m, H 4 m) rectangular concrete block, 3.5 m bsl. The depth of the core hole in the concrete was 1.10 m, and the core recovered was L 1.10 m (100% recovery) in four fragments. Coring stopped when wood was encountered, probably a horizontal wooden tie beam; an empty tie-beam hole at the same height left behind by decay of the formwork was visible on the western side of the block. The upper surface of the block was covered with marine encrustations.

*Description:* Compact, greenish-grey mortar (Table A3.29; Figs. A3.58–59). *Kurkar* and pumiceous tuff *caementa.*

***CAE.2005.02.*** Taken 7 October 2005 from a large (L 4.7 m, W 3.6 m, H 1.7 m) rectangular concrete block on the south breakwater, with tie beam marks on the upper surface (UTM 3597740), and located on the 1980 Survey Line no. 3, m 50 (Oleson, in Raban 1989: 213, 496–97; Brandon 1996: 32–33).

*Description:* Compact, greenish grey to light greenish grey mortar, with large *kurkar caementa* (Table A3.30; Figs. A3.60–62). The top of the block was at 3.0 m bsl; the core hole was 1.65 m deep, through to the bottom of the concrete block, and the core recovered was L 1.65 m (100% recovery) in five segments. The upper and lower tips of the core ends are darker green, perhaps the result of direct, long-term contact with sea-water.

*Table A3.29: CAE.2005.01 drill core summary.*

| Depth | Description |
|---|---|
| 0.0 to -0.20 m | The top 0.10 m of the core was moist. The mortar is compact, and generally greenish grey (Gley 1 5/1 10Y to 5/1 5GY) with a varied mix of small fragments of tuff or pumice (D < 0.015 m), generally greenish grey (Gley 1 6/1 10Y), along with occasional dark reddish brown (2.5R 4/3) ash fragments (D 0.005 m), and common white inclusions, as relict lime clasts (up to D 0.015 m). Nine large fragments of very hard *kurkar* sandstone *caementa* appear in the core, in contrast to only three substantial fragments of pumiceous tuff. |
| -0.20 to -0.30 m | The mortar is the same colour as above, but is dry and appears more porous. |
| -0.35 m | A layer of very fine-grained mortar with volcanic ash pozzolan, but no relict lime clasts or *caementa* (Th 0.024 m), may record a pause in the installation of the concrete. |
| -1.0 to -1.10 m | Mortar and *caementa* are similar to the upper levels of the structure, but the lowermost 0.10 m of the core was moist. A large potsherd (7.5R 4/3) was cut by the corer (Th 0.006 m, L 0.059 m). Coring was stopped when the bit encountered a large wooden object, probably a tie beam. |

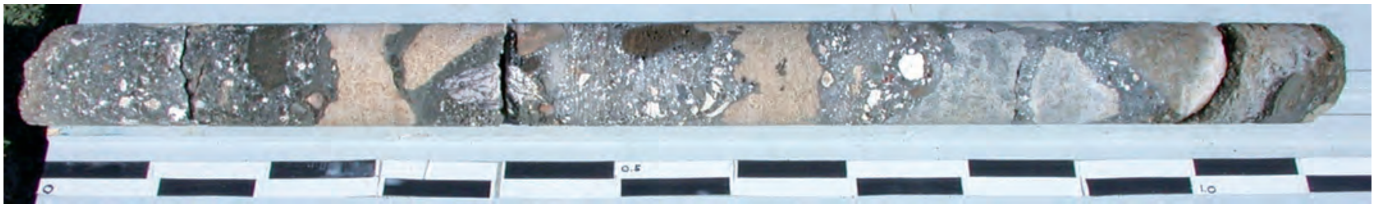

*Fig. A3.58: CAE.2005.01. Overview of core, with calcareous sandstone and pumiceous tuff* caementa*, and pumiceous mortar with relict lime clasts. Scale bar is 10 cm.*

*Fig. A3.59: CAE.2005.01, detail -0.65 to -0.78 m. Mortar with diverse aggregate particles including yellowish-gray pumiceous ash, clots of relict lime putty, calcarenite rock fragments, and ceramic fragments. Calcareous sandstone (calcarenite) on left.*

*Table A3.30: CAE.2005.02, drill core summary.*

| **Depth** | **Description** |
|---|---|
| 0.0 to -1.65 m | A compact, generally greenish grey to light greenish grey (Gley 1 5/1 10Y to 7/1 10Y) mortar with small fragments of tuff or pumice (D < 0.003 to 0.015 m), generally greenish grey (Gley 1 6/1 10Y), and relict lime clasts (up to D 0.015 m). There are occasional large (D 0.06 m) relict lime inclusions streaked with grey. Large *kurkar* sandstone *caementa* commonly occupy the entire core diameter. Common voids, some *ca.* D 0.03 m, most D 0.002 m. |

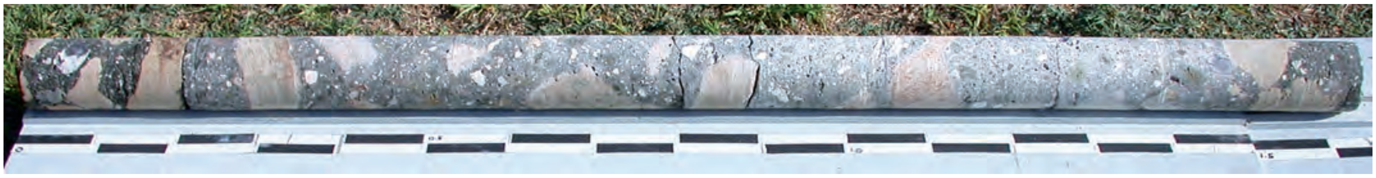

*Fig. A3.60: CAE.2005.02. Overview of core, calcareous sandstone* caementa *and mortar with relict lime clasts.*

*Fig. A3.61: CAE.2005.02, detail -0.28 to -0.80 m. Calcareous sandstone* caementa *and mortar with greenish-gray pumiceous pozzolan and relict lime clasts.*

*Fig. A3.62: CAE.2005.02, detail -1.10 to -1.25 m. Mortar with greenish-gray pumiceous ash pozzolan, altered pumiceous tuff, and relict lime fragments with the fragmented texture that occurs only in the Caesarea concrete.*

***CAE.2005.03.*** Taken 10 October 2005 from the north edge of a large (L 15 m, W 11.5 m, H 2 m) rectangular block of concrete with some preserved wooden formwork on the North Breakwater, Area G (UTM 3598046).

*Description:* Concrete like that of CAE.2005.01-02 (Table A3.31; Fig. A3.63). The top of the block was at 3.0 m bsl; the core hole was 1.0 m deep, and the core recovered was L 0.80 m (60% recovery), although in very fragmentary condition. The action of the coring barrel, which jammed several times in the top 0.10 m, may have broken up the concrete; the largest fragment is L 0.15 m. There is *kurkar* sandstone at the top and the bottom of the core, the only intact portions, but none surviving in the middle section. The *kurkar* in this portion seems to have come loose from the mortar and then was ground up by the core bit.

***CAE.2005.04.*** Taken 10 October 2005 from the lower half of a large (L 8.75 m, W 6.8 m, H 2.4 m) rectangular block in Area K on the south breakwater (UTM 3597965), which previously fractured horizontally, and split in half prior to drilling.

*Description:* Concrete like that of CAE.2005.01-03 (Table A3.32; Figs. A3.64–65). The top of the block was at 3.0 m bsl; the core hole was 2.30–2.40 m deep, and the core recovered was L 2.10 m (91% recovery). The core penetrated through to the lower surface of the block; there were marine encrustations on both the top and bottom tips of the core, indicating a complete traverse of the structure. There are nine fragments. The longest is L 0.60 m and the shortest 0.05 m. Some loss of material occurred in a crumbly section at -1.5 m to 1.8 m.

***CAE.2005.05.*** Taken 11 October 2005 from a large (L 12 m, W 9.5 m, H 4.3 m) *pila* in Area CO.01 on the South Breakwater (UTM 3597893). The top of the *pila* was at 2.5 m bsl; the core hole was *ca.* 2.0 m deep, and core recovered was L 1.95 m (98% recovery). The irregularity of the upper surface of the block, along with a strong wave surge, made mounting of the coring frame very difficult. Coring was slowed by the hardness of the *kurkar* aggregate, and by fragmentation of the upper 0.30 m of the block, which jammed the corer. Equipment problems caused cessation of coring after 2.0 m of core was recovered; the base of the structure was not reached.

*Description:* Concrete like that of CAE.2005.01-04 (Table A3.33; Figs. A3.66–67).

*Mortar to coarse rubble aggregate (caementa) ratio, as volume %:* CAE.2005.01 59/41 (1.4 to 1 ratio). CAE.2005.02 75/25 (3 to 1 ratio). CAE.2005.03 N/A. CAE.2005.04 83/17 (4 to 1 ratio). CAE.2005.05 67/33 (2 to 1 ratio).

*Coarse rubble aggregate (caementa):* These are mainly fragments up to D 0.02 m of local aeolian calcarenite *kurkar* deposits (Vola *et al.* 2011), composed of Pleistocene grainstones and packstones with detrital quartz, which crop out along Mediterranean coastal cliffs in ridges parallel to the modern shoreline (Sneh *et al.* 1998). There are also fragments of yellowish-grey pumiceous tuff *caementa* in some cores.

*Lime/limestone source:* The lime and poorly calcined marine limestone particles in the mortar may come from Mid-Cretaceous limestone and dolomite deposits several km northeast of the harbour, in the Mount Carmel area (Mart and Perecman 1996: 19). The Mount Carmel region was well forested in antiquity (Baly 1974: 81; *Isaiah* 33:9, *Jeremiah* 50:19), so there was an abundance of wood fuel. Lime could have been calcined at the quarries or near the construction site.

*Mortar pozzolan:* Yellowish-brown, pale yellowish orange, and/or greenish-grey pumiceous volcanic ash with sanidine, analcite, and illite crystal fragments is the predominant mortar pozzolan in all the cores. In addition, there are particles of the

*Table A3.31: CAE.2005.03 drill core summary.*

| Depth | Description |
|---|---|
| 0.0 to -1.00 m | The greenish grey (Gley 1 5/1 5GY) mortar resembles that of cores 01 and 02, but seems more granular, perhaps because the binding matrix disaggregated and washed away during drilling. The longest segment is 0.15 m, and composed mainly of *kurkar* sandstone. There are numerous small fragments of greenish-grey pumice or tuff in the mix and, possibly, a higher proportion of relict lime clasts than in the other cores. A few voids (< D 0.015 m) were visible in the surviving fragments. |

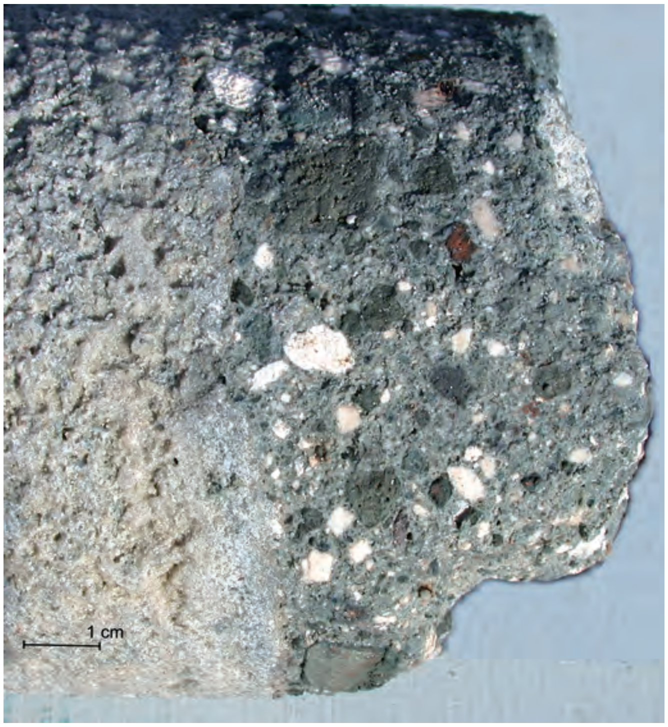

*Fig. A3.63: CAE.2005.03, detail -0.07 to -0.15 m. Weathered concrete with altered pumiceous ash pozzolan and calcareous sandstone* caementa.

Table A3.32: CAE.2005.04 drill core summary.

| Depth | Description |
|---|---|
| 0.0 to -1.50 m | A coherent concrete with a generally dark greenish grey (wet, Gley 1 4/1 5GY; dry, 7/1 10GY) mortar that contains many small pumice fragments (D 0.002 to 0.03 m), generally greenish grey (Gley 1 6/1 10Y). There are common relict lime clasts (D 0.005 to 0.03 m), voids (D 0.001 to 0.005 m), and large fragments of hard *kurkar* sandstone *caementa*. |
| -1.50 to -1.70 m. | A porous concrete. The mortar in this section is light olive brown (2.5Y 5/3) rather than greenish grey; pumice fragments are yellowish-grey (10YR 7/6), and mortar seems more moist than that elsewhere in the central part of the core. It is possible the core passed close to a tie beam hole. |
| -1.70 to -2.10 m | Coherent concrete as in the uppermost section. Light reddish brown (5YR 6/3) potsherd at -2.0 m (L 0.033 m, Th 0.003 m). At -2.0 m there is a large (0.03 by 0.06 m) inclusion of relict lime with black streaks. |

*Fig. A3.64: CAE.2005.04. Overview of core, calcareous sandstone* caementa*, occasional pumiceous tuff* caementa*, and mortar with relict lime clasts. Scale bar is 10 cm.*

*Fig. A3.65: CAE.2005.04, detail -1.25 to -1.33 m. Mortar with greenish-gray pumiceous ash pozzolan, relict lime as small and large clasts, and poorly calcined limestone particles.*

local *kurkar* eolianite calcareous sandstone and fossiliferous marine limestone (Vola *et al.* 2011a). Trace element analyses of three pumice specimens show somewhat dispersed results. One specimen, CAE-1983.P1, falls in the Campi Flegrei compositional field (Fig. 7.12). The mineral assemblage and trace element signatures of a pale orangish-yellow specimen (CAE.2005.02.P2) and a greenish-grey specimen (CAE.2005.05.P1) fall in the general compositional field of Campi Flegrei and Vesuvian pumice deposits (Figs. 7.12–13), but cannot be identified with specific eruptive deposits. These do not, however, correspond to the compositions of Minoan pumice deposits on Crete (Fig. 7.11).

*Mortar fabric and cementitious matrix:* The mortars are strongly enriched in volcanic pozzolan, including small vitric tuff and lava fragments, pumice clasts, shards of dark volcanic glass, white inclusions of relict lime clasts, as well as bits of *kurkar* sandstone, fossiliferous limestone, ceramics, and wood fragments, possibly derived from the original formwork (Vola *et al.* 2011a) (Figs. 7.6e, 8c–f). Poorly-calcined limestone clasts range up to D 0.07 m, and are now composed of calcite and Mg-calcite; relict lime clasts are composed of calcite, Al-tobermorite, and associated ettringite. Some white inclusions exhibit alternating zones of dark grey and dull white material, and are composed of calcite and and a small amount of Al-tobermorite (Table A4.1). These appear to be clots of relict lime, but their distinctive fabric with grey striations does not occur in concretes from any other harbour sites. Poorly crystalline C-A-S-H is the predominant cementitious hydration product (Vola *et al.* 2011a). The bulk composition of the mortar has $CaO/(Al_2O_3+SiO_2)=0.23$ to 0.46, and $Al_2O_3+SiO_2=45$ to 55 weight % (Fig. 7.16; Tables A4.2, A4.3). MgO ranges from 1.78 and 2.20 weight % for the CAE.2005.01 and CAE.2005.02 specimens, to 3.94 and 4.21 weight % for the CAE.2005.05 and CAE.2005.04 specimens.

*Concrete fabric and material properties:* The mortar porosity ranges from 47% to 66% (Fig. 7.18; Table 7.4). The predominant void diameter varies from about 6 nm for a CAE.2005.03 specimen, to 20 to 40 nm for a CAE.2005.01 specimen, two CAE.2005.02 specimens, and one CAE.2005.04 specimen. A CAE.2005.03 specimen, however, has a bimodal distribution with peaks at 5 nm and 300 to 400 nm. The very small pores seem to reflect the pore structure of the pumiceous ash pozzolan (Fig. 7.20). Pervasive millimetre-scale voids are visible at the macro-scale. These may have developed during

*Table A3.33: CAE.2005.05 drill core summary.*

| Depth | Description |
|---|---|
| 0 to -1.35 m | Coherent concrete. The generally dark greenish grey (wet, Gley 1 6/1 10Y) mortar contains common small pumice fragments (D 0.002 to 0.03 m), generally greenish grey (Gley 1 6/1 10Y), occasional hard, reddish brown (5YR 5/3) ceramics (D 0.003 to 0.005 m), and common relict lime clasts (D 0.001 to 0.03 m), several relict lime inclusions are streaked black and white. Numerous round voids (D 0.001 to 0.01 m) throughout. There are large pieces of very hard *kurkar* sandstone *caementa.* |
| -1.35 to -1.45 m | The concrete is porous and more brown in colour. There are traces of marine borers in the kurkar aggregate at this point. The borers and the water probably gained access through an adjacent beam hole. |
| -1.45 to -1.95 m | Coherent concrete as in the topmost section. |

*Fig. A3.66: CAE.2005.05. Overview of sea-water saturated core, calcareous sandstone* caementa*, occasional small pumiceous tuff clasts, and mortar with relict lime. Scale bar is 10 cm.*

*Fig. A3.67: CAE.2005.05, detail -1.30 to -1.75 m. Contact between two mortar formulations in sea-water saturated core, one with yellowish-brown pumiceous ash pozzolan (left), and one with greenish-gray pumiceous ash pozzolan (right), which also has large particles of poorly calcined limestone and calcarenite particles.*

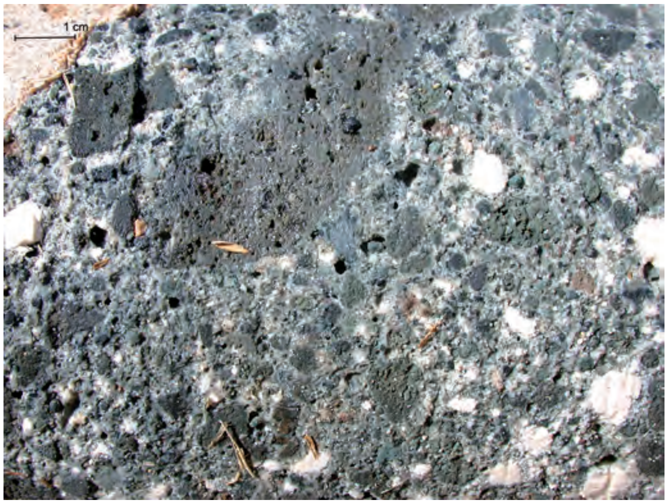

*Fig. A3.68: CAE.2005.05, detail -1.75 to 1.80 m. Sea-water saturated mortar with greenish gray pumiceous ash.*

wave action at the unprotected construction site, which impeded thorough manual compaction, or perhaps the warm water temperature accelerated the rate of setting and precluded self-compaction. The unit weights are also rather uniform, 1570 Kg/m$^3$ for CAE.2005.02, 1560 Kg/m$^3$ for CAE.2005.04, and 1520 Kg/m$^3$ for CAE.2005.05, with compressive strengths that range, repectively, from 6.4 MPa, 5.7 MPa, to 3.0 MPa (Fig. 7.15; Table 7.3). The CAE.05.01 speceimen has higher unit weight, 1720 Kg/m$^3$, but lower strength, 3.2 MPa, possibly the result of debonding of the *kurkar* sandstone *caementa* with the mortar.

## A3.14. Alexandria harbour, modern Alexandria (Egypt)

Four cores were recovered from submerged harbour structures in the great eastern harbour basin of Alexandria (pp. 85–89; Fig. 4.36). The upper surfaces of these structures now lie between 2.0 and 4.0 m bsl, but in antiquity the top of the *pila* that supplied core ALE.2007.03 was most likely 0.50–1.0 m asl; the other structures were probably constructed and designed to remain underwater. Two cores (ALE.2007.01 and 02) were recovered from a thin bed of concrete within a single-use barge form at the base of the Antirhodos Island (Brandon 1996). A third core (ALE.2007.03) was taken from the largest of several large concrete *pilae* extending south from the modern western breakwater. The fourth core (ALE.2007.04) was taken on a jetty extending north-northeast from a peninsula at the south end of the Royal Harbour. The mortar is a distinctive bluish-green colour with abundant fine- grained volcanic ash; the *caementa* consist mostly of oolitic limestone, a carbonate rock composed mainly of sand-sized, rounded, calcareous concretions. Given

*Table A3.34: ALE.2007.01 drill core summary.*

| Depth | Description |
|---|---|
| 0 to -0.75 m | The light grey-green mortar (Gley 1 7/10Y) transitions to dark grey with depth. The mortar contains common pumice fragments (D 0.005 to 0.02 m); many are grey to greenish grey (10YR 7/1). Relict lime clasts (D 0.002 to 0.005 m) are less common than in other harbour concretes. The *caementa* are hard, white to very pale brown (10YR 8/1-8/2) oolitic grainstone. The *caementa* fragments are quite angular and vary substantially in size (for example, D 0.025 m, 0.065 m, 0.075 m, 0.010 m). |
| -0.10 m | Ceramic sherd. |
| -0.22 m | Twig or reed (D 0.009 m), possibly from a basket. |

*Fig. A3.69: ALE.2007.01. Overview of broken core, with oolitic limestone* caementa *and greenish-gray compact mortar. Scale bar is 10 cm.*

the design of the formwork and the macroscopic appearance of the mortar, which resembles that of the central Italian harbour concretes, it seems likely that all these structures belong to the Roman period, a dating confirmed by the $^{14}$C date.

***ALE.2007.01.*** Taken 8 May 2007 from the thin bed of concrete remaining at the bottom of a large rectangular block installed in a single-use barge form (L *ca.* 16 m, W *ca.* 7.5 m, original H *ca.* 2.5 m), at the base of Antirhodos island (Figs. 8.53–54; UTM 3455981). Goddio dates this structure to the Ptolemaic period on the basis of a single $^{14}$C analysis at *ca.* 390 to 130 BC, but this result is very unlikely in terms of technological history (Oleson *et al.* 2011a). There is no other evidence for the use of pozzolanic concrete in Egypt at such an early date, and the technique of construction with floating barge forms is equally unattested. The top of the block was at 4 m bsl; the core hole was 0.75 m deep, and the core recovered was L 0.75 m (98% recovery), although in crumbly condition.

*Description:* Compact grey-green mortar with hard white *caementa* of oolitic grainstone (Table A3.34; Figs. A3.69–70).

***ALE.2007.02.*** Taken 8 May 2007 from the same structure as ALE.2007.01, at the base of Antirhodos island (UTM 3455981). Because of time constraints and uncertain weather, the team simply turned the frame around on the already installed feet and took a second core 2.0 m away from the first. The top of the block was at 4 m bsl; the core hole was 1.10 m deep. The core recovered was 1.03 m (94% recovery), in a continuous segment from the recent marine concretions on the top surface to the scrapings from the wood floor of the form at its base. A fragment of wood recovered from the core during testing at CTG Italcementi provided a $^{14}$C date of 1960 ± 50 BP, for a calendric age of AD 31 ± 54 years, or 23 BC to AD 84.

*Fig. A3.70: ALE.2007.01, detail -0.15 to -0.40 m. Oolitic limestone* caementa *and compact mortar with greenish-gray pumiceous ash pozzolan and relatively few relict lime clasts.*

*Description:* Concrete like that of ALE.2007.01 (Table A3.35; Figs. A3.71–73).

***ALE.2007.03.*** Taken 9 May 2007 from the largest of the *pilae* extending south from the local landmark, the Ball Trap Shooting Club (UTM 3456696). The top of the *pila* was at 2 m bsl; the core hole was 3.10 m deep, and the core recovered was L 3.05 (98% recovery). This concrete has a different macroscale appearance from cores ALE.2007.01 and ALE.2007.02, with common relict lime clasts and subrounded oolitic limestone *caementa*. A fragment of wood recovered from the core during testing at CTG Italcementi provided a $^{14}$C date of 1950 ± 50 BP, for a calendric age of AD 44 ± 56 years, or 12 BC to AD 100.

*Description:* Concrete like that of ALE.2007.01-02 (Table A3.36; Figs. A3.74–76).

***ALE.2007.04.*** Taken 10 May 2007 from the top surface of a section of jetty extending NNE from the peninsula at the south end of the so-called Royal Harbour (UTM: 3456235). The top of the block was at 6 m bsl; the core hole was 1.03 m deep,

*Table A3.35: ALE.2007.02 drill core summary.*

| **Depth** | **Description** |
|---|---|
| 0.0 to -0.21 m | Compact concrete with light grey to dark grey mortar. There are common pumice fragments (when wet, close to Gley 7/10Y; dries to yellowish grey, 10YR 7/1) and less common small relict lime clasts (D 0.002 to 0.006 m). The *caementa* are angular fragments of a very pale brown to light grey oolitic limestone (D 0.05 to 0.10 m). |
| -0.21 to -0.26 m | Fine sediment occurs in layers as if sifted by the water; there were no *caementa* or pumice fragments. |
| -0.26 to -1.03 m | Compact concrete as in the topmost section. |
| -1.03 m | At the base of the core, there is a layer of strong brown (7.5R 4/6) to yellow brown (10YR 7/6) pitch, and then a thin layer of wood pulled from the formwork. The wood grain is clearly visible. This same sequence of pitch and wood on the mortar occurs in the single-use barge forms at Caesarea. |

*Fig. A3.71: ALE.2007.02. Oolitic limestone* caementa *and compact mortar with greenish-gray pumiceous ash pozzolan and relatively few relict lime clasts.*

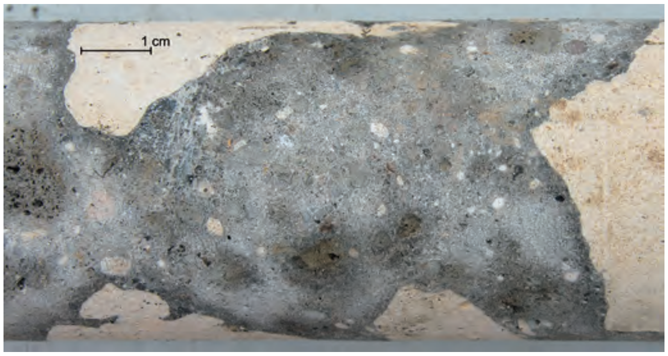

*Fig. A3.72: ALE.2007.02, detail, -0.36 to -0.53 m. Oolitic limestone* caementa *and compact mortar fabric with greenish-gray pumiceous ash pozzolan and relatively few relict lime clasts.*

and the core recovered was L 1.03 (100% recovery). There were marine concretions on the upper surface of the structure and on the lower surface. For logistical reasons the core had to be left in the coring tube for 12 hours after recovery, resulting in some surface discolouration by rust.

*Description:* Concrete similar to that of ALE.2007.01-03 (Table A3.37; Figs. A3.77–78).

*Mortar to coarse rubble aggregate (*caementa*) ratio, as volume %:* ALE.2007.01 56/44 (2.1 to 1 ratio). ALE.2007.02 57/43 (1.3 to 1 ratio). ALE.2007.03 54/ 46 (1.2 to 1 ratio). ALE.2007.04 51/49 (1 to 1 ratio).

*Coarse rubble aggregate (*caementa*):* These are predominantly oolitic limestone, of unknown provenance, but there are also occasional fragments of yellowish-grey pumiceous tuff.

*Fig. A3.73: ALE.2007.02, detail of base of core, -1.03 m. Wood from formwork.*

*Mortar pozzolan:* Pale orangish-yellow (Fig. 7.8i) and greenish-grey glassy pumiceous volcanic ash are the predominant pozzolanic components of the mortar. No trace element analyses have been performed on these materials but, at the macroscale, they resemble the pumices in the mortars of the Sebastos harbour concretes.

*Table A3.36: ALE.2007.03 drill core summary.*

| Depth | Description |
|---|---|
| 0.0 to -1.14 m | Compact concrete with light grey to grey green (Gley 1 8/N to 5/10Y) mortar, with poorly-sorted pumiceous ash particles. There are common relict lime clasts (D 0.006 to 0.014 m), and light yellowish-grey to light greenish-grey pumice particles, both rounded and sub-angular in shape. The oolitic limestone is sub-rounded, in contrast to ALE.2007.01 and ALE. 2007.02, and also irregular in size (D 0.05 to 0.12 m). |
| -1.0 m | Large, fibrous fragment of wood. |
| -1.45 m | Thick potsherd. |
| -1.45 to -2.50 m | The mortar is similar to the upper section, with common relict lime clasts (D 0.03 to 0.011 m) and soft, light greenish-grey (Gley 1 5/10Y) pumice fragments, and hard, dark lava lithic fragments. The limestone *caementa* in this area are sub-angular and irregular in size. |
| -2.50 to -3.05 m | The mortar is darker (Gley 1 6/10Y to 5/10Y) and more porous than that in the upper portion of the core. |

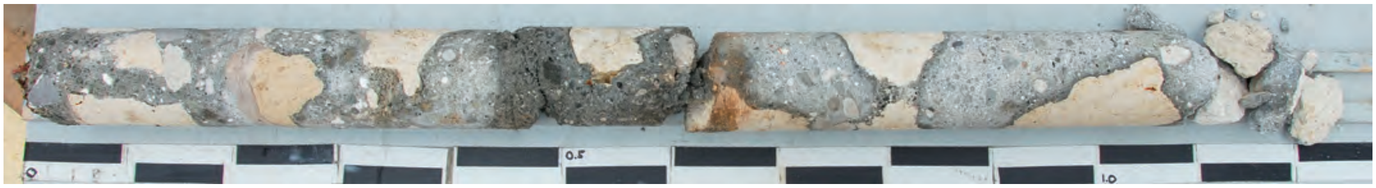

*Fig. A3.74: ALE.2007.03, detail, 0 to -1.20 m. Oolitic limestone and occasional ceramic* caementa*, and compact mortar with greenish-gray pumiceous ash pozzolan and relatively few relict lime clasts. Scale bar is 10 cm.*

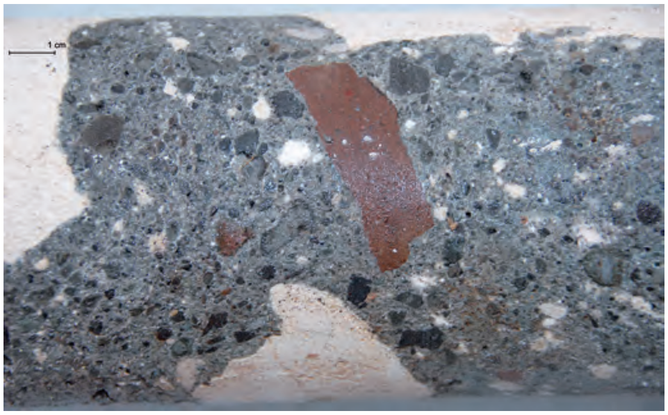

*Fig. A3.75: ALE.2007.03, detail -1.35 to -1.45 m. Sea-water saturated oolitic limestone and ceramic* caementa*, and mortar with greenish-gray pumiceous ash pozzolan and relatively few relict lime clasts.*

*Fig. A3.76: ALE.2007.03, detail -2.15 to -2.70 m. Sea-water saturated oolitic limestone* caementa *and mortar with greenish-gray pumiceous ash pozzolan and relatively few relict lime clasts.*

*Lime/limestone source:* The absence of limestone bedrock and forests in this region in antiquity suggests that lime for the mortars was calcined elsewhere or that both limestone and wood fuel were imported to the construction site. The closest sources of marine limestones are Middle to Upper Eocene deposits exposed on the Mokattam and Helwan plateaus (Klitzsch *et al.* 1987) and the Alkoraymat area (Solan *et al.* 2010) in the Nile River valley south of Cairo, about 180 to 300 km south of the harbour at Alexandria. These sites produce very pure lime, and, in ancient times, this could possibly been transported down the Nile River as a matured slaked product.

*Mortar fabric:* The ALE.07.02 mortar contains 19 to 24 volume % fine vitric ash pozzolan, composed of fine tuff particles, pumiceous clasts, sanidine and augite crystal fragments, and zeolite surface coatings in vesicles of the pyroclastic particles and about 6 volume % fragments of oolitic limestone, based on point counts of thin sections (Vola *et al.* 2010a). The cementitious matrix is composed of about 32 to 35 volume % poorly crystalline calcium-aluminium-silicate-hydrate (C-A-S-H), and 30 to 36 volume % microcyrstalline sparry calcite cement, underburned lime clasts, and occasional dull grains of reacted lime, about 1%. Spherical pores are commonly filled with zeolite, mainly phillipsite with rossete-like morphology, forming up to 4 volume % of the mortar. The total porosity at the millimetre scale is 3 to 5 volume %. The binder aggregate ratio is 2.2 (ALE.2007.02 and ALE.2007.03), up to 3.3 (ALE.2007.01). The bulk composition of the mortar has relatively high $CaO/(Al_2O_3+SiO_2)$=0.36 to 0.71 and low $Al_2O_3+SiO_2$=0.36 to 0.47 compared with harbours along the

*Table A3.37: ALE.2007.04 drill core summary.*

| Depth | Description |
|---|---|
| 0.0 to -1.03 m | A somewhat porous to coherent concrete. The mortar is bluish grey to greenish grey (Gley 1 5/10Y) and sea-water saturated from top to bottom, so perhaps disaggregation has occurred. There are occasional large relict lime clasts (D 0.01 to 0.03 m); common fragments of bluish green to light brown pumice (up to D 0.03 m) and dark lava lithic fragments. The mortar may contain a small amount of beach sand. There are occasional small limestone *caementa*. At several points along the core (at -0.18 m, -0.27 m, -0.37 m, -0.48 m) there are very thin (≤ 0.001 m) calcareous horizons, perhaps a settling layers of relict lime. |

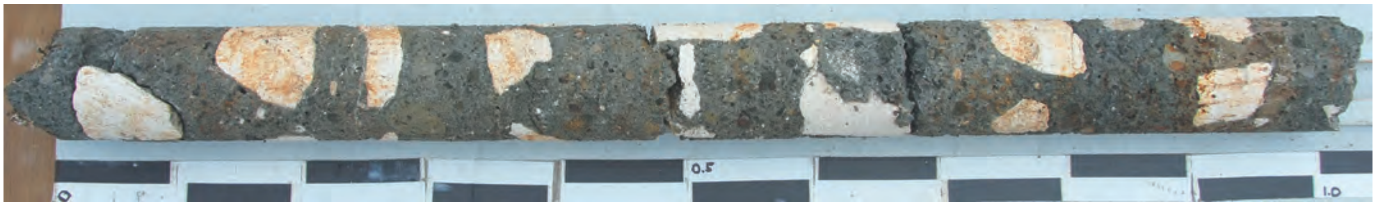

*Fig. A3.77: ALE.2007.04. Overview of sea-water saturated, iron-stained core, an artefact of the drilling process, with oolitic limestone* caementa *and mortar with greenish-gray pumiceous ash pozzolan. The red tint is caused by rust in core tube. Scale bar is 10 cm.*

central Italian coast (Fig. 7.16; Table A4.3), perhaps the result of the addition of limestone particles to the mortar. MgO is 0.8 weight % in the ALE.2007.03a mortar, 2.4 weight % in the ALE.2007.02 mortar, and 5.74 to 7.19 weight % in the ALE.2001.01 mortar. This may reflect the addition of variable proportions of dolomitic limestone particles or, perhaps, diverse lime or dolomitic lime sources.

*Concrete fabric and material properties:* The mortar porosity is quite regular, 43% to 44% (Fig. 7.17; Table 7.4). The predominant void diameter is about 35 nm for an ALE.2007.01 specimen and 70 nm for an ALE.2007.02 specimen. The small pores seem to reflect the pore structure of the pumiceous ash pozzolan (Fig. 7.20). Two specimens from the ALE.2007.03 core have moderate unit weight, 1607 Kg/m$^3$ and 1624 Kg/m$^3$, but low compressive strength, 2.5 MPa and 2.7 MPa (Fig. 7.15; Table 7.3). The ALE.2007.02 specimen is a more compact, coherent concrete with higher unit weight, 1723 Kg/m$^3$ and strength 5.0 MPa. The ALE.2007.04 core was not analysed.

*Fig. A3.78: ALE.2007.04, detail -0.55 to -0.68 m. Sea-water saturated oolitic limestone and a large clot of lime putty in mortar with abundant gravel-sized pale orange and greenish-gray pumiceous ash pozzolan.*

# Appendix 4

# Compositional Analyses of Concretes Drilled from Harbour Structures by ROMACONS

*M. D. Jackson and G. Vola*

Compositional analyses of various components of the ancient maritime concretes and the concrete reproduction at Brindisi add to the descriptions of the drill cores in Appendix 3. These include the mineral assemblages detected in powdered specimens determined through X-ray diffraction analyses, mainly at CTG Italcementi Laboratories in Bergamo, Italy (Table A4.1); major and trace element geochemistry of the tuff *caementa*, pumice pozzolan clasts, and pozzolanic mortars determined through ICP-MS analyses of 3 to 5 gram powdered specimens in fused glass beads at Activation Laboratories in Ancaster, Canada (Table A4.2); and major element compositions of the pozzolanic mortars determined through X-ray Fluorescence analyses of powdered specimens at CTG Italcementi Laboratories in Bergamo, Italy (Table A4.3). Note that the volcanic tuff and pozzolanic mortar specimens are hybrid materials and have a mixed character. The tuffs are composed of "juvenile" components of pumice and crystals derived from the magma of the eruption, as well as lithic fragments, mainly lava rock particles, derived from the volcanic edifice. The ratios of immobile trace elements are, therefore, only qualitative estimates of eruptive provenance. The consistent pyroclastic fabrics of the tuff *caementa* of the central Italian harbour concretes – with the exception of the distinctive Tufo Lionato *caementa* at Portus – suggest that their clustered compositions in the diagrams of Figs 7.10–11 can be interpreted as a qualitative representation of volcanic provenance. The mortars are also mixed materials, or *materies miscenda as* described by Vitruvius (*De architectura* 2.4.1, pp. 15–16, Passage 5), and their composition is very heterogeneous both at the centimeter scale of the powdered samples and the point counts of thin sections with the petrographic microscope (Table 7.1). Numerous processes could have influenced their bulk chemical compositions, so the results of major element chemical analyses are described only as qualitative chemical trends (Figs. 7.16, 7.17). For descriptions of analytical methods, see pp. 186–87. For results of laboratory analyses describing the material and mechanical characteristics of the concretes see Chapter 7.

*Table A4.1: Mineralogical compositions of components of the sea-water concretes, determined through powder X-ray diffraction analyses.*

| Specimen | Predominant Cementitious Phases | Accessory Cementitious Phases | Mortar Aggregate Minerals | Other Primary Aggregates | Type of Material |
|---|---|---|---|---|---|
| **PORTUS COSANUS** | | | | | |
| **Mortar composition** | | | | | |
| PCO.2003.01 A | Cal | – | San, Aug, Anl, Lct, Bt, Kao, Mnt, Cbz | Qtz | Mortar |
| PCO.2003.01 C | Cal | – | San, Anl, Lct, Bt, Kao, Mnt | Qtz, Ort | Mortar |
| PCO.2003.02 A | Cal, Tbm | – | San, Aug, Lct, Kao | Qtz | Mortar |
| PCO.2003.02 C | Cal | – | San, Aug, Lct, Bt, Anl, Mnt, Kao, Cbz | Qtz | Mortar |
| PCO.2003.03 A | Cal, Tbm | – | San, Aug, Lct, Bt | Qtz | Mortar |
| PCO.2003.03 C | Cal, Tbm | Hyt | Anl, Bt, Mnt, Kao, Cbz | Qtz | Mortar |
| PCO.2003.04 B | Cal, Tbm | Hyt | San, Aug, Anl, Bt, Kao | Qtz | Mortar |
| PCO.2003.05 A | Cal | | San, Aug, Anl, Lct, Bt, Kao | Qtz | Mortar |
| *PCO.2003.01A.M1* | Cal, Vat | Etr, Str, Phi | San, Anl | Qtz | *Cementitious matrix*[1, 3] |
| **White inclusion** | | | | | |
| PCO.2003 01A | Tbm, Cal | Str, Wo, Etr, Vat | – | – | White inclusion |
| PCO.2003 01C/1 | Tbm, Cal | Str, Wo, Nor, Vat | – | Qtz, Mus | White inclusion |
| PCO.2003 01C/2 | Tbm, Cal | Str, Wo, Etr, Vat | – | – | White inclusion |
| PCO.2003 01C/3 | Tbm, Cal | Str, Wo, Nor, Vat | – | (Qtz) | White inclusion |
| PCO.2003 1Cw | Cal, Tbm | Br, Vat, Etr, Gp | San | – | White inclusion |
| **Volcanic pozzolan** | | | | | |
| PCO.2003 01A | Phi, Cbz | Cal | Anl, Ab, Mic | – | Pumiceous tuff |
| PCO.2003 01A | Phi | Vat, Tbm | – | – | Pumice |
| PCO.2003 01A | Phi | Vat, Tbm, Cbz, Cal | San, Anl | – | Pumice |
| PCO.2003 01A | Phi | Cal, Vat | Anl, San | Qtz, Mus | Lava, local sand |
| PCO.2003.01 | Phi | Vat, Tbm, Cbz, Cal | San, Anl | – | Volcanic sand |
| *PCO.2003.01.AC.P1* | Phi, Cal | Cbz | Ill, Non | – | *Pumice*[1] |

| | | | | | |
|---|---|---|---|---|---|
| **SANTA LIBERATA** | | | | | |
| **Mortar composition** | | | | | |
| SLI.2003.01 (middle) | Vat | Cal, Gyp | San, Anl, Ms, Phi | – | Mortar |
| SLI.2003.01 | Cal | Gp, Vat, Phi | San, Anl, Ms | – | Mortar |
| SLI.2004.01a* | Cal | Cbz, Vat | San, An, Anl | Cal, Qtz, Ill | Mortar[2] |
| SLI.2003.01 | Cal | Cbz, Br | San, Anl, Phi | Ill | Cementitious matrix |
| **White Inclusion** | | | | | |
| SLI.2003.01 | Cal, Tbm | Phi, Br, Hal | – | – | White inclusion |
| SLI.2003.01 | Etr, Tbm | Vat, Hyc, Cal | – | – | White inclusion |
| SLI.2003.01 (middle) | Cal, Gp | Vat | – | – | White inclusion |
| SLI.2003.01a | Cal, Tbm | Hal, Vat, Arg | | – | White inclusion |
| SLI.2004.01c | Tbm, Etr | Cal, Hyc, Vat | – | – | White inclusion |

| Specimen | Predominant Cementitious Phases | Accessory Cementitious Phases | Mortar Aggregate Minerals | Other Primary Aggregates | Type of Material |
|---|---|---|---|---|---|
| **Volcanic pozzolan** | | | | | |
| SLI.2003.01 (top) | Phi, Cal | – | San, Anl | – | |
| SLI.2004.01 | – | – | Cal, Phi, Cbz | – | Black glass shard |
| **Volcanic tuff *caementa*** | | | | | |
| SLI.2003.01 | – | Cal, Tbm | San, Anl, Phi, Cbz | – | Pumiceous tuff |
| SLI.2003.01 | – | Gp, Cal | Phi, Cbz | – | Pumiceous tuff |
| SLI.2003.01 | – | Cal, Mg-Cal | San, Anl, Phi, Cbz | Ill | Pumiceous tuff |
| SLI.2004.01a | – | Cal, Hyt | San, Anl, An, Clc | – | Pumiceous tuff |
| SLI.2004.01a | – | Cal, Mg-Cal, Hal | San, Anl, Phi, Cbz | Ill | Pumiceous tuff |
| SLI.2004.01b | – | Cal, Hyt | San, Anl, An, Clc | – | Pumiceous tuff |
| SLI.2004.01c | – | Cal, Hyt | San, Anl, An, Clc | – | Pumiceous tuff |
| SLI.2004.01 | – | Cbz, Clc, Vat | Ill, San, An, Anl | – | Pumiceous tuff |

| | | | | | |
|---|---|---|---|---|---|
| **PORTUS CLAUDIUS** | | | | | |
| **Mortar composition** | | | | | |
| POR.2002.PO2 | Cal | Hyc, Phi | San | Qtz, Alb | Mortar |
| **White inclusion** | | | | | |
| POR.2002.PO2C | Cal, Vat | Arg, Hyc | – | – | White inclusion |
| POR.2002.PO2C | Cal, Vat | Arg, Hyc | – | – | Poorly-calcined lime clast |
| POR.2002.PO2A | Tbm, Cal | Wo, Etr, Hyc, Gp | – | – | Relict lime clast |
| POR.2002.PO2Ca | Cal, Vat | Afw, Etr, Hyc | – | – | inner zone |
| POR.2002.PO2Ca’ | Cal | Afw, Hyc | – | – | outer zone |
| **Volcanic pozzolan** | | | | | |
| *POR.2002.PO2C.P1* | Cal, Vat | Arg, Phi, Tbm | San | – | *Pumice*[1] |

| | | | | | |
|---|---|---|---|---|---|
| **PORTUS TRAIANI** | | | | | |
| **Mortar composition** | | | | | |
| PTR.02.PTO2 | Cbz, Cal | (Hyc) | San, Di, Anl | (Qtz) | Mortar |
| PTR.02.01 C1 | Cal, Vat | (Hyc) | Anl, Di, San | – | Cementitious matrix |
| PTR.2002.01 C1 | Cal, Vat, | Afw, Etr, Phi | Anl, Di, San, Ill | – | Cementitious matrix |
| PTR.2002.02 C2 | Cal, Vat | Etr, Hyc, Phi | Anl, Di, San, Ill | – | Cementitious matrix |
| **White inclusion** | | | | | |
| PTR.02.02 | Tbm, Cal | Wo, Etr, Nor, Vat, Flr, Hyc | – | – | White inclusion |
| **Volcanic pozzolan** | | | | | |
| *PTR.2002.01.P1* | Cbz | Cal, Phi | Alb, Di, Hem, Kao, Hal | – | *Pumice*[1] |

| | | | | | |
|---|---|---|---|---|---|
| **PORTUS NERONIS** | | | | | |
| **Mortar composition** | | | | | |
| ANZ.2002.A1 | Cal | Brc, Phi, (Hyc) | San, Anl | (Qtz) | Mortar |
| ANZ.2002.A1 | Cal, Vat | Tbm, Phi, Cbz | San, Anl | – | Mortar |

| **Specimen** | **Predominant Cementitious Phases** | **Accessory Cementitious Phases** | **Mortar Aggregate Minerals** | **Other Primary Aggregates** | **Type of Material** |
|---|---|---|---|---|---|
| **White inclusion** | | | | | |
| ANZ.2002.A1 | Tbm, Cal | Wo, Etr, Vat, Brc, Hyc | – | – | White inclusion |
| ANZ.2002.A1w | Cal, Tbm | Brc, Vat, Arg | – | (Qtz) | White inclusion |
| **Volcanic tuff *caementa*** | | | | | |
| *ANZ.2002.01.T1* | Phi | Cal | Ill, Alb | – | *Pumiceous tuff*[1] |
| ANZ.2002.A1 | Phi | Cal | San | – | Pumiceous tuff |

| | | | | | |
|---|---|---|---|---|---|
| **BAIANUS LACUS,<br>BAIANUS SINUS,<br>PORTUS IULIUS** | | | | | |
| **Mortar composition** | | | | | |
| BAI.2006.01* | Cal, Tbm | Phi, Cbz, Hyt | San, Anl, Ill | – | Mortar |
| BAI.2006.02* | Cal | Phi, Cbz | San, Anl, Ill | – | Mortar |
| BAI.2006.03* | Cal, Tbm | Phi, Cbz, Hyt | San, Anl, Ill | – | Mortar |
| BAI.2006.04* | Cal | Phi, Cbz, Hyt | San, Anl, Ill | – | Mortar |
| BAI.2006.05* | – | Phi, Cbz | San, Anl, Ill | – | Mortar |
| **White inclusion** | | | | | |
| BAI.2006.01/1 | Tbm | Cal, Vat, Brc | – | – | White inclusion |
| BAI.2006.1/2 | Tbm | Cal, Vat, Brc | – | – | White inclusion |
| BAI.2006.01wi | Tbm | Cal, Vat | San, Alb | – | White inclusion |
| **Volcanic pozzolan** | | | | | |
| *BAI.2006.01.P1* | Phi, Cal | Tbm | Ill, San, An | – | *Pumice*[1] |
| BAI.2006.02 base | Cal | Phi | Anl, Ill, San | – | Pumice |
| BAI.2006.03 top | Cal | Phi | Anl, San, Orth | – | Glassy lithic fragment |
| *BAI.2006.05B.P1* | Phi, Cal | Cbz | San, Non, Hal | – | *Pumice*[1] |
| **Volcanic tuff *caementa*** | | | | | |
| BAI.2006.02 | Cal, Phi | Cbz | Anl, Ill, San, Orth | – | Pumiceous tuff |
| BAI.2006.03 (top) | Cal, Phi | Cbz | Anl, Ill, San, Orth | – | Pumiceous tuff |
| BAI.2006.05 (top) | – | Hal | San, An | – | Pumiceous tuff |
| BAI.2006.05 (top) | – | Hal | San, An | – | Pumiceous tuff |

| | | | | | |
|---|---|---|---|---|---|
| **EGNATIA** | | | | | |
| **Overall mortar composition** | | | | | |
| EGN.2008.01 (top)* | Cal | Phi, Cbz, Gp | San, Anl, Ill | Cal | Mortar |
| EGN.2008.01 (middle)* | Cal, Etr | Phi, Cbz, Gp | San, Anl, Ill | Cal | Mortar |
| EGN.2008.01 (base)* | Cal, Etr | Phi, Cbz, Gp, Hal | San, Anl, Ill | Cal | Mortar |
| EGN.2008.02 (top)* | Cal, Tbm, Etr | Phi, Cbz, Gp | San, Anl, Ill | Cal | Mortar |
| EGN.2008.02 (top)* | Cal, Etr | Phi, Cbz, Gp | San, Anl, Ill | Cal | Mortar |
| EGN.2008.02 (middle)* | Cal, Tbm, Etr | Phi, Cbz, Gp, Bsn | Qtz, San, Anl, Ill | Cal | Mortar |
| EGN.2008.02 (middle)* | Cal, Etr | Phi, Cbz, Gp | San, Anl, Ill | Cal | Mortar |
| EGN.2008.02 (base)* | Cal, Tbm, Etr | Phi, Cbz, Gp, Bsn | Qtz, San, Anl, Ill | Cal | Mortar |

| Specimen | Predominant Cementitious Phases | Accessory Cementitious Phases | Mortar Aggregate Minerals | Other Primary Aggregates | Type of Material |
|---|---|---|---|---|---|
| **Volcanic pozzolan** | | | | | |
| *EGN.2008.01.P1* | Phi, Cal | Cbz | San, Non, Ill | | *Pumice*[1] |
| *EGN.2008.02.P2* | Phi, Cal | Cbz | San, Ill | | *Pumice*[1] |
| **Calcarenite *caementa*** | | | | | |
| EGN.2008.01 (top) | – | – | – | Cal | Limestone |
| EGN.2008.01 (middle) | – | Etr | – | Cal | Limestone |
| EGN.2008.01 (base) | – | Hal | – | Cal, Arg | Limestone |
| EGN.2008.02 (top) | – | Hal | – | Cal, Arg | Limestone |
| EGN.2008.02 (top) | – | Etr, Hal | – | Cal | Limestone |
| EGN.2008.02 (middle) | – | Hal | – | Cal | Limestone |
| EGN.2008.02 (middle) | – | Hal | Ill | Cal | Limestone |
| EGN.2008.02 (base) | – | Hal | – | Cal | Limestone |
| **CHERSONESOS** | | | | | |
| **Mortar composition**[5] | | | | | |
| CHR.2007.01 (base)* | Cal, Tbm | Phi | San | Cal, Dol | Mortar |
| CHR.2007.01 (middle)* | Cal, Tbm | Phi | San | Dol, Cal | Mortar |
| CHR.2007.01 (top)* | Cal | Phi | San | Cal | Mortar |
| CHR.2007.02 (base)* | Cal | Phi | San | Cal, Dol | Mortar |
| CHR.2007.02 (middle)* | Cal | Phi | San | Cal | Mortar |
| CHR.2007.02 (top)* | Cal | Phi | San | Cal, Dol | Mortar |
| **Volcanic pozzolan** | | | | | |
| *CHR.2007.2A/B.P1* | Phi, Cal | Cbz | San, Non, Ill | | *Pumice*[1] |
| **Limestone *caementa*** | | | | | |
| CHR.2007.01 (base) | – | Hal | – | Cal, Dol | Limestone |
| CHR.2007.01 (middle) | – | Hal | – | Dol, Cal | Limestone |
| CHR.2007.01 (top) | – | Hal | Ms | Cal, Dol, Qtz | Limestone |
| CHR.2007.02 (base) | – | Hal | – | Dol, Cal | Limestone |
| CHR.2007.02 (middle) | – | Hal, Brc | – | Cal, Ank | Limestone |
| CHR.2007.02 (top) | – | Phi, Hal | – | Cal, Dol | Limestone |
| **POMPEIOPOLIS** | | | | | |
| **Mortar composition** | | | | | |
| POM.2009.01 (top)* | Cal, Tbm, Etr | – | San, Ms, Phi[4] | – | Mortar |
| POM.2009.01 (middle) | Cal, Tbm | – | Ms, Phi[4] | – | Mortar |
| POM.2009.02 (top)* | Cal, Tbm, Etr | – | San, Ms, Phi[4] | Qtz, (Hal) | Mortar |
| POM.2009.02 (top)* | Cal, Tbm | – | San, Anl, Phi[4], Cbz[4] | – | Mortar |
| POM.2009.02 (middle) | Cal, Tbm | – | San, Ms, Phi[4], Cbz[4], Sm | (Hal) | Mortar |
| **Volcanic pozzolan** | | | | | |
| *POM.2009.2/A.P1* | Phi, Cal | Cbz | San, Non, Ill | | *Pumice*[1] |

| Specimen | Predominant Cementitious Phases | Accessory Cementitious Phases | Mortar Aggregate Minerals | Other Primary Aggregates | Type of Material |
|---|---|---|---|---|---|
| **Diverse *caementa*** | | | | | |
| POM.2009.02 (base) | – | – | San | Prg, Cal | Amphibolite cobble |
| POM.2009.02 (base) | – | – | – | Cal | Coral cobble |
| **CAESAREA PALAESTINAE** | | | | | |
| **Mortar composition**[5] | | | | | |
| CAE.2005.01* | Cal, Tbm | Phi, Cbz | San, Anl | Qtz, Ill | Mortar |
| CAE.2005.02* | Cal, Tbm, Etr | Phi | San, Anl | Ill | Mortar |
| CAE.2005.03* | Cal | Phi | San, Anl, Aug, An | Qtz, Ill | Mortar |
| CAE.2005.04* | Cal | Phi, Cbz | San, Cpx, Anl | Qtz, Ill | Mortar |
| CAE.2005.05* | Cal, Tbm | Phi | San, Cpx, Anl | Cal, Ill | Mortar |
| CAE2005.03cm | Cal | Mg-Cal, Hal, Sjg | San, Anl, Phi | Qtz, Ill | Cementitious matrix |
| White inclusion | | | | | |
| CAE.2005.02 | Cal | Tbm, Etr | – | (Qtz) | White inclusion |
| CAE.2005.02 | Mg-Cal | Cal | – | – | White inclusion |
| **Volcanic pozzolan** | | | | | |
| *CAE.2005.02.P2* | Cal, Phi | – | Anl, San | – | *Pumice*[1] |
| CAE.2005.02 | – | Phi, Cbz | San, Anl | – | Tuff-ash particle |
| **ALEXANDRIA** | | | | | |
| **Mortar composition**[5] | | | | | |
| ALE.2007.03 (top)* | Cal, Tbm, Etr | Phi | San | Cal | Mortar |
| ALE.2007.03 (bottom)* | Cal, Tbm | Phi | San | Cal | Mortar |
| ALE.2007.02* | Cal, Tbm | Phi | San | Cal | Mortar |
| ALE.2007.01* | Cal, Tbm, Etr | Phi | San | Cal | Mortar |
| **Calcarenite *caementa*** | | | | | |
| ALE.2007.03 (top) | – | – | – | Cal, Arg | Limestone |
| ALE.2007.03 (bottom) | – | Hal | – | Cal, Arg | Limestone |
| ALE.2007.02 | – | Hal | – | Cal, Arg | Limestone |
| ALE.2007.01 | – | Hal, Brc | – | Cal, Arg | Limestone |
| **BRINDISI PILA RECONSTRUCTION** | | | | | |
| **Mortar composition** | | | | | |
| **6 Months** | | | | | |
| BRI.2005.01 top | Cal, Vat | Hyc, Chm | Anl, San | – | Mortar |
| BRI.2005.01 bottom | Cal, Vat | Hyc, Chm, Por | Anl, San | – | Mortar |
| BRI.2005.01A | Cal, Vat | Hyc | Anl, San | – | Cementitious matrix |
| BRI.2005.01B. P1 | Cal, Vat | Hyc | Anl, Di | – | Pumice, Bacoli Tuff |

| Specimen | Predominant Cementitious Phases | Accessory Cementitious Phases | Mortar Aggregate Minerals | Other Primary Aggregates | Type of Material |
|---|---|---|---|---|---|
| **12 months** | | | | | |
| BRI.2005.02* | Cal, Vat | Cbz, Phi | Anl, San | – | Cementitious matrix |
| **24 months** | | | | | |
| BRI.2006.03* | Cal, Vat | Phi | Anl, San | – | Cementitious matrix |
| **48 months** | | | | | |
| BRI.2008.01 | Cal, Phi | Cbz, Hyc, Hal | San, Anl, Ill | – | Mortar (6 analyses) |
| BRI.2008.01 (top) | Cal, Vat, Hyc | Cbz, Phi | San, Anl, Ill | – | Cementitious matrix |
| BRI.2008.01 (base) | Cal, Vat, Hyc | Phi | Anl, San, Ill | – | Cementitious matrix |
| **White inclusion** | | | | | |
| BRI.2008.w1 | Cal, Por | Vat, Hyc, Sjg | Cal, Por | – | White inclusion |
| BRI.2008.w2 | Cal, Vat | Hyc, Sjg | Cal, Vat | – | White inclusion |
| **60 months** | | | | | |
| BRI.2009.01(top) | Cal, Por | Hyc, Sjg | Anl, San | – | Mortar |
| BRI.2009.02 (middle) | Cal, Por | Hyc, Sjg | Anl, San | – | Mortar |
| BRI.2009.03 (middle) | Cal, Por | Hyc, Sjg | Anl, San | – | Mortar |
| BRI.2009.04 (base) | Cal | Hyc, Sjg | Anl, San | – | Mortar |
| BRI.2009.C2 | Cal, Vat | Hyc | Anl, Di | – | Cementitious matrix |
| **White inclusion** | | | | | |
| BRI.2009.C2 | Cal, Por | Ett, Hyc | – | – | White inclusion, relict lime |
| **Volcanic tuff *caementa*** | | | | | |
| *BRI.2005.02.T1* | – | – | Anl, San, Phi, Cbz | – | *Bacoli Tuff*[1] |
| BRI.2008.01 | – | Cal | Anl, Ill, San, Phi, Cbz | – | Bacoli Tuff |
| Bacoli, Flegrean tuff* | – | – | Phi, Cbz, Anl, San | – | Bacoli Tuff |

(1) Italics denote specimen with XRD, major and trace element analyses (Table A4.2)
(2) Asterisk (*) denotes specimen XRD and major element analyses (Table A4.3)
(3) Cementitious matrix is the <0.145 mm size fraction, lightly crushed and sieved from the mortar
(4) Zeolites in the mortar are unreacted constituents of the pumiceous pozzolan (Stanislao *et al.* 2011)
(5) Vola *et al.* 2011

Abbreviations of crystalline phases identified through X-ray diffraction analyses of components of ancient mortars and coarse aggregate (caementa). **Crystalline phases** include: Afw: Afwillite; Ank: Ankerite; Arg: Aragonite; Brc: Brucite; Bsn: Bassanite; Cal: Calcite; Cbz: Chabazite; Clc: Clinochlore; Etr: Ettringite; Fl: Fluorite; Gp: Gypsum; Hal: Halite; Hyc: Hydrocalumite; Hyt: Hydrotalcite; Mnt: Montmorillonite; Non: Nontronite; Nor: Nordstrandite; Phi: Phillipsite; Por: Portlandite; Sjg: Sjogrenite; Sm: Smectite; Str: Strätlingite; Tbm: Tobermorite; Vat: Vaterite, Wo: Wollastonite. **Volcanic pozzolan (tuff pumice and lava fragments) phases** include primary crystals: Alb: Albite; Anl: Analcime; An: Anorthite; Aug: Augite; Bio: Biotite; Di: Diopside; Hem: Hematite; Lct: Leucite; San: Sanidine; and authigenic alteration components: Cal: Calcite; Cbz: Chabazite; Hal: Halloysite; Ill: Illite; Kao: Kaolinite; Phi: Phillipsite. **Sedimentary sands and coarse aggregates** include: Cal: Calcite; Dol: Dolomite; Mg-Cal: Magnesium Calcite; Mic: Microcline; Ms, Mus: Muscovite; Ort: Orthoclase; Prg: Pargasite; Qtz: Quartz; San: Sanidine.

*Table A4.2: Major and trace element compositions of pumices, volcanic tuff* caementa*, and mortars, determined through ICP-MS analyses of fused glass beads.*

| **Specimen** | | **PCO.03.01.AC.P1** | **SLI.04.01C.P1** | **POR.02.PO2C.P** | **PTR.02.01.P1** | **ANZ.02.01.P1 TOP** | **ANZ.02.01.P2** |
|---|---|---|---|---|---|---|---|
| | | mortar pumice | mortar pumice | mortar pumice | mortar pumice | mortar pumice | mortar pumice |
| Analyte | | | | | | | |
| $SiO_2$ | wt% | 44.56 | 42.30 | 35.11 | 43.19 | 42.72 | 47.38 |
| $Al_2O_3$ | wt% | 13.89 | 13.89 | 11.07 | 13.54 | 12.37 | 14.49 |
| $Fe_2O_3$(T) | wt% | 2.83 | 2.77 | 2.45 | 2.56 | 2.50 | 2.8 |
| MnO | wt% | 0.134 | 0.10 | 0.09 | 0.10 | 0.10 | 0.119 |
| MgO | wt% | 0.78 | 0.65 | 0.78 | 0.46 | 5.05 | 5.05 |
| CaO | wt% | 10.67 | 7.98 | 19.66 | 11.66 | 1.35 | 1.91 |
| $Na_2O$ | wt% | 3.4 | 4.29 | 1.53 | 1.88 | 4.92 | 5.33 |
| $K_2O$ | wt% | 4.88 | 5.34 | 3.22 | 4.98 | 4.18 | 4.76 |
| $TiO_2$ | wt% | 0.31 | 0.33 | 0.27 | 0.31 | 0.30 | 0.361 |
| $P_2O_5$ | wt% | 0.08 | 0.04 | 0.07 | 0.08 | 0.05 | 0.05 |
| LOI | wt% | 18.47 | 21.13 | 24.93 | 19.85 | 21.00 | 17.64 |
| Total | wt% | 81.53 | 98.8 | 99.2 | 98.6 | 94.6 | 99.89 |
| Sc | ppm | 2 | 2 | 2 | 2 | 1 | 2 |
| Be | ppm | 14 | 8 | 9 | 10 | 12 | 13 |
| V | ppm | 34 | 57 | 37 | 26 | 31 | 27 |
| Cr | ppm | < 20 | < 20 | < 20 | <20 | < 20 | < 20 |
| Co | ppm | 1 | 1 | < 1 | 2 | 2 | 2 |
| Ni | ppm | < 20 | < 20 | < 20 | <20 | < 20 | < 20 |
| Cu | ppm | 160 | < 10 | 40 | 20 | 30 | 40 |
| Zn | ppm | 90 | 60 | 60 | 50 | 70 | 80 |
| Ga | ppm | 18 | 15 | 10 | 12 | 16 | 14 |
| Ge | ppm | 1 | < 1 | < 1 | <1 | < 1 | 1 |
| As | ppm | 8 | 6 | 6 | 29 | 12 | 24 |
| Rb | ppm | 309 | 357 | 206 | 221 | 260 | 210 |
| Sr | ppm | 347 | 240 | 579 | 302 | 172 | 405 |
| Y | ppm | 36 | 22 | 23 | 25 | 24 | 33.5 |
| Zr | ppm | 442 | 249 | 280 | 332 | 389 | 450 |
| Nb | ppm | 61.0 | 36 | 38 | 44 | 53 | 65.5 |
| Mo | ppm | < 2 | < 2 | 3 | <2 | < 2 | 2 |
| Ag | ppm | 3.8 | 2.0 | 0.7 | 1.2 | 1.0 | 2.8 |
| In | ppm | < 0.2 | < 0.2 | < 0.2 | <0.2 | < 0.2 | < 0.1 |
| Sn | ppm | 12 | 4 | 5 | 8 | 6 | 6 |
| Sb | ppm | 1.3 | 0.9 | 0.6 | <0.5 | 1.2 | 1 |

| **Specimen** | | **PCO.03.01.AC.P1** | **SLI.04.01C.P1** | **POR.02.PO2C.P** | **PTR.02.01.P1** | **ANZ.02.01.P1 TOP** | **ANZ.02.01.P2** |
|---|---|---|---|---|---|---|---|
| | | mortar pumice | mortar pumice | mortar pumice | mortar pumice | mortar pumice | mortar pumice |
| Analyte | | | | | | | |
| Cs | ppm | 13.2 | 19.0 | 13.3 | 21.6 | 11.5 | 14.6 |
| Ba | ppm | 414 | 482 | 817 | 170 | 117 | 90 |
| La | ppm | 99.2 | 53.3 | 62.3 | 60.6 | 62.2 | 84.2 |
| Ce | ppm | 180 | 101 | 116 | 116 | 140 | 155 |
| Pr | ppm | 19.7 | 10.9 | 11.7 | 12.5 | 12.7 | 16.6 |
| Nd | ppm | 64.5 | 38.5 | 40.0 | 43.7 | 43.2 | 58.1 |
| Sm | ppm | 11.1 | 7.0 | 7.3 | 7.8 | 8.2 | 10.3 |
| Eu | ppm | 1.35 | 1.47 | 1.21 | 1.26 | 1.13 | 1.53 |
| Gd | ppm | 9.0 | 5.4 | 5.4 | 5.7 | 5.9 | 6.85 |
| Tb | ppm | 1.2 | 0.8 | 0.8 | 0.8 | 0.9 | 1.02 |
| Dy | ppm | 6.8 | 4.2 | 4.4 | 4.5 | 5.0 | 5.63 |
| Ho | ppm | 1.3 | 0.8 | 0.9 | 0.9 | 1.0 | 1.08 |
| Er | ppm | 3.7 | 2.2 | 2.4 | 2.5 | 2.7 | 3.12 |
| Tm | ppm | 0.54 | 0.34 | 0.38 | 0.39 | 0.45 | 0.482 |
| Yb | ppm | 3.7 | 2.2 | 2.5 | 2.6 | 2.9 | 3.29 |
| Lu | ppm | 0.63 | 0.35 | 0.40 | 0.39 | 0.49 | 0.517 |
| Hf | ppm | 10.1 | 5.1 | 5.5 | 7.2 | 7.7 | 9.1 |
| Ta | ppm | 3.8 | 1.9 | 2.3 | 2.7 | 3.4 | 3.59 |
| W | ppm | < 1 | < 1 | 1 | 1 | 5 | 2.6 |
| Tl | ppm | 2.1 | 1.2 | 1.0 | 2.2 | 2.1 | 1.3 |
| Pb | ppm | 57 | 34 | 32 | 22 | 48 | 49 |
| Bi | ppm | 0.9 | < 0.4 | < 0.4 | 0.9 | 0.5 | 0.2 |
| Th | ppm | 48.0 | 24.6 | 28.7 | 32.6 | 39.5 | 43.9 |
| U | ppm | 13.9 | 7.6 | 9.7 | 10.4 | 13.8 | 11.5 |

| **Specimen** | | **BAI.06.01.P1** | **BAI.06.03.P2** | **BAI.06.03.P3** | **BAI.06.05.B.P1** | **BAI.06.05.P2** |
|---|---|---|---|---|---|---|
| | | mortar pumice | mortar pumice | mortar pumice | mortar pumice | mortar pumice |
| Analyte | | | | | | |
| $SiO_2$ | wt% | 46.41 | 40.90 | 50.28 | 49.75 | 50.99 |
| $Al_2O_3$ | wt% | 15.46 | 14.48 | 14.83 | 14.83 | 15.91 |
| $Fe_2O_3$(T) | wt% | 2.58 | 2.53 | 3.06 | 2.65 | 3.00 |
| MnO | wt% | 0.12 | 0.10 | 0.14 | 0.14 | 0.13 |
| MgO | wt% | 0.51 | 0.48 | 4.62 | 1.40 | 4.81 |
| CaO | wt% | 7.55 | 11.49 | 2.63 | 2.27 | 1.89 |
| $Na_2O$ | wt% | 4.40 | 3.60 | 4.31 | 5.18 | 4.43 |
| $K_2O$ | wt% | 6.93 | 5.01 | 5.34 | 5.48 | 5.92 |
| $TiO_2$ | wt% | 0.34 | 0.31 | 0.38 | 0.40 | 0.41 |
| $P_2O_5$ | wt% | 0.05 | 0.06 | 0.08 | 0.02 | 0.07 |
| LOI | wt% | 16.23 | 20.99 | 15.28 | 17.25 | 13.38 |
| Total | wt% | 100.6 | 100.0 | 101.0 | 99.4 | 100.9 |
| Sc | ppm | 2 | 2 | 2 | 1 | 2 |
| Be | ppm | 13 | 11 | 14 | 10 | 14 |
| V | ppm | 35 | 35 | 57 | 25 | 38 |
| Cr | ppm | < 20 | < 20 | < 20 | < 20 | < 20 |
| Co | ppm | < 1 | 2 | 3 | 1 | 2 |
| Ni | ppm | < 20 | < 20 | < 20 | < 20 | < 20 |
| Cu | ppm | 10 | 80 | < 10 | 30 | < 10 |
| Zn | ppm | 70 | 80 | 70 | 100 | 80 |
| Ga | ppm | 19 | 16 | 16 | 12 | 17 |
| Ge | ppm | 1 | < 1 | 1 | 1 | 2 |
| As | ppm | 16 | 16 | 25 | 16 | 28 |
| Rb | ppm | 313 | 277 | 247 | 123 | 249 |
| Sr | ppm | 155 | 221 | 207 | 237 | 508 |
| Y | ppm | 34 | 27 | 33 | 23 | 34 |
| Zr | ppm | 439 | 375 | 498 | 453 | 512 |
| Nb | ppm | 66 | 54 | 64 | 83 | 69 |
| Mo | ppm | < 2 | 3 | 2 | < 2 | 4 |
| Ag | ppm | 2.2 | 2.4 | 3.3 | 2.0 | 3.8 |
| In | ppm | < 0.2 | < 0.2 | < 0.2 | < 0.2 | < 0.2 |
| Sn | ppm | 6 | 9 | 7 | 8 | 7 |
| Sb | ppm | 1.5 | 1.4 | 1.5 | 0.5 | 1.6 |

| **Specimen** | | **BAI.06.01.P1** | **BAI.06.03.P2** | **BAI.06.03.P3** | **BAI.06.05.B.P1** | **BAI.06.05.P2** |
|---|---|---|---|---|---|---|
| | | mortar pumice | mortar pumice | mortar pumice | mortar pumice | mortar pumice |
| Analyte | | | | | | |
| Cs | ppm | 9.0 | 11.3 | 23.8 | 7.5 | 20.9 |
| Ba | ppm | 94 | 112 | 245 | 902 | 289 |
| La | ppm | 99.1 | 73.7 | 79.6 | 54 | 87.1 |
| Ce | ppm | 185 | 136 | 150 | 193 | 165 |
| Pr | ppm | 18.8 | 13.7 | 15.6 | 11.5 | 17.2 |
| Nd | ppm | 62.8 | 46.8 | 53.5 | 38.2 | 58.9 |
| Sm | ppm | 10.6 | 8.2 | 9.5 | 7.6 | 10.5 |
| Eu | ppm | 1.38 | 1.21 | 1.33 | 1.24 | 1.43 |
| Gd | ppm | 7.7 | 6.1 | 7.6 | 6.0 | 8.1 |
| Tb | ppm | 1.1 | 0.9 | 1.1 | 1.0 | 1.1 |
| Dy | ppm | 5.9 | 5.0 | 5.6 | 5.7 | 6 |
| Ho | ppm | 1.2 | 1.0 | 1.1 | 1.1 | 1.1 |
| Er | ppm | 3.5 | 2.8 | 3.3 | 3.5 | 3.4 |
| Tm | ppm | 0.52 | 0.44 | 0.51 | 0.59 | 0.52 |
| Yb | ppm | 3.4 | 3.0 | 3.4 | 3.9 | 3.4 |
| Lu | ppm | 0.50 | 0.48 | 0.56 | 0.57 | 0.54 |
| Hf | ppm | 9.8 | 7.5 | 9.3 | 12.3 | 10.0 |
| Ta | ppm | 3.4 | 3.2 | 3.3 | 4.7 | 3.7 |
| W | ppm | 2 | 12 | 4 | 7 | 4 |
| Tl | ppm | 1.5 | < 0.1 | 2.0 | < 0.1 | 1.3 |
| Pb | ppm | 52 | 58 | 48 | 76 | 51 |
| Bi | ppm | < 0.4 | 0.5 | 0.6 | 0.7 | 0.5 |
| Th | ppm | 43.5 | 36.6 | 43.8 | 55.8 | 47.6 |
| U | ppm | 14.1 | 11.9 | 13 | 8.1 | 11.9 |

| **Specimen** | | **EGN.08.01.P1** | **EGN.08.02.P1** | **CHR.07.2/ AB.P1** | **CHR.07.02.P2** | **POM.09.2/ A.P1** | **CAE.05.05.P1** | **CAE.05.02.P2** |
|---|---|---|---|---|---|---|---|---|
| | | mortar pumice | mortar pumice | mortar pumice | mortar pumice | mortar pumice | mortar pumice | mortar pumice |
| Analyte | | | | | | | | |
| $SiO_2$ | wt% | 48.94 | 45.80 | 43.18 | 43.29 | 48.25 | 42.65 | 57.27 |
| $Al_2O_3$ | wt% | 14.16 | 13.94 | 13.37 | 14.07 | 13.88 | 13.42 | 17.32 |
| $Fe_2O_3$(T) | wt% | 2.59 | 2.87 | 2.55 | 2.50 | 2.67 | 2.53 | 2.60 |
| MnO | wt% | 0.13 | 0.11 | 0.11 | 0.12 | 0.13 | 0.10 | 0.14 |
| MgO | wt% | 5.19 | 0.51 | 4.23 | 6.31 | 7.21 | 8.65 | 0.84 |
| CaO | wt% | 1.92 | 7.41 | 5.13 | 1.99 | 2.01 | 0.95 | 3.17 |
| $Na_2O$ | wt% | 4.69 | 4.53 | 5.09 | 5.18 | 3.83 | 4.65 | 4.39 |
| $K_2O$ | wt% | 4.96 | 4.81 | 4.27 | 4.32 | 4.41 | 3.78 | 6.67 |
| $TiO_2$ | wt% | 0.34 | 0.36 | 0.32 | 0.32 | 0.34 | 0.33 | 0.43 |
| $P_2O_5$ | wt% | 0.05 | 0.06 | 0.05 | 0.03 | 0.04 | 0.03 | 0.01 |
| LOI | wt% | 16.59 | 18.58 | 20.96 | 21.11 | 17.17 | 20.84 | 8.13 |
| Total | wt% | 99.6 | 99.0 | 99.2 | 99.2 | 99.9 | 97.9 | 101.0 |
| Sc | ppm | 1 | 2 | 1 | 1 | 1 | 1 | 1 |
| Be | ppm | 17 | 12 | 13 | 14 | 17 | 11 | 17 |
| V | ppm | 24 | 37 | 28 | 26 | 30 | 34 | 30 |
| Cr | ppm | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 |
| Co | ppm | 2 | 3 | 2 | 2 | 2 | 2 | < 1 |
| Ni | ppm | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 |
| Cu | ppm | 20 | 40 | 10 | < 10 | 20 | < 10 | < 10 |
| Zn | ppm | 90 | 100 | 80 | 70 | 100 | 70 | 60 |
| Ga | ppm | 23 | 20 | 19 | 16 | 25 | 14 | 22 |
| Ge | ppm | 1 | 2 | 1 | 1 | 1 | < 1 | 2 |
| As | ppm | 25 | 24 | 12 | 10 | 16 | 11 | 17 |
| Rb | ppm | 392 | 542 | 145 | 109 | 325 | 134 | 230 |
| Sr | ppm | 103 | 158 | 169 | 170 | 155 | 107 | 126 |
| Y | ppm | 39 | 29 | 24 | 23 | 40 | 23 | 29 |
| Zr | ppm | 532 | 371 | 407 | 494 | 552 | 405 | 647 |
| Nb | ppm | 99 | 72 | 78 | 64 | 104 | 49 | 84 |
| Mo | ppm | < 2 | < 2 | < 2 | < 2 | < 2 | < 2 | < 2 |
| Ag | ppm | 2.2 | 1.7 | 1.8 | 3.2 | 2.3 | 2.4 | 4.4 |
| In | ppm | < 0.2 | < 0.2 | < 0.2 | < 0.2 | < 0.2 | < 0.2 | < 0.2 |
| Sn | ppm | 8 | 7 | 7 | 6 | 8 | 5 | 9 |
| Sb | ppm | 2.1 | 1.6 | 1.3 | 0.9 | 2.5 | 1.2 | 3.1 |

| **Specimen** | | **EGN.08.01.P1** | **EGN.08.02.P1** | **CHR.07.2/AB.P1** | **CHR.07.02.P2** | **POM.09.2/ A.P1** | **CAE.05.05.P1** | **CAE.05.02.P2** |
|---|---|---|---|---|---|---|---|---|
| | | mortar pumice | mortar pumice | mortar pumice | mortar pumice | mortar pumice | mortar pumice | mortar pumice |
| Analyte | | | | | | | | |
| Cs | ppm | 17.2 | 21.0 | 4.3 | 4.0 | 11.0 | 4.3 | 7.2 |
| Ba | ppm | 185 | 125 | 149 | 206 | 207 | 291 | 129 |
| La | ppm | 129 | 102 | 85.4 | 58.5 | 128 | 39.4 | 84.1 |
| Ce | ppm | 252 | 196 | 219 | 149 | 258 | 88.3 | 207 |
| Pr | ppm | 25.1 | 19.2 | 18.6 | 12.7 | 25.7 | 9.77 | 17.4 |
| Nd | ppm | 84.0 | 65.2 | 62.2 | 42.4 | 85.5 | 33.7 | 56.6 |
| Sm | ppm | 14.5 | 11.1 | 11.0 | 7.8 | 15.0 | 6.7 | 10.0 |
| Eu | ppm | 1.71 | 1.83 | 1.58 | 0.96 | 1.61 | 1.08 | 1.28 |
| Gd | ppm | 10.8 | 8.4 | 8.2 | 5.8 | 11.0 | 5.1 | 7.7 |
| Tb | ppm | 1.6 | 1.3 | 1.2 | 0.9 | 1.7 | 0.8 | 1.2 |
| Dy | ppm | 8.7 | 6.5 | 6.2 | 4.5 | 8.9 | 4.2 | 6.0 |
| Ho | ppm | 1.6 | 1.3 | 1.1 | 0.9 | 1.7 | 0.8 | 1.1 |
| Er | ppm | 4.8 | 3.6 | 3.4 | 2.7 | 4.9 | 2.4 | 3.5 |
| Tm | ppm | 0.75 | 0.57 | 0.53 | 0.41 | 0.77 | 0.37 | 0.54 |
| Yb | ppm | 5.0 | 3.8 | 3.3 | 2.8 | 5.1 | 2.5 | 3.6 |
| Lu | ppm | 0.73 | 0.54 | 0.48 | 0.46 | 0.73 | 0.42 | 0.57 |
| Hf | ppm | 14.1 | 9.9 | 11.0 | 9.6 | 14.3 | 7.4 | 13.0 |
| Ta | ppm | 5.1 | 3.7 | 4.1 | 3.4 | 5.4 | 2.7 | 4.6 |
| W | ppm | 14 | 13 | 18 | 2 | 28 | 2 | 2 |
| Tl | ppm | 0.1 | 0.1 | < 0.1 | 2.0 | 0.1 | 1.5 | 1.4 |
| Pb | ppm | 56 | 47 | 50 | 37 | 73 | 46 | 58 |
| Bi | ppm | 0.7 | 0.6 | 0.4 | 0.5 | 0.5 | 0.6 | 0.6 |
| Th | ppm | 65.1 | 45.9 | 51.8 | 45.5 | 65.5 | 34.6 | 65.6 |
| U | ppm | 20.5 | 14.5 | 10.7 | 8.6 | 20.2 | 8.2 | 10.9 |

| **Specimen** | | **CAE.1983.P1** | **PCO.03.04A/B.T1** | **PCO.SPRH.T1** | **SLI.04.01.T1** | **PTR.02.02.TL1** | **97.11B.TL** |
|---|---|---|---|---|---|---|---|
| | | mortar pumice | tuff *caementa* | tuff *caementa* | tuff *caementa* | tuff *caementa* | Tufo Lionato |
| Analyte | | | | | | | |
| $SiO_2$ | wt% | 53.04 | 48.28 | 54.50 | 48.29 | 36.79 | 42.3 |
| $Al_2O_3$ | wt% | 16.62 | 14.55 | 16.44 | 15.51 | 14.74 | 15.65 |
| $Fe_2O_3$(T) | wt% | 3.18 | 3.11 | 3.16 | 4.10 | 6.18 | 6.68 |
| MnO | wt% | 0.12 | 0.099 | 0.082 | 0.11 | 0.153 | 0.153 |
| MgO | wt% | 4.28 | 0.75 | 0.78 | 2.49 | 2.05 | 3.05 |
| CaO | wt% | 2.37 | 5.17 | 2.35 | 1.34 | 12.65 | 11.14 |
| $Na_2O$ | wt% | 3.96 | 3.79 | 3.22 | 4.77 | 2.54 | 0.76 |
| $K_2O$ | wt% | 6.21 | 6.97 | 6.71 | 6.77 | 6.04 | 5.49 |
| $TiO_2$ | wt% | 0.40 | 0.356 | 0.397 | 0.44 | 0.606 | 0.666 |
| $P_2O_5$ | wt% | 0.09 | 0.12 | 0.11 | 0.14 | 0.32 | 0.41 |
| LOI | wt% | 9.93 | 16.23 | 11.51 | 15.65 | 18.11 | 13.77 |
| Total | wt% | 100.19 | 99.41 | 99.26 | 99.6 | 100.2 | 100.1 |
| Sc | ppm | 2 | 3 | 3 | 4 | 8 | 12 |
| Be | ppm | 10 | 7 | 8 | 7 | 13 | 13 |
| V | ppm | 46 | 67 | 58 | 70 | 194 | 228 |
| Cr | ppm | <20 | < 20 | <20 | < 20 | < 20 | 30 |
| Co | ppm | 27 | 2 | 6 | 6 | 14 | 19 |
| Ni | ppm | 24 | < 20 | <20 | < 20 | < 20 | 20 |
| Cu | ppm | 14 | < 10 | 21 | < 10 | 40 | 60 |
| Zn | ppm | 46 | 60 | 46 | 70 | 90 | 90 |
| Ga | ppm | 17 | 16 | 16 | 15 | 17 | 18 |
| Ge | ppm | 1 | 1.4 | 1.1 | 1 | 1.6 | 1.6 |
| As | ppm | <5 | 13 | 9 | 8 | 37 | 28 |
| Rb | ppm | 182 | 337 | 288 | 230 | 317 | 349 |
| Sr | ppm | 510 | 269 | 801 | 355 | 1557 | 2349 |
| Y | ppm | 25.2 | 23.7 | 26.5 | 23 | 38.4 | 38.4 |
| Zr | ppm | 348 | 241 | 263 | 238 | 365 | 375 |
| Nb | ppm | 50 | 37.4 | 37.2 | 32 | 36.7 | 35.4 |
| Mo | ppm | 4 | < 2 | <2 | < 2 | < 2 | < 2 |
| Ag | ppm | <0.5 | 1.3 | <0.5 | 1.9 | 1.7 | 2.4 |
| In | ppm | <0.1 | < 0.1 | <0.1 | < 0.2 | < 0.1 | < 0.1 |
| Sn | ppm | 2 | 3 | 3 | 4 | 3 | 4 |
| Sb | ppm | 0.2 | 0.3 | 0.7 | 0.7 | 1.3 | 1.3 |

| **Specimen** | | **CAE.1983.P1** | **PCO.03.04A/B.T1** | **PCO.SPRH.T1** | **SLI.04.01.T1** | **PTR.02.02.TL1** | **97.11B.TL** |
|---|---|---|---|---|---|---|---|
| | | mortar pumice | tuff *caementa* | tuff *caementa* | tuff *caementa* | tuff *caementa* | Tufo Lionato |
| Analyte | | | | | | | |
| Cs | ppm | 11.0 | 18.3 | 38.6 | 16.1 | 19.0 | 24.3 |
| Ba | ppm | 412 | 591 | 782 | 1394 | 2456 | 2815 |
| La | ppm | 53.7 | 57.9 | 51.4 | 51.9 | 166 | 159 |
| Ce | ppm | 99.20 | 105 | 90.3 | 99.2 | 290 | 286 |
| Pr | ppm | 11.6 | 11.6 | 11.3 | 10.6 | 31.1 | 31.2 |
| Nd | ppm | 39.4 | 41.5 | 40.0 | 38.5 | 107.0 | 111.0 |
| Sm | ppm | 6.89 | 7.37 | 7.17 | 7.1 | 18.2 | 18.8 |
| Eu | ppm | 1.49 | 1.76 | 1.92 | 1.8 | 3.55 | 3.71 |
| Gd | ppm | 5.63 | 5.31 | 6.06 | 5.7 | 10.9 | 11.8 |
| Tb | ppm | 0.83 | 0.79 | 0.9 | 0.8 | 1.46 | 1.52 |
| Dy | ppm | 4.51 | 4.14 | 4.67 | 4.2 | 7.38 | 7.28 |
| Ho | ppm | 0.83 | 0.75 | 0.87 | 0.8 | 1.2 | 1.19 |
| Er | ppm | 2.45 | 2.18 | 2.48 | 2.2 | 3.15 | 3.17 |
| Tm | ppm | 0.394 | 0.334 | 0.37 | 0.33 | 0.429 | 0.421 |
| Yb | ppm | 2.59 | 2.22 | 2.45 | 2.1 | 2.56 | 2.51 |
| Lu | ppm | 0.376 | 0.343 | 0.348 | 0.34 | 0.383 | 0.364 |
| Hf | ppm | 8.6 | 5.0 | 6.5 | 4.9 | 6.5 | 7.0 |
| Ta | ppm | 3.44 | 2.03 | 2.53 | 1.7 | 1.59 | 1.49 |
| W | ppm | 68.5 | 1.3 | 28.5 | 1.0 | 1.2 | 2.8 |
| Tl | ppm | 0.35 | 0.85 | 1.13 | 0.9 | 2.18 | 3.33 |
| Pb | ppm | 8 | 35 | 26 | 39 | 118 | 117 |
| Bi | ppm | <0.1 | 0.2 | 0.2 | 0.5 | 0.7 | 0.8 |
| Th | ppm | 39.90 | 24.1 | 30.1 | 22.6 | 79.5 | 77.7 |
| U | ppm | 10.6 | 6.92 | 5.33 | 4.2 | 16.2 | 9.64 |

| **Specimen** | | **ANZ.02.01.T1** | **BAI.06.03.T1** | **POZ-01.T1** | **BAIAE-02.T1** | **BRI.05.02.T1** | **BRI.06.01.T1** |
|---|---|---|---|---|---|---|---|
| | | tuff *caementa* | tuff *caementa* | tuff *caementa* | tuff *caementa* | Bacoli Tuff *caementa* | |
| Analyte | | | | | | | |
| $SiO_2$ | wt% | 46.96 | 49.18 | 57.05 | 59.49 | 51.77 | 52.17 |
| $Al_2O_3$ | wt% | 14.17 | 14.9 | 17.42 | 17.4 | 15.33 | 15.33 |
| $Fe_2O_3$(T) | wt% | 3.23 | 3.47 | 4.02 | 3.34 | 3.49 | 3.47 |
| MnO | wt% | 0.101 | 0.107 | 0.11 | 0.18 | 0.11 | 0.11 |
| MgO | wt% | 3.35 | 3.63 | 1.48 | 0.35 | 0.85 | 0.8 |
| CaO | wt% | 4.27 | 1.79 | 1.28 | 2.06 | 2.48 | 2.41 |
| $Na_2O$ | wt% | 4.66 | 4.33 | 3.92 | 4.66 | 3.65 | 3.04 |
| $K_2O$ | wt% | 5.69 | 5.81 | 8.66 | 6.89 | 7.75 | 7.87 |
| $TiO_2$ | wt% | 0.355 | 0.391 | 0.46 | 0.39 | 0.381 | 0.385 |
| $P_2O_5$ | wt% | 0.13 | 0.13 | 0.19 | 0.05 | 0.13 | 0.13 |
| LOI | wt% | 16.62 | 16.73 | 5.61 | 4.32 | 14.12 | 14.14 |
| Total | wt% | 99.53 | 100.5 | 99.62 | 99.08 | 100.1 | 99.86 |
| Sc | ppm | 3 | 3 | 4 | 2 | 3 | 3 |
| Be | ppm | 8 | 8 | 8 | 19 | 8 | 8 |
| V | ppm | 64 | 72 | 85 | 19 | 66 | 63 |
| Cr | ppm | < 20 | < 20 | <20 | <20 | < 20 | < 20 |
| Co | ppm | 3 | 4 | 12 | 25 | 3 | 3 |
| Ni | ppm | < 20 | < 20 | <20 | <20 | < 20 | < 20 |
| Cu | ppm | < 10 | < 10 | <10 | <10 | < 10 | < 10 |
| Zn | ppm | 70 | 70 | 75 | 90 | 70 | 70 |
| Ga | ppm | 16 | 16 | 17 | 22 | 16 | 16 |
| Ge | ppm | 1.6 | 1.1 | 1.2 | 1.8 | 1.5 | 1.6 |
| As | ppm | 26 | 10 | 17 | 28 | 11 | 12 |
| Rb | ppm | 204 | 244 | 236 | 379 | 281 | 301 |
| Sr | ppm | 263 | 312 | 772 | 43(?) | 453 | 511 |
| Y | ppm | 25.1 | 25.7 | 28.4 | 54.7 | 24.2 | 25.9 |
| Zr | ppm | 271 | 252 | 274 | 608 | 245 | 259 |
| Nb | ppm | 39.4 | 38 | 39.8 | 90.1 | 38.1 | 39.4 |
| Mo | ppm | 4 | < 2 | <2 | 6 | < 2 | < 2 |
| Ag | ppm | 1.1 | 1.4 | <0.5 | <0.5 | 1.1 | 1.7 |
| In | ppm | < 0.1 | < 0.1 | <0.1 | <0.1 | < 0.1 | < 0.1 |
| Sn | ppm | 3 | 3 | 4 | 7 | 3 | 3 |
| Sb | ppm | 0.4 | < 0.2 | 0.9 | 1.8 | < 0.2 | < 0.2 |

| **Specimen** | | **ANZ.02.01.T1** | **BAI.06.03.T1** | **POZ-01.T1** | **BAIAE-02.T1** | **BRI.05.02.T1** | **BRI.06.01.T1** |
|---|---|---|---|---|---|---|---|
| | | tuff *caementa* | tuff *caementa* | tuff *caementa* | tuff *caementa* | Bacoli Tuff *caementa* | |
| Analyte | | | | | | | |
| Cs | ppm | 16.3 | 18.8 | 15.1 | 33.7 | 14.7 | 15.2 |
| Ba | ppm | 809 | 648 | 1230 | 33(?) | 824 | 839 |
| La | ppm | 63 | 60.9 | 58.8 | 116 | 58.8 | 63.3 |
| Ce | ppm | 114 | 111 | 107 | 200 | 109 | 115 |
| Pr | ppm | 12.2 | 12.4 | 12.6 | 24.9 | 11.8 | 12.6 |
| Nd | ppm | 42.6 | 44.3 | 44.2 | 81.9 | 41.0 | 44.8 |
| Sm | ppm | 7.78 | 8.29 | 7.99 | 14.1 | 7.35 | 8.21 |
| Eu | ppm | 1.67 | 1.89 | 2.22 | 1.75 | 1.77 | 1.94 |
| Gd | ppm | 5.43 | 5.81 | 6.75 | 11.7 | 5.48 | 5.75 |
| Tb | ppm | 0.81 | 0.84 | 0.93 | 1.69 | 0.81 | 0.83 |
| Dy | ppm | 4.42 | 4.56 | 5.05 | 9.34 | 4.31 | 4.77 |
| Ho | ppm | 0.82 | 0.86 | 0.92 | 1.77 | 0.78 | 0.88 |
| Er | ppm | 2.33 | 2.35 | 2.62 | 5.12 | 2.23 | 2.52 |
| Tm | ppm | 0.359 | 0.358 | 0.374 | 0.825 | 0.344 | 0.391 |
| Yb | ppm | 2.32 | 2.38 | 2.47 | 5.3 | 2.3 | 2.52 |
| Lu | ppm | 0.389 | 0.36 | 0.373 | 0.78 | 0.361 | 0.383 |
| Hf | ppm | 5.4 | 5.2 | 6.2 | 14.6 | 5.1 | 5.5 |
| Ta | ppm | 2.17 | 2.1 | 2.48 | 7.38 | 2 | 2.17 |
| W | ppm | 2.5 | 0.6 | 28.2 | 171 | 0.9 | 0.8 |
| Tl | ppm | 1.52 | 1.09 | 1.75 | 2.18 | 1.54 | 1.92 |
| Pb | ppm | 39 | 37 | 43 | 65 | 35 | 41 |
| Bi | ppm | 0.2 | 0.1 | 0.2 | 0.4 | < 0.1 | 0.2 |
| Th | ppm | 27.1 | 25.5 | 29.7 | 74.3 | 24.8 | 26.5 |
| U | ppm | 8.59 | 6.73 | 6.03 | 18.6 | 6.0 | 5.89 |

| **Specimen** | | **PCO.03.02A.M1** | **PCO.03.04AB.M1** | **PCO.03.05A.M1** | **PTR.02.02.M1** | **PTR.02.01.CM** | **ANZ.02.01.M1** |
|---|---|---|---|---|---|---|---|
| | | bulk mortar | bulk mortar | bulk mortar | bulk mortar | bulk mortar | bulk mortar |
| Analyte | | | | | | | |
| $SiO_2$ | wt% | 41.93 | 35.76 | 43.33 | 42.91 | 33.71 | 40.79 |
| $Al_2O_3$ | wt% | 9.1 | 10.5 | 11.92 | 12.7 | 9.95 | 12.14 |
| $Fe_2O_3$(T) | wt% | 2.61 | 2.83 | 4.03 | 2.66 | 2.63 | 2.49 |
| MnO | wt% | 0.111 | 0.093 | 0.111 | 0.148 | 0.102 | 0.092 |
| MgO | wt% | 1.59 | 1.11 | 11.4 | 1.38 | 1.26 | 5.09 |
| CaO | wt% | 21.19 | 19.37 | 6.23 | 15.13 | 24.1 | 10 |
| $Na_2O$ | wt% | 1.05 | 2.76 | 2.57 | 2.57 | 1.28 | 3.2 |
| $K_2O$ | wt% | 3.51 | 2.94 | 2.74 | 4.5 | 2.44 | 4.21 |
| $TiO_2$ | wt% | 0.211 | 0.3 | 0.408 | 0.327 | 0.266 | 0.303 |
| $P_2O_5$ | wt% | 0.07 | 0.11 | 0.13 | 0.09 | 0.18 | 0.09 |
| LOI | wt% | 19.35 | 22.75 | 16.45 | 17.23 | 23.51 | 18.95 |
| Total | wt% | 100.7 | 98.52 | 99.32 | 99.65 | 99.43 | 97.35 |
| Sc | ppm | 5 | 3 | 9 | 2 | 2 | 2 |
| Be | ppm | 3 | 7 | 7 | 12 | 9 | 10 |
| V | ppm | 56 | 62 | 93 | 57 | 42 | 61 |
| Cr | ppm | 20 | < 20 | 50 | < 20 | 40 | 20 |
| Co | ppm | 4 | 2 | 7 | 2 | 4 | 2 |
| Ni | ppm | < 20 | < 20 | < 20 | < 20 | <20 | < 20 |
| Cu | ppm | < 10 | 50 | 30 | < 10 | 160 | 50 |
| Zn | ppm | 60 | 80 | 70 | 70 | 180 | 50 |
| Ga | ppm | 9 | 11 | 14 | 16 | 10 | 14 |
| Ge | ppm | 1.2 | 1.1 | 1.2 | 1.4 | <1 | < 1 |
| As | ppm | 29 | 14 | 14 | 26 | 39 | 10 |
| Rb | ppm | 145 | 126 | 102 | 220 | 115 | 198 |
| Sr | ppm | 767 | 682 | 606 | 604 | 863 | 384 |
| Y | ppm | 16.2 | 21.4 | 23 | 30.2 | 26 | 24 |
| Zr | ppm | 100 | 224 | 223 | 387 | 311 | 299 |
| Nb | ppm | 10.8 | 32.5 | 28.9 | 54.2 | 44 | 42 |
| Mo | ppm | < 2 | < 2 | < 2 | 3 | 3 | 2 |
| Ag | ppm | < 0.5 | 1.1 | 1.1 | 2.1 | 1.2 | 2.9 |
| In | ppm | < 0.1 | < 0.1 | < 0.1 | < 0.1 | <0.2 | < 0.2 |
| Sn | ppm | < 1 | 5 | 9 | 3 | 10 | 4 |
| Sb | ppm | 0.5 | < 0.2 | < 0.2 | 0.5 | <0.5 | < 0.5 |

| **Specimen** | | **PCO.03.02A.M1** | **PCO.03.04AB.M1** | **PCO.03.05A.M1** | **PTR.02.02.M1** | **PTR.02.01.CM** | **ANZ.02.01.M1** |
|---|---|---|---|---|---|---|---|
| | | bulk mortar | bulk mortar | bulk mortar | bulk mortar | bulk mortar | bulk mortar |
| Analyte | | | | | | | |
| Cs | ppm | 5.9 | 6.9 | 6.9 | 17.5 | 9.2 | 16.5 |
| Ba | ppm | 881 | 742 | 875 | 369 | 329 | 368 |
| La | ppm | 32 | 50.5 | 49.6 | 82.9 | 60.8 | 73.5 |
| Ce | ppm | 52.7 | 92.4 | 93.3 | 150 | 116 | 132 |
| Pr | ppm | 6.52 | 10.1 | 10.9 | 15.6 | 12.5 | 14.1 |
| Nd | ppm | 24.3 | 36.3 | 40.1 | 53.3 | 43.5 | 46.0 |
| Sm | ppm | 4.63 | 6.69 | 7.79 | 9.19 | 7.9 | 8.0 |
| Eu | ppm | 1.35 | 1.33 | 1.7 | 1.43 | 1.13 | 1.33 |
| Gd | ppm | 3.79 | 4.67 | 5.5 | 6.11 | 5.7 | 6.4 |
| Tb | ppm | 0.54 | 0.7 | 0.79 | 0.94 | 0.9 | 0.9 |
| Dy | ppm | 2.95 | 3.79 | 4.1 | 5.18 | 4.5 | 4.8 |
| Ho | ppm | 0.53 | 0.71 | 0.75 | 0.96 | 0.9 | 0.9 |
| Er | ppm | 1.39 | 1.99 | 2.02 | 2.81 | 2.5 | 2.5 |
| Tm | ppm | 0.204 | 0.302 | 0.301 | 0.436 | 0.38 | 0.37 |
| Yb | ppm | 1.29 | 2.12 | 1.91 | 2.98 | 2.5 | 2.6 |
| Lu | ppm | 0.192 | 0.316 | 0.314 | 0.467 | 0.38 | 0.45 |
| Hf | ppm | 2.3 | 4.5 | 4.8 | 7.8 | 6.6 | 6.7 |
| Ta | ppm | 0.65 | 1.79 | 1.97 | 2.92 | 2.5 | 2.3 |
| W | ppm | 1.2 | 2.3 | 1.1 | 4.8 | 6.0 | 2.0 |
| Tl | ppm | 0.88 | 1.32 | 1.11 | 2.74 | 0.9 | 1.1 |
| Pb | ppm | 48 | 33 | 51 | 55 | 29 | 35 |
| Bi | ppm | < 0.1 | < 0.1 | < 0.1 | 0.2 | 0.6 | < 0.4 |
| Th | ppm | 11.1 | 21.8 | 19.6 | 40.8 | 33.2 | 32.3 |
| U | ppm | 3.37 | 7.36 | 6.42 | 12.6 | 9.8 | 10.7 |

*Table A4.3: Major element compositions of mortars of the sea-water concretes, determined through powder XRF analyses.*

| | | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | $Mn_2O_3$ | MgO | CaO | $Na_2O$ | $K_2O$ | $TiO_2$ | $P_2O_5$ | L.o.i. | $Cl^-$ | $SO_3$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Ancient mortar specimen** | | wt% | wt% | wt% | wt% | wt% | wt% | wt% | wt% | wt% | wt% | wt% | | |
| SLI.04.01.A | *bulk*[1] | 40.89 | 12.22 | 3.28 | 0.09 | 2.38 | 12.15 | 3.11 | 4.72 | 0.34 | 0.14 | 19.20 | 1.13 | 0.29 |
| COSA-40 | bulk | 47.50 | 12.50 | 2.81 | 0.11 | 7.57 | 2.81 | 3.44 | 4.09 | 0.38 | 0.09 | 18.57 | n.d | n.d |
| PCO.03.01 | >1mm | 43.30 | 11.30 | 2.83 | 0.09 | 1.46 | 18.60 | 1.73 | 4.08 | 0.32 | 0.09 | 15.20 | 0.54 | 0.21 |
| PCO.03.02 | 0.2-1mm | 43.30 | 10.60 | 2.99 | 0.11 | 1.63 | 20.30 | 1.41 | 3.49 | 0.32 | 0.09 | 14.90 | 0.64 | 0.29 |
| POR.02.01 | bulk | 39.04 | 15.84 | 6.66 | 0.21 | 2.32 | 9.79 | 2.24 | 5.15 | 0.66 | 0.31 | 16.72 | n.d | n.d |
| POR.02.02 | bulk | 38.45 | 16.05 | 6.24 | 0.15 | 2.54 | 11.35 | 1.87 | 5.46 | 0.81 | 0.25 | 16.34 | n.d | n.d |
| ANZIO-42 | bulk | 46.60 | 11.20 | 2.41 | 0.11 | 7.80 | 5.26 | 3.64 | 3.94 | 0.35 | 0.09 | 18.97 | n.d | n.d |
| BAIA-38 | bulk | 47.40 | 10.80 | 2.01 | 0.11 | 1.20 | 9.65 | 4.37 | 5.84 | 0.30 | 0.09 | 17.33 | n.d | n.d |
| BAI.06.01 | bulk | 43.32 | 12.85 | 2.27 | 0.10 | 1.78 | 17.67 | 3.10 | 4.76 | 0.26 | 0.08 | 13.37 | 1.49 | 0.18 |
| BAI 06.03 | bulk | 45.58 | 13.96 | 2.56 | 0.12 | 0.93 | 15.76 | 2.95 | 5.39 | 0.28 | 0.09 | 11.93 | 1.25 | 0.20 |
| BAI 06.02 | bulk | 52.80 | 15.66 | 3.00 | 0.14 | 6.01 | 2.09 | 4.29 | 6.17 | 0.33 | 0.10 | 8.97 | 1.10 | 0.16 |
| BAI 06.04 | bulk | 52.90 | 16.15 | 3.25 | 0.13 | 4.79 | 0.75 | 4.45 | 6.26 | 0.33 | 0.13 | 10.03 | 0.98 | 0.61 |
| BAI 06.05 | bulk | 52.17 | 15.26 | 2.80 | 0.14 | 7.78 | 1.01 | 4.09 | 6.04 | 0.31 | 0.11 | 9.90 | 1.03 | 0.18 |
| EGN.08.01 | bulk, top | 37.45 | 9.95 | 2.20 | 0.10 | 6.36 | 12.89 | 2.83 | 3.66 | 0.30 | 0.11 | 23.24 | n.d. | 0.61 |
| EGN.08.01 | bulk, middle | 39.09 | 10.67 | 2.23 | 0.11 | 2.15 | 12.06 | 2.93 | 3.91 | 0.29 | 0.08 | 25.03 | n.d. | 1.22 |
| EGN.08.01 | bulk, base | 41.15 | 11.34 | 2.49 | 0.12 | 5.88 | 8.07 | 3.45 | 3.95 | 0.33 | 0.09 | 21.93 | n.d. | 0.97 |
| EGN.08.02 | bulk, top | 40.74 | 11.09 | 2.33 | 0.11 | 0.97 | 12.78 | 2.95 | 4.14 | 0.29 | 0.08 | 23.74 | n.d. | 0.56 |
| EGN.08.02 | bulk, top | 39.26 | 10.51 | 2.26 | 0.11 | 0.86 | 13.32 | 2.86 | 3.96 | 0.30 | 0.08 | 24.36 | n.d. | 1.90 |
| EGN.08.01 | bulk, middle | 40.70 | 10.85 | 2.37 | 0.11 | 0.88 | 16.72 | 3.10 | 3.88 | 0.32 | 0.08 | 17.64 | n.d. | 3.09 |
| EGN.08.01 | bulk, middle | 44.31 | 11.90 | 2.58 | 0.13 | 0.86 | 12.55 | 3.10 | 4.62 | 0.34 | 0.09 | 18.86 | n.d. | 0.42 |
| EGN.08.01 | bulk, base | 43.46 | 11.52 | 2.56 | 0.12 | 0.98 | 15.17 | 2.88 | 4.44 | 0.35 | 0.10 | 17.21 | n.d. | 0.97 |
| EGN.08.02 | bulk, middle | 44.07 | 12.84 | 2.24 | 0.07 | 0.74 | 10.37 | 4.22 | 4.10 | 0.33 | 0.11 | 18.98 | 1.42 | 0.41 |
| EGN.08.01 | bulk, middle | 43.21 | 11.74 | 2.25 | 0.08 | 4.03 | 7.72 | 4.32 | 3.72 | 0.33 | 0.07 | 20.43 | 1.42 | 0.53 |
| CHR.07.01 | bulk, base | 32.19 | 8.98 | 1.92 | 0.08 | 10.98 | 15.45 | 2.88 | 2.16 | 0.29 | 0.08 | 24.25 | n.d. | 0.53 |
| CHR.07.01 | bulk, middle | 15.28 | 4.45 | 1.18 | 0.06 | 14.51 | 24.82 | 1.40 | 1.11 | 0.13 | 0.06 | 36.35 | n.d. | 0.45 |
| CHR.07.01 | bulk, top | 22.15 | 6.85 | 1.84 | 0.06 | 6.30 | 28.26 | 1.75 | 1.82 | 0.21 | 0.06 | 30.14 | n.d. | 0.30 |
| CHR.07.02 | bulk, base | 29.08 | 7.79 | 1.69 | 0.08 | 12.74 | 16.49 | 2.18 | 1.86 | 0.19 | 0.07 | 27.20 | n.d. | 0.39 |
| CHR.07.02 | bulk, middle | 39.10 | 11.40 | 2.30 | 0.09 | 9.58 | 9.58 | 3.91 | 3.42 | 0.35 | 0.09 | 19.46 | n.d. | 0.44 |
| CHR.07.02 | bulk, top | 29.74 | 8.62 | 1.82 | 0.08 | 8.80 | 18.12 | 2.55 | 2.76 | 0.21 | 0.08 | 26.65 | n.d. | 0.32 |
| POM.09.01 | bulk, top | 36.65 | 10.13 | 2.13 | 0.05 | 0.94 | 23.72 | 1.81 | 2.47 | 0.29 | 0.06 | 21.19 | 0.27 | 0.16 |
| POM.09.02 | bulk, top | 32.81 | 8.54 | 2.09 | 0.04 | 1.14 | 23.01 | 3.09 | 1.95 | 0.28 | 0.08 | 24.05 | 1.15 | 1.69 |
| POM.09.02 | bulk, top | 42.85 | 12.40 | 2.69 | 0.09 | 1.09 | 17.94 | 2.78 | 4.42 | 0.34 | 0.11 | 14.98 | 0.43 | 0.14 |
| POM.09.02 | bulk, base | 46.93 | 12.88 | 2.84 | 0.10 | 6.92 | 5.53 | 2.73 | 3.38 | 0.37 | 0.08 | 17.66 | 0.41 | 0.08 |
| CAE.06 | bulk | 48.30 | 12.20 | 2.20 | 0.10 | 9.24 | 4.89 | 2.84 | 3.50 | 0.36 | 0.09 | 16.49 | n.d | n.d |
| CAE.05.01 | bulk | 41.69 | 11.90 | 2.49 | 0.10 | 1.78 | 15.54 | 3.25 | 4.09 | 0.27 | 0.12 | 16.69 | 0.94 | 0.98 |
| CAE.05.02 | bulk | 34.94 | 10.39 | 2.31 | 0.10 | 2.20 | 20.87 | 2.89 | 2.86 | 0.25 | 0.13 | 20.69 | 1.00 | 1.40 |
| CAE.05.03 | bulk | 38.32 | 9.02 | 2.14 | 0.09 | 17.51 | 6.29 | 2.00 | 1.87 | 0.24 | 0.10 | 19.41 | 1.43 | 1.60 |
| CAE.05.04 | bulk | 42.33 | 12.64 | 2.55 | 0.11 | 4.21 | 12.40 | 3.52 | 4.55 | 0.28 | 0.10 | 15.87 | 0.87 | 0.41 |
| CAE.05.05 | bulk | 39.70 | 11.61 | 2.51 | 0.12 | 3.94 | 15.65 | 3.14 | 3.74 | 0.29 | 0.13 | 16.94 | 0.96 | 1.08 |
| ALE.07.03a | bulk | 29.02 | 8.82 | 1.60 | 0.08 | 0.80 | 26.94 | 2.25 | 2.49 | 0.19 | 0.06 | 25.59 | n.d. | 1.29 |
| ALE.07.03b | *bulk* | 35.55 | 10.03 | 2.04 | 0.08 | 5.74 | 16.26 | 3.38 | 2.76 | 0.33 | 0.09 | 22.39 | n.d. | 0.70 |
| ALE.07.02 | *bulk* | 36.29 | 10.42 | 2.16 | 0.08 | 2.40 | 18.60 | 3.42 | 3.11 | 0.32 | 0.09 | 21.36 | n.d. | 1.14 |
| ALE.07.01 | *bulk* | 27.68 | 8.41 | 1.78 | 0.09 | 7.19 | 20.55 | 2.02 | 2.05 | 0.20 | 0.06 | 28.02 | n.d. | 1.31 |

| | | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | $Mn_2O_3$ | MgO | CaO | $Na_2O$ | $K_2O$ | $TiO_2$ | $P_2O_5$ | L.o.i. | $Cl^-$ | $SO_3$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Young mortar reproduction** | | | | | | | | | | | | | | |
| BRI-2005-01-A | *bulk, top* | 42.51 | 11.70 | 2.63 | 0.09 | 0.74 | 14.45 | 14.45 | 6.00 | 0.29 | 0.09 | 18.40 | 0.47 | 0.15 |
| BRI-2005-01-B | *bulk, top* | 41.70 | 11.70 | 2.57 | 0.09 | 0.92 | 14.75 | 14.75 | 5.67 | 0.28 | 0.09 | 18.99 | 0.95 | 0.23 |
| BRI-2005-01-C | bulk, base | 39.25 | 11.05 | 2.36 | 0.08 | 0.74 | 21.01 | 21.01 | 5.35 | 0.26 | 0.08 | 16.71 | 0.77 | 0.21 |
| BRI-2005-02-A | *bulk, top* | 46.32 | 13.96 | 2.68 | 0.10 | 0.93 | 12.67 | 12.67 | 6.27 | 0.27 | 0.11 | 12.69 | 0.80 | 0.22 |
| BRI-2005-02-B | bulk, base | 39.68 | 12.62 | 2.49 | 0.09 | 0.88 | 18.56 | 18.56 | 5.54 | 0.24 | 0.10 | 15.85 | 0.92 | 0.27 |
| BRI-2006-03 | bulk, top | 41.48 | 12.47 | 2.56 | 0.10 | 0.66 | 13.08 | 13.08 | 5.97 | 0.33 | 0.10 | 19.93 | 0.39 | 0.20 |
| BRI-2008-04 | bulk, top | 43.93 | 12.24 | 2.89 | 0.10 | 1.22 | 12.20 | 12.20 | 6.39 | 0.36 | 0.11 | 17.71 | n.d | 0.26 |
| BRI-2008-04 | bulk, top | 51.28 | 14.36 | 3.39 | 0.13 | 1.20 | 4.81 | 4.81 | 7.65 | 0.40 | 0.11 | 12.78 | n.d | 0.26 |
| BRI-2008-04 | bulk, middle | 45.26 | 12.56 | 2.92 | 0.11 | 1.18 | 13.02 | 13.02 | 6.09 | 0.34 | 0.10 | 15.37 | n.d | 0.27 |
| BRI-2008-04 | bulk, base | 47.84 | 13.33 | 3.13 | 0.12 | 0.98 | 8.74 | 8.74 | 7.07 | 0.38 | 0.11 | 15.08 | n.d | 0.20 |
| BRI-2008-04 | bulk, top | 45.06 | 12.53 | 2.84 | 0.11 | 0.93 | 12.02 | 12.02 | 6.43 | 0.35 | 0.10 | 16.61 | n.d | 0.23 |
| BRI-2008-04 | bulk, base | 48.71 | 13.61 | 3.17 | 0.13 | 1.60 | 7.21 | 7.21 | 7.35 | 0.39 | 0.10 | 14.28 | n.d | 0.27 |
| BRI-2009-05 | bulk, base | 35.41 | 10.54 | 2.09 | 0.05 | 0.73 | 14.39 | 14.39 | 4.59 | 0.25 | 0.05 | 28.03 | 0.86 | 0.17 |
| BRI-2009-05 | bulk, middle | 34.14 | 10.16 | 2.05 | 0.05 | 0.78 | 17.34 | 17.34 | 4.50 | 0.26 | 0.05 | 26.78 | 0.76 | 0.18 |
| BRI-2009-05 | bulk, middle | 45.07 | 13.39 | 2.76 | 0.08 | 0.89 | 12.19 | 12.19 | 5.93 | 0.34 | 0.08 | 14.96 | 0.70 | 0.16 |
| BRI-2009-05 | bulk, top | 39.35 | 11.70 | 2.36 | 0.06 | 0.86 | 14.04 | 14.04 | 5.04 | 0.27 | 0.05 | 22.24 | 0.75 | 0.19 |
| Bacoli Tuff | | 52.45 | 15.45 | 3.42 | 0.11 | 0.83 | 2.37 | 3.33 | 7.85 | 0.36 | 0.12 | 13.41 | n.d. | <0.06 |

| **Other ROMACONS specimens, not from drill cores** | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| COSA-1 | tuff *caementa* | 54.98 | 16.58 | 3.19 | 0.80 | 0.78 | 2.37 | 3.25 | 6.77 | 0.41 | 0.11 | 11.51 | | |
| COSA-28 | tuff *caementa* | 55.8 | 14.8 | 3.1 | 0.08 | 0.69 | 2.11 | 2.97 | 6.4 | 0.43 | 0.09 | 12.76 | | |
| CUMAE-22 | mortar | 49 | 11.6 | 1.7 | 0.11 | 0.3 | 13.7 | 3.08 | 4.39 | 0.26 | 0.09 | 16.04 | | |
| MISENUM-21 | mortar | 47.9 | 13.5 | 13.5 | 0.15 | 9.22 | 1.7 | 3.48 | 4.12 | 0.40 | 0.08 | 16.70 | | |
| CH-02 | mortar pumice | 48.69 | 14.28 | 3.36 | 0.11 | 3.16 | 2.1 | 5.17 | 4.65 | 0.36 | 0.06 | 98.88 | | |
| POM-7 | mortar pumice | 45.16 | 13.65 | 2.6 | 0.11 | 3.22 | 2.25 | 4.39 | 4.66 | 0.34 | 0.04 | 22.96 | | |

(1) Italics denote specimen with powder X-ray diffraction analysis

# BIBLIOGRAPHY

Adam, J- P. 1994 *Roman Building: Materials and Techniques*. London: Batsford.

Alberti, L. B. 1955 *Ten Books on Architecture.* J. Rykwert, ed. London: Alec Tiranti Ltd.

Allen, R. T., ed. 1998 *Concrete in Coastal Structures*. London: Telford.

Allen, S. R. and McPhie, J. 2000 "Water-settling and resedimentation of submarine rhyolitic pumice at Yali, eastern Aegean, Greece." *Journal of Volcanology and Geothermal Research* 85: 285–307.

Arangio-Ruiz, V. 1943 *Fontes Iuris Romani Antejustiniani*, vol. 3. Florence: Barbèra.

Arnaud, P. 2005 *Les routes de la navigation antique. Itinéraires en Méditerranée.* Paris: Editions Errance.

Arnaud, P. 2011 "Ancient Sailing-Routes and Trade Patterns: the Impact of human factors." pp. 61–80 in Robinson and Wilson, eds 2011.

Atzeni, C., Farci, A., Floris, D. and Meloni, P. 2004 "Effect of Aging on Rheological Properties of Lime Putty." *Journal of the American Ceramic Society* 87.1: 1764–66.

Auriemma, R. 2003 "Le Strutture Sommerse di Egnazia (BR): Una Rilettura." pp. 77–97 in A. Benini and M. Giacobelli, eds, *Atti del II Convegno Nazionale di Archeologia Subacquea, Castiglioncello, 7–9 Settembre 2001*.

Auriemma, R. 2004 *Salentum a Salo: Porti, approdi merci e scambi lungo la costa adriatica del Salento. I.* Galatina: Collana del Dipartimento 9.

Auriemma, R., Mastronuzzi, G. and Sensò, P. 2004a "Middle to Late Holocene Relative Sea-level Changes Recorded on the Coast of Apulia (Italy)". *Géomorphologie: relief, processus, environment* 10.1: 19–33.

Auriemma, R., Iannone, A., Mastronuzzi, G., Mauz, B., Sensò, P. and Selleri, G. 2004b "Late Holocene Sea-level Changes in Southern Apulia (Italy)." *GI$^2$S Coast, Research Publication* 4: 31–34.

Ayuso, R., De Vivo, B., Rolandi, G., Seal, R. and Paone, A. 1998 "Geochemical and isotopic (Nd-Pb-Sr-O) variations bearing on the genesis of volcanic rocks from Vesuvius, Italy." *Journal of Volcanological and Geothermal Research* 82: 53–78.

Bakos, F. *et al*. 1992 "Saggi di caratterizzaione petrologica e geochimica di pozzolane e malte pozzolaniche." *Materiali e Strutture* 2: 1–12.

Bakos, F. *et al.* 1994 "Saggi di caratterizzaione petrologica e chimica di malte pozzolaniche antiche (II)." *Materiali e Strutture* 4: 1–20.

Baly, D. 1974 *The Geography of the Bible.* 2nd ed. New York: Harper & Row.

Bartoccini, R. 1958 "Il Porto Romano de Leptis Magna." *Bull. Del Centro di Studi per la Storia dell' Architettura,* Suppl. 13: 27–31.

Basaran, S. 2008 " 'Iron Ways' and an Ancient Harbour on the Marmara Coast." pp. 1–22 in U. Kocabaş, ed., *The 'Old Ships' of the 'New Gate,'* vol. 1. Istanbul: Ege Yayinlari.

Bathrellos, G. D., Vasilatos, C., Skilodmiou, H. D. and Stamatakis, M. 2009 "On the occurrence of a pumice-rich layer in Holocene deposits of the western Peloponnesus, Ionian Sea. A geomorphological and geochemical approach." *Central European Journal of Geosciences* 1.1: 19–32.

Beaufort, F. 1817 *Karamania, or a brief description of the South Coast of Asia-Minor and of the Remains of Antiquity*. London: Printed for R. Hunter.

Begley, V. *et al.,* ed. 1996 *The Ancient Port of Arikamedu: New Excavations and Researches 1989–1992, vol. 1*. Pondichéry: École Française d'Extrême-Orient.

Bekker, E. 1846 *Iulii Pollucis Onomasticon.* Berlin: F. Nicolai.

Beloch, J. 1890 *Campanien. Geschichte und Topographie des antiken Neapel und seiner Umgebung*. 2nd ed. Breslau: Morgenstern.

Beltrame, C. 2012 "New Evidence for the Submerged Ancient Harbour Structures at Tolmetha and Leptis Magna, Libya." *International Journal of Nautical Archaeology* 41: 315–26.

Benini, A. 2002 "Note sulla tecnica edilizia del molo romano di S. Marco di Castellabate." *Archeologia subacquea* 3: 30–46.

Benini, A. 2006 "Strutture Sommerse a Miseno." *L'Archeologo Subacqueo* 12: 1–2: 19–20.

Benini, A. 2008 "Il porto e la peschiera di Miseno (NA): nuovi dati archeologici per lo studio delle variazioni per del livello del mare nell' area flegrea." pp. 89–94 in R. Auriemma and S. Karinja, eds, *Terre di Mare; L'Archeologia dei Paesaggi Costieri e le Variazioni Climatiche*, Proceedings of the Internal Congress, Trieste 8–10 November 2007. Trieste: Università degli studi di Trieste.

Benini, A. and Lanteri, L. 2010 "Il porto romano di *Misenum*: nuove acquisizioni." pp. 109–17 in D. J. Blackman and M. C. Lentini, eds, *Ricoveri per Navi Militari nei Porti del Mediterraneo Antico e Medievale*. Proceedings of the workshop held in Ravello, 4–5th November 2005. Bari: Edipuglia.

Bertacchi, L. 2003 *Nuova pianta archeologica di Aquileia.* Aquileia: Edizione del Confine.

Bertagnini, A. and Landi, P. 1996 "The Secche di Lazzaro pyroclastics of Stromboli volcano: a phreatomagmatic eruption related to the Sciara del Fuoco sector collapse." *Bulletin of Volcanology* 58 (2/3): 239–45.

Bishop, M. C. and Coulston, J. C. N. 2006 *Roman Military Equipment from the Punic Wars to the Fall of Rome.* 2nd ed. Oxford: Oxbow Books.

Blackman, D. J. 1978 "Researches at Phaselis" pp. 829–39 in E. Akurgal, ed., *Türk Tarih Kurumu Basimevi*, *Proceedings of the 10th International Congress of Classical Archaeology, Ankara-Izmir*. Ankara: Türk Tarik Kurumu.

Blackman, D. J. 1982 "Ancient Harbours in the Mediterranean." *International Journal of Nautical Archaeology* 11: 79–104, 185–211.

Blackman, D. J. 1988 "Bollards and Men." *Mediterranean Historical Review* 3: 7–20.

Blackman, D. J. 1996 "Further Evidence for the Use of Concrete in Ancient Harbour Construction." pp. 41–49 in Raban and Holum 1996.

Blackman, D. J. 2008 "Sea Transport, Part 2: Harbors." pp. 638–70 in J. P. Oleson, ed., *The Oxford Handbook of Engineering and Technology in the Classical World*. New York: Oxford University Press.

Blake, M. E. 1947 *Ancient Roman Construction in Italy from the Prehistoric Period to Augustus*. Washington DC: Smithsonian Institution.

Blake, M. E. 1959 *Roman Construction in Italy from Tiberius through the Flavians.* Washington DC: Smithsonian Institution.

Blake, M. E. 1973 *Roman Construction in Italy from Nerva through the Antonines.* Philadelphia: American Philosophical Society.

Bliquez, L. and Oleson, J. P. 1995 "The Origins, Early History, and Applications of the *Pyoulkos* (Syringe)." pp. 83–119 in G. Argoud, ed., *Science et vie intellectuelle à Alexandrie (Ier-IIIe siècle après J.C.)*. Saint-Étienne: Université de Saint-Étienne.

Bode, M. 1999 *Apicius – Anmerkungen zum römischen Kochbuch. Das Kochbuch des Apicius als Quelle zur Wirtschafts- und Sozialgeschichte*. St. Katharinen: Scripta Mercaturae Verlag.

Bolondi, L., Nijland, T. G. and van Hees, R. P. G. 2007 "Performance of stone outside its original environment: Neapolitan Yellow Tuff as replacement stone for Rhenish tuff in the Netherlands." pp. 121–26 in V. Calvanese, ed., CITTAM Conference, *'Stone' building, between innovation and tradition.* Naples: Luciano.

Bonnamour, L. 2000 "Les ponts romains de Chalon-sur-Saône, Étude préliminaire de la pile no. 3." *Gallia* 57: 273–305.

Bonora, G., Chiari, G., Santarelli, M. L. and Torraca, G. 2003 "Analisi di malte antiche. Confronto tra techniche di indagine." *Materiali e strutture* 1.1: 39–68.

Bourgeois, J. 1987 "Chapter II. Geography and Geology." pp. 44–57 in McCann *et al.*1987.

Boyce, A. A. 1958 "The Harbor of Pompeiopolis." *American Journal of Archaeology* 62: 67–78.

Branda, F., Luciani, G., Costantini, A. and Piccioli, C. 2001 "Interpretation of the Termogravimetric curves of ancient pozzolanic concretes." *Archaeometry* 43: 447–53.

Brandon, C. J. 1996 "Cements, concrete, and settling barges at Sebastos: comparisons with other Roman harbor examples and the descriptions of Vitruvius." pp. 25–40 in Raban and Holum 1996.

Brandon, C. J. 1997a "The Concrete-Filled Barges of King Herod's Harbor of Sebastos." pp. 45–58 in S. Swiny, R. L. Hohlfelder and H. W. Swiny, eds, *Res Maritimae: Cyprus and the eastern Mediterranean from Prehistory to Late Antiquity*. Atlanta: Scholars Press.

Brandon, C. J. 1997b "Techniques d'architecture navale dans la construction des caissons en bois du port du roi Hérode à Cesarée." *Cahiers d'archéologie subaquatique* 13: 13–33.

Brandon, C. J. 1999 "Pozzolana, lime, and single-mission barges (Area K)." pp. 169–78 in K. G. Holum, A. Raban and J. Patrich, eds, *Caesarea Papers 2 – Herod's Temple, The Provincial Governor's Praetorium and Granaries, The Late Harbor, A Gold Coin Hoard, and Other Studies.* Journal of Roman Archaeology, Suppl. 35. Portsmouth RI: JRA.

Brandon, C. J. 2001 "Unterwasser-Konstructionen in der Antike." *Skyllis* 4.1: 34–40.

Brandon, C. J. 2011 "Roman Formwork Used for Underwater Concrete Construction." pp. 121–38 in Ringbom and Hohlfelder 2011.

Brandon, C., Hohlfelder, R. L. and Oleson, J. P. 2008. "The Concrete Construction of the Roman Harbours of Baiae and Portus Iulius: The ROMACONS 2006 Field Season." *International Journal of Nautical Archaeology* 37: 374–92.

Brandon, C. J., Hohlfelder, R. L., Oleson, J. P. and Rauh, N. 2010a "Geology, Materials, and the Design of the Roman Harbour of Soli-Pompeiopolis, Turkey: the ROMACONS field campaign of August 2009." *International Journal of Nautical Archaeology* 39: 390–99.

Brandon, C. J., Hohlfelder, R. L., Oleson, J. P., Rauh, N. and Yagçı, R. 2010b "The Roman Harbour of Pompeiopolis: The 2009 ROMACONS Field Campaign." *News of Archaeology for Anatolia's Mediterranean Area* 8: 1–4.

Brandon, C. J., Hohlfelder, R. L., Oleson, J. P. and Stern, C. 2005 "The Roman Maritime Concrete Study (ROMACONS). The Roman harbour of Chersonisos in Crete and its Italian connection." *Mediterranée,* 1.2: 25–9.

Brandon, C. J., Kemp, S. and Grove, M. 1999 "Pozzolana, Lime, and Single-mission Barges (Area K)." pp. 169–78 in K. Holum, A. Raban and J. Patrich, eds, *Caesarea Papers 2, Journal of Roman Archaeology* Supplementary Series 35, Portsmouth, RI: JRA.

Branton, G. and Oleson, J. P. 1992a "The Technology of King Herod's Harbour." pp. 49–67 in R. L. Vann, ed., *Caesarea Papers. Straton's Tower, Herod's Harbour, and Roman and Byzantine Caesarea*, Journal of Roman Archaeology, Suppl. 5. Ann Arbor: JRA.

Branton, G. and Oleson, J. P. 1992b "The Harbour of Caesarea Palaestinae: A Case Study of Technology Transfer in the Roman Empire." *Mitteilungen, Leichtweiß-Institut für Wasserbau* 117: 387–421.

Brizzi, B. 1999 *Il Tevere. Un secolo di immagini.* Rome: Colombo.

Broekmans, M. A. T. M. 2012 "Deleterious reactions of aggregate with alkalis in concrete." *Reviews in Mineralogy and Geochemistry* 74: 279–364.

Brown, F. E. 1951 "Cosa I: History and Topography." *Memoirs of the American Academy in Rome* 20: 1–114.

Brown, F. E. 1980 *Cosa: The Making of a Roman Town.* Ann Arbor: University of Michigan Press.

Brun, J- P. 1999 "Le Var 83/2." pp. 797–803 in *Carte Archeologique de la Gaule*. Paris: Académie des inscriptions et belles-lettres.

Brune, P. 2011 "The mechanics of imperial Roman concrete and the structural design of the Roman monuments." Ph.D thesis, University of Rochester, Rochester, New York.

Brune, P., Ingraffea, A. R., Jackson, M. D. and Perucchio, R. 2013 "The fracture toughness of an Imperial Roman mortar." *Engineering Fracture Mechanics* 102: 65–76.

Bruni, S. 2000 *Le navi antiche di Pisa: Ad un anno dall'inizio delle ricerche*. Florence: Edizioni Polystampa.

Caley, E. R. and Richards, J. F. C. 1956 *Theophrastus on Stones. Introduction, Greek Text, English Translation, and Commentary.* Columbus OH: Ohio State University.

Calia A., Giannotta M., Quarta G., Sileo M. and Delle Rose, M. 2011 "Le antichi cave nei depositi calcarenitici lungo la costa pugliese: un esempio di geoarcheositi da tutelare e valorizzare." pp. 249–58 in M. Bentivenga, ed., Atti del Convegno Nazionale: Il Patrimonio Geologico. Supplement to *Geologia dell'Ambiente* 2. Rome: SIGEA.

Callebat, L., Gros, P. and Jacquemard, C. 1999 *Vitruve, De l'architecture. Livre II.* Paris: Les Belles Lettres.

Calza, G. 1925 "Ricognizioni topografiche nel porto di Traiano." *Notizie degli Scavi di Antichità* 1925: 54–80.

Caputo, P. 1995/96 "Attività di tutela della Soprintendenza Archeologica per le Province di Napoli e Caserta." *Bollettino di Archeologia Subacquea*, 1–2: 237–41.

Carpano, C. M. 1982 "Tevere, Premesse per una Archeologia Fluviale." *Archeologia Subacquea.* Bollettino d'Arte, Supplemento 4: 151–70.

Cary, E. 1917 *Dio Cassius, Roman History, Books XLVI–L.* Cambridge MA: Harvard University Press.

Casadio, F., Chiari, G. and Simon. S. 2005 "Evaluation of binder/aggregate ratios in archaeological lime mortars with carbonate aggregate: A Comparative assessment of chemical, mechanical, and microscopic approaches." *Archaeometry* 47.4: 671–89.

Cassano, R. 2009 "La vicenda urbana di Egnazia ridisegnata dalle recenti indagini." *The Journal of Fasti Online*, Associazione Internazionale di Archeologia Classica, www.fastionline.org/docs/FOLDER-it-2009-161.pdf.

Cassieri, N. 1995 "Primi interventi di scavo archeologico e conservazione nella villa romano di Gianola." *Formianum* 3: 25–34.

Casson, L. 1980 "The Role of the State in Rome's Grain Trade." *Memoirs of the American Academy in Rome* 36: 21–33.

Casson, L. 1989 *The Periplus Maris Erythraei. Text with Introduction, Translation and Commentary.* Princeton: Princeton University Press.

Castagnoli, F. 1980 "Installazioni portuali a Roma." pp. 35–42 in D'Arms and Kopff 1980.

Cazalla, O., Rodriguez-Navarro, C., Sebastian, E., Cultrone, G. and De la Torre, M. J. 2000 "Aging of Lime Putty: Effects on Traditional Lime Mortar Carbonation." *Journal of the American Ceramic Society* 83.5: 1070–76.

Celik, K., Jackson, M. D., Mancio, M., Meral, C., Emwas, A. M., Mehta, P. K. and Monteiro, P. J. M. Submitted "High-volume natural volcanic pozzolan and limestone powder as partial replacements for Portland cement in self-compacting and sustainable concrete." *Cement and Concrete Composites*.

Chiari, G., Cimmitàn, L., della Ventura, G., Filetici, M. G., Santarelli, M. L. and Torraca, G. 1992 "Caratterizzazione delle malte antiche mediante l'analisi di campioni non frazionati." *Materiali e Strutture* 2: 111–37.

Chiari, G., Cimmitàn, L., della Ventura, G., Filetici, M. G., Santarelli, M. L. and Torraca, G. 1996 "Le malte pozzolaniche di Sant' Elena e le pozzolane di Tor Pignattara." *Materiali e Strutture* 4: 1–36.

Choisy, A. 1909 *Vitruve*, 2 vols Paris: Lahure.

Ciampoltrini, G. 1991 "Porti dell'Etruria Augustea." *Athenaeum* 17: 236–59.

Ciampoltrini, G. 1998 "*Domitiana positio:* la villa di Santa Liberata." pp. 195–205 in Poggesi and Rendini 1998

Ciampoltrini, G. and Rendini, P. 2004 "Il systema portuale dell'ager Cosanus e delle isole del Giglio e di Giannutri. Porti dell'Etruria Augustea." pp. 276–92 in A. Gallina Zevi and R. Turchetti, eds, *Le strutture dei porti e degli approdi antichi*. Soveria Manelli: Rubbettino.

Ciccioli, P., Cattuto, C., Plescia, P., Valentini, V. and Negrotti, R. 2010 "Geochemical and engineering properties of the volcanic tuffs used in the Etruscan tombs of Norchia (Northern Latium, Italy) and a study of the factors responsible for their rapid surface and structural decay." *Archaeometry* 52.2: 229–51.

Ciccone, S. 1996 "*Piscinae* in litore Formiano." *Formianum* 4: 13–30.

Cioni, R., Civetta, L., Marianelli, P., Metrich, N., Santacroce, R. and Sbrana, A. 1995 "Compositional layering and syn-eruptive mixing of a periodically refilled shallow magma chamber: the AD 79 Plinian eruption of Vesuvius."*Journal of Petrology* 36.3: 739–76.

Cioni, R., Sulpizio, R. and Garruccio, N. 2003 "Variability of the eruption dynamics during a Subplinian event: the Greenish Pumice eruption of Somma-Vesuvius (Italy)." *Journal of Volcanological and Geothermal Research* 124: 89–114.

Civetta, L., Carluccio, E., Innocenti, F., Sbrana, A. and Taddeucci, G. 1991 "Magma chamber evolution under the Phlegraean Fields during the last 10 ka: trace element and isotope data." *European Journal of Mineralogy* 3: 415–28.

Civetta, L., Galati, R. and Santacroce, R. 1991 "Magma mixing and convective compositional layering within the Vesuvius magma chamber." *Bulletin of Volcanology* 53: 287–300.

Coarelli, F. 1982 *Guide Archeologiche Laterza: Lazio*. Bari and Rome: Laterza.

Colella, A., Calcaterra, D., Cappelletti, P., Langella, A., Papa, L. and de' Gennaro, M. 2009 " I tufi zeolitizzati nell'architettura della Campania." pp. 327–41 in M. Cuzzolin, ed., *La diagnostica per il restauro del patrimonio culturale*. Naples.

Colella, C., de' Gennaro, M. and Aiello, R. 2001 "Use of zeolitic tuff in the building industry.*" Reviews in Mineralogy and Geochemistry* 45.1: 551–87.

Colini, A. M. 1980 "Il porto fluviale del Foro Boario a Roma." pp. 43–53 in J. H. D'Arms and E. C. Kopff, eds, *The Seaborne Commerce of Ancient Rome: Studies in Archaeology and History.* Memoirs of the American Academy in Rome, 36.

Corcoran, T. H. 1971 *Seneca, Natural Questions*. 2 vols. Cambridge MA: Harvard University Press.

Cornick, H. F. 1962 *Dock and Harbour Construction, IV: Construction*. London: Griffin.

Coulston, J. S. N. 1990 "Architecture and Construction Scenes on Trajan's Column." pp. 39–50 in M. Henig*, ed., Architecture and Architectural Sculpture in the Roman Empire*. Oxford: Oxford U.P., 1990.

Cowper, A. D. 1927 *Lime and Lime Mortars*. London: H.M. Stationery Office.

Crupi, U. 2008 "Contributi alla ricostruzione del Porto Antico di Otranto." *Archaeologia Maritima Mediterranea: International Journal of Underwater Archaeology* 5: 91–137.

Cuomo, S. 2007 *Technology and Culture in Greek and Roman Antiquity.* Cambridge: Cambridge University Press.

Cüppers, H. 1969 *Die Trierer Römerbrücken*. Mainz: P. von Zabern.

Curtis, C. D. 1913 "The Difference between Sand and Pozzolana." *Journal of Roman Studies* 3: 197–203.

Dallas, M. F. and Yorke, R. A. 1968 "Underwater surveys of North Africa, Jugoslavia and Italy." *Underwater Association Report*: 21–34.

D'Arms, J. H. 1970 *Romans on the Bay of Naples A Social and Cultural Study of their Villas and their Owners from 150 B.C. to A.D. 400.* Cambridge, Harvard University Press.

D'Arms, J. H. and Kopff, E. C., eds 1980 *The Seaborne Commerce of Ancient Rome: Studies in Archaeology and History*. Memoirs of the American Academy in Rome. 36. Rome: American Academy in Rome.

Davidson, D. P. and Yorke, R. A. 2014 "The Enigma of the Great Thapsus Harbour Mole." *International Journal of Nautical Archaolog*y 43: 35–40

Davì, M., De Rosa, R., Donato, P. and Sulpizio, R. 2011 "The Lami pyroclastic succession (Lipari, Aeolian Islands): A clue for unravelling the eruptive dynamics of the Monte Pilato rhyolitic pumice cone." *Journal of Volcanology and Geothermal Research* 201: 285–300.

Davis, L. H. 1981 "A Note on some Cistern Mortars Found at Carthage." pp. 43–49 in J. H. Humphrey, ed., *Excavations at Carthage 1977, Conducted by the University of Michigan,* vol. 6. Ann Arbor: Kelsey Museum.

De Astis, G., La Volpe, L., Peccerillo, A. and Civetta, L. 1997 "Volcanological and petrological evolution of Vulcano island (Aeolian Arc, southern Tyrrhenian Sea)." *Journal of Geophysical Research* 102, B4: 8021–50.

De Astis, G., Pappalardo, L. and Piochi, M. 2004 "Procida volcanic history: new insights into the evolution of the Phlegraean Volcanic District (Campania region, Italy)." *Bulletin of Volcanology* 66: 622–41.

De Casa, G., Lombardi, G., Meucci, C., Galloni, R. and Vitali, P. 1999 "Il Tufo Lionato dei monumenti Romani: caratteri petrografici, geomeccanici, e trattamenti conservativi." *Geologia Romana* 35: 1–25.

de' Gennaro, M., Cappelletti, P., Langella, A., Perrotta, A. and Scarpati, C. 2000 "Genesis of zeolites in the Neapolitan Yellow Tuff: Geological, volcanological and mineralogical evidence." *Contributions to Mineralogy and Petrology* 139: 17–35.

de' Gennaro, M., Incoronato, A., Mastrolorenzo, G., Adabbo, M. and Spina G. 1999 "Depositional mechanisms and alteration processes in different types of pyroclastic deposits from Campi Flegrei volcanic field (Southern Italy)." *Journal of Volcanology and Geothermal Research* 91.2: 303–20.

De Graauw, A. 2000 "Port Engineering Aspects of the Magnus Portus in Alexandria." *Bulletin of the International Navigation Association* 103: 31–41.

Degryse, P., Elsen, J. and Waelkens, M. 2002 "Study of ancient mortars from Sagalassos (Turkey) in view of their conservation." *Cement and Concrete Research* 32: 1457–63.

DeLaine, J. 1995 "The supply of building materials to the city of Rome: Some economic implications." pp. 555–62 in N. Christie, ed., *Settlement and economy in Italy, 1500 BC–AD 1500: papers of the Fifth Conference of Italian Archaeology*. Oxford: Oxbow Books.

DeLaine, J. 1996 "'*De aquis suis*'? The '*Commentarius*' of Frontinus." *Entretiens Hardt* 42: 117–45.

DeLaine, J. 1997 *The Baths of Caracalla; A study in the design, construction, and economics of large-scale building projects in imperial Rome*. Journal of Roman Archaeology, Suppl. 25. Portsmouth, RI: JRA.

DeLaine, J. 2000 "Building the Eternal City: the construction industry of imperial Rome." pp. 119–41 in J. C. N. Coulston and H. Dodge, eds, *Ancient Rome: the archaeology of the eternal city*. Oxford: Oxford University Committee for Archaeology.

DeLaine, J. 2001 "Bricks and mortar: exploring the economics of building techniques at Rome and Ostia." pp. 230–68 in D. J. Mattingly and J. Salmon, eds, *Economies beyond agriculture in the Classical World*. London: Routledge.

DeLaine, J. 2002 "Building Activity in Ostia in the second century AD." pp. 41–101 in Brunn, A Gallina Zevi, eds, *Ostia e Portus nelle loro relazioni con Roma.* Acta Instituti Romani Finlandiae, 27. Rome: Finnish Institute.

Delgado, J. 2008 "Nautical and Maritime Archaeology, 2006–2007 Seasons." *American Journal of Archaeology* 112, 307–35.

de Vita, S., Orsi, G., Civetta, L., Carandente, A., D'Antonio, M., Deino, A., di Cesare, T., Di Vito, M. A., Fisher, R.V., Isaia, R., Marotta, E., Necco, A., Ort, M., Pappalardo, L., Piochi, M. and Southon, J. 1999 "The Agnano-Monte Spina eruption, 4100 years BP in the restless Campi Flegrei caldera, Italy." *Journal of Volcanology and Geothermal Research* 91: 269–301.

De Vivo. B., Rolandi, R., Gans, P. B., Calvert, A., Bohrson, W. A., Spera, F. J. and Belkin, H. E. 2001 "New constraints on the pyroclastic eruptive history of the Campanian volcanic Plain (Italy)." *Mineralogy and Petrology* 73: 47–65.

Dey, H. and Goodman-Tchernov, B. 2010 "Tsunamis and the port of Caesarea Maritima over the *longue durée*: a geoarchaeological perspective." *Journal of Roman Archaeology* 23: 265–84.

Di Fraia, G. 1993 "Baia sommersa. Nuove evidenze topografiche e monumentali." *Archeologia Subacquea* 1: 21–48.

Di Renzo, V., Di Vito, M. A., Arienzo, I., Caradente, A., Civetta, L., D'Antonio, M., Giordano, F., Orsi, G. and Tonarini, S. 2007 "Magmatic History of Somma-Vesuvius on the Basis of New Geochemical and Isotopic Data from a Deep Borehole (Camaldoli dellaTorre)." *Journal of Petrology* 48.4: 758–84.

Di Vito, M. A., Arienzo, I., Braia, G., Civetta, L., D'Antonio, M., Di Renzo, V. and Orsi, G. 2011 "The Averno 2 fissure eruption: a recent small-size explosive event at the Campi Flegrei Caldera (Italy)." *Bulletin of Volcanology* 73: 295–320.

Di Vito, M. A., Isaia, R., Orsi, G., Southon, J., de Vita, S., D'Antonio, M., Pappalardo, L. and Piochi, M. 1999 "Volcanism and deformation since 12,000 years at the Campi Flegrei caldera, Italy." *Journal of Volcanology and Geothermal Research* 91: 221–46.

Dix, B. 1982 "The Manufacture of Lime and its Uses in the Western Roman Provinces." *Oxford Journal of Archaeology* 13: 331–45.

Döring, M. 2003 "Römische Hafen- und Tunnelbauten der Phlegräischen Felder." pp. 35–53 in C. Ohlig, ed., *Wasserhistorische Forschungen. Schwerpunkt Antike.* Siegburg: DWHG.

Drachmann, A. G. 1932 *Ancient Oil Mills and Presses*. Copenhagen: Levin and Munksgaard.

Druitt, T. H., Edwards, L., Mellors, R. M., Pyle, D. M., Sparks, R. S. J., Lanphere, M., Davies, M. and Barreiro, B. 1999 *Santorini Volcano*. Geological Society, London, Memoir 19. London: Geological Society.

Dubois, C. 1902 "Observations sur un passage de Vitruve." *Mélanges de l'École française de Rome* 22: 439–67.

Dubois, C. 1907 *Pozzuoles antique: Histoire et topographies*. Bibliothèque des Écoles françaises d'Athènes et de Rome, 98. Paris: Écoles françaises d'Athènes et de Rome.

Dunsch, B. 2012 "*Arte rates reguntur*: Nautical Handbooks in Antiquity?" *Studies in History and Philosophy of Science* 43: 270–83.

Duxson, P., Fernández-Jiménez, A., Provis, J. L., Lukey, G. C. and Van Deventer, J. S. C. 2007 "Geopolymer technology: the current state of the art." *Journal of Material Science* 42: 2912–33.

Dvorak, J. and Mastrolorenzo, G. 1991 "The mechanisms of recent vertical crustal movements in Campi Flegrei caldera, southern Italy." *Geological Society of America Special, Paper* 263. Boulder: Geological Society of America.

Eastwood, W. J., Pearce, N. J. G., Westgate, J. A., Perkins, W. T., Lamb, H. F. and Roberts, N. 1999 "Geochemistry of Santorini tephra in lake sediments from Southwest Turkey." *Global and Planetary Change* 21: 17–29.

Efstathiadis, E. 1978 *Greek Concrete of Three Millenniums*. Technical Report, Research Centre of the Hellenic Ministry of Public Works. Athens: Hellenic Ministry of Public Works.

Elsen, J. 2006 "Microscopy of historic mortar--A review." *Cement and Concrete Research* 36: 1416–24.

Elsen, J., Van Balen, K. and Mertens, G. 2012 "Hydraulicity in historic lime mortars." pp. 125–39 in J. Válek, C. Groot and J. Hughes, eds, *Historic Mortars: Characterization, Assessment, Conservation and Repair.* Berlin, New York: Springer-RILEM.

Esposito, E., Felici, E., Gianfrotta, P. A. and Scognamiglio, E. 2002 "Il Porto di Kyme." *Archeologia subacquea* 3: 1–37.

Excoffon, P. and Dubar, M. 2011 "L'Emploi de tuf volcanique et de la pouzzolane dans quelques constructions de Forum Iulii (Fréjus, Var)." *Revue du Centre Archéologique du Var* 2011: 271–81.

Fabre. D. and Goddio, F. 2010 "The Development and Operation of Portus Magnus in Alexandria: An Overview." pp. 53–74 in Robinson and Wilson, eds 2011.

Fairclough, H. R. and Goold, G. P. 1999 *Virgil. Eclogues, Georgics, Aeneid*. 2 vols. Cambridge MA: Harvard University Press.

Fedele, L., Insinga, D. D., Calvert, A. T., Morra, V., Perrotta, A. and Scarpati, C. 2011 "40Ar/39Ar dating of tuff vents in the Campi Flegrei caldera (southern Italy): toward a new chronostratigraphic reconstruction of the Holocene volcanic activity." *Bulletin of Volcanology* 73: 1323–36.

Felici, E. 1993 "Osservazioni sul Porto Neroniano di Anzio e sulla tecnica romana delle costruzioni portuali in calcestruzzo." *Archeologia Subacquea* 1: 71–104.

Felici, E. 1995 "Anzio: Un porto per Nerone." *Archeologia Viva* 52: 65–63.

Felici, E. 1998 "La ricerca sui Porti romani in cementizio: Metodi e obiettivi." pp. 275–340 in G. Volpe, ed., *Come opera l'archeologo sott'acque. Storie dalle acque. VIII Ciclo di lezioni sulla ricerca applicata in archeologia*. Florence: Edizioni all'Insegna del Giglio.

Felici, E. 2001a "Costruire nell' Acqua: I Porti Antichi." pp. 161–78 in M. Giacobelli, ed., *Lezioni Fabio Faccenna*, Conferenze di archeologia Subacquea. Bari.

Felici, E. 2001b "Recenti ricerche nel Porto Neroniano di Anzio (RM)." pp. 121–28 in P. A. Gianfrotta and F. Maniscalco, eds, *Proceedings of the Forum Internazionale di Archeologica Subacquea, Pozzuoli, 22–24 September 1998, Forma Maris*. Naples: Massa.

Felici, E. 2002 "Scoperte epigrafici e topografiche sulla costruzione de port neroniano di Antium." *Archeologica Subacquea* 3: 107–22.

Felici, E. 2006 "Ricerche sulle tecniche costruttive dei porti romani. Note preliminari sul porto di Astura (Latina)." *Journal of Ancient Topography, Rivista di Topografia Antica* 16: 59–84.

Felici, E. 2008 "Le Strutture Portuali Romane." pp. 369–76 in R. Auriemma and S. Karinja, eds, *Cementizio: Questioni Progettuali, Problemi Cronologici. Terre di Mare; L'Archeologia dei Paesaggi Costieri e le Variazioni Climatiche*, Proceedings of the Internal Congress, Trieste 8–10 November 2007.

Felici, E. 2009 "Il porto di Claudio e Vitruvio." *ATTA, Atlante tematico di topografia antica: rivista di studi di topografia antica* 19: 111–37.

Felici, E. and Balderi, G. 1997a "Il porto romano di Cosa: appunti per l'interpretazione tecnica di un'opera marittima in cementizio." *Archeologia Subacquea* 2: 11–19.

Felici, E. and Balderi, G. 1997b "Nuovi Documenti per la 'Topografia Portuale' di Antium. pp. 11–20 in *Atti del Convegno Nazionale di Archeologia Subacquea, Anzio 30–31 Maggio e 1 Giugno 1996*. Bari: Edipuglia.

Fentress, E. 2009 "Review of Hohlfelder ed. 2008." *American Journal of Archaeology,* Online Book Reviews 2009.

Feuser, S. 2011 "The Roman Harbour of Alexandria Troas, Turkey." *International Journal of Nautical Archaeology* 40: 256–73.

Finneran, N. 2005 *Alexandria, a City and Myth.* London: Tempus, Stroud.

Flemming, N. C. 1996 "Sea Level, Neotectonics and Changes in Coastal Settlements: Threat and Response." pp. 23–52 in E. E. Rice, ed., *The Sea and History*. Gloucester: Sutton Publishing.

Fleury, P. 1996 "Traités de méchanique et texts sur les machines." *Entretiens Hardt* 42: 45–75.

Flinder, A. 1985 "The Piscinas at Caesarea and Lapithos." pp. 173–78 in A. Raban, ed., *Harbour Archaeology; Proceedings of the First International Workshop on Ancient Mediterranean Harbours, Caesarea Maritima, 24–28th June 1983*. British Archaeological Reports, Intl. Series, S257. Oxford: BAR.

Forster, A. 2004 "Hot-lime mortars: a current perspective." *Journal of Architectural Conservation* 3: 7–27.

Francalanci, L., Varekamp, J. C., Vougioukalakis, G., Defant, M. J., Innocenti, F. and Manetti, P. 1995 "Crystal retention, fractionation and crustal assimilation in a convecting magma chamber, Nisyros Volcano, Greece." *Bulletin of Volcanology* 56: 601–20.

Francis, J. 2010 "A Re-evaluation of Rock-cut Fishing Installations in Roman Crete." *Creta Antica* 11: 255–78.

Franklin, A. J. D., *et al.* 1990 *Underwater Concreting: Report of a Concrete Society Working Party.* Concrete Society Technical Report no. 35. Slough: Concrete Society.

Frost, H. 1973 "The Offshore Island Harbour at Sidon and other Phoenician Sites in the Light of New Dating Evidence." *International Journal of Nautical Archaeology* 2: 75–94.

Frost, H. 2000 "Installations on the Ancient Offshore Anchorage at Sidon (the rock island of Zire)." N*ational Museum News* 10: 69–73.

Frydas, D. and Bellas, S. 2009 "Calcareous phytoplankton stratigraphy of Neogene marine sediments east of Heraklion, Crete, Greece." *Berliner Paläobiologische Abhandlungen* 10: 151–69.

Fusi, N. 1996 "Structural settings of the carbonatic 'basement' and its relationship with magma uprising in the Gulf of Naples (Southern Italy)." *Annali di Geofisica* 39: 493–509.

Fytikas, M., Innocenti, F., Kolios, N., Manetti, P., Mazzuoli, R., Poli, G., Rita, F. and Villari, L. 1996 "Volcanology and volcanic products from the island of Milos and neighbouring islets." *Journal of Volcanology and Geothermal Research* 28: 297–317.

Galili, E. and Sharvit, J. 1998 "Ancient Coastal Installations and the Tectonic Stability of the Israeli Coast in Historical Times." pp. 147–63 in I. S. Stewart and C. Vita-Finzi, eds, *Coastal Tectonics.* Geological Society, London, Special Publications 146. London: Geological Society.

Galili, E., Oleson, J. P. and Rosen, B. 2010 "A Group of Exceptionally Heavy Ancient Sounding Leads: New Data Concerning Deep-Water Navigation in The Roman Mediterranean." *Mariner's Mirror* 96: 136–48.

Gambogi, P. 2008 "Protection and Conservation of Ancient Harbor Structures in Tuscany: Two Examples on the Coast of Grosseto." pp. 255–63 in Hohlfelder, ed. 2008.

Gavarini, C., Ferretti, A. S. and Santarelli, M. 2006 "Mechanical Characteristics of Roman 'Opus Caementicium'." pp. 107–20 in S. Kourkoulis, ed., *Failure and Fracture of Natural Building Stones.* Dordrecht: Springer.

Gazda, E. K. 1987 "The Port and Fishery: Description of Extant Remains and Sequence of Construction." pp. 74–97 in McCann *et al.* 1987.

Gazda, E. K. 2001 "Cosa's Contribution to the Study of Roman Hydraulic Concrete: An Historiographic Commentary." pp. 145–77 in N. W. Goldman, ed., *Classical Studies in Honor of Cleo Rickman Fitch*. New York: P. Lang.

Gazda, E. K. 2008 "Cosa's Hydraulic Concrete: Towards a Revised Chronology." pp. 265–90 in R. L. Hohlfelder, ed., 2008.

Gébara, C. and Morhange, C. 2010 *Fréjus (Forum Julii): Le Port Antique/The Ancient Harbour.* Journal of Roman Archaeology, Suppl. Series, 77. Portsmouth, RI: JRA.

Ghini, G. 1996"Prospezioni Subacquee nei Laghi Albano e Nemorense." *Bollettino di Archeologia Subacquea*, 1–2: 184–96.

Giachi, G. and Pallecchi, P. 2000 "Analisi preliminari sui materiali." pp. 348–51 in S. Bruni, ed., *Le navi antiche di Pisa ad un anno dall'inizio delle ricerche.* Firenze: Edizioni Polistampa.

Giampaola, D. *et al.* 2005 "La scoperta del porto di *Neapolis*: dalla ricostruzione topografica allo scavo e al recupero dei relitti." *Archaeologia Maritima Mediterranea* 2: 47–91.

Giampaola, D. and Carsana, V. 2010 "Fra *Neapolis* e *Parthenope*: il paesaggio costiero ed it porto." pp. 119–29 in D. J. Blackman and M. C. Lentini, eds, *Ricoveri per navi militari nei porti del mediterraneo antico e medievale*. Proceedings of the workshop held in Ravello, 4–5th November 2005. Bari: Edipuglia.

Gianfrotta, P. A. 1996 "Harbour Structures of the Augustan Age in Italy." pp. 65–76 in A. Raban and K. G. Holum, eds, *Caesarea Maritima: A Retrospective after Two Millennia*. Leiden: Brill.

Gianfrotta, P. A. 1997 "Le Peschiere Scomparse di Nettuno (RM)." pp. 21–24 in *Atti del Convegno Nazionale di Archeologia Subacquea, Anzio 30–31 Maggio e 1 Giugno 1996*. Bari: Edipuglia.

Gianfrotta, P. A. 1999 "Il contributo della ricerca subacquea agli studi di topografia antica in Italia." pp. 75–90 in L. Quilici, ed., *La Forma della Città e del Territorio: Esperienze metodologiche e risultati a confronto.* Rome: L'Erma di Bretschneider.

Gianfrotta, P. A. 2002 "Ponza (puntualizzazioni maritime)." *Archeologia subacquea* 3: 67–90.

Gianfrotta, P. A. 2007a "Il commercio marittimo in età tardo-republicana: merci, mercanti, infrastrutture." pp. 65–78 in J. Ballester and G. Pascual, eds, *Actas V Jornadas Internacionales de Arqueologia Subacquatica.* Valencia: 2007.

Gianfrotta, P. A. 2007b "Note di topografia marina e marittima." *Rivista di Topografia Antica* 15: 7–36.

Gianfrotta, P. A. 2009 "Questioni di *pilae* e di *pulvis puteolanus*." *Rivista di Topografia Antica* 19: 101–20.

Gianfrotta, P. A. 2010 "Le terme di M. Licinio Crasso Frugi a Baia." *Archeologia Classica* 61: 193–209.

Gianfrotta, P. A. 2011a "Comments Concerning Recent Fieldwork on Roman Maritime Concrete." *International Journal of Nautical Archaeology* 40.1: 188–93.

Gianfrotta, P. A. 2011b "La topografia sulle bottiglie di Baia." *Rivista di Archeologia* 35: 13–39.

Giavarini, C., Samuelli Ferretti, A. and Santarelli, M. L. 2006 "Mechanical Characteristics of Roman 'Opus Caementicium.'" pp. 107–20 in S. K. Kourkoulis, ed., *Fracture and Failure of Natural Building Stones.* Berlin-New York: Springer.

Gill, D. 1999 "Neo-tectonic Settlement of the Herodian Harbor in Caesarea." *Israel Geological Society Annual Meeting 1999: Dead Sea, 8–10 March 1999*. Jerusalem: Israel Geological Society.

Gioncada, A., Mazzuoli, R., Bisson, M. and Pareschi, M. T. 2003 "Petrology of volcanic products younger than 42 ka on the Lipari Vulcano complex (Aeolian Islands, Italy): an example of volcanism controlled by tectonics." *Journal of Volcanology and Geothermal Research* 122: 191–220.

Giuliani, C. F. 1997 "L'*opus caementicium* nell'edilizia romana." *Materiali e strutture* 7.2–3: 49–62.

Giuliano, M. 2010 "I materiali da costruzione di Pompei: provenienza, estrazione, tecniche edilizie." Tesi di Laurea, Università degli Studi Suor Orsola Benincasa, Napoli.

Goddio, F. 2011 "Heracleion-Thonis and Alexandria, Two Ancient Egyptian Emporia." pp. 121–37 in Robinson and Wilson, eds, 2011.

Goddio, F., Bernand, A., Bernand, E., Darwish, I., Kiss, Z. and Yoyotte, J. 1998 Ale*xandria: The Submerged Royal Quarters*. London: Periplus Publishing.

Goddio, F. and Fabre, D., eds, Forthcoming *Alexandria. The Topography of the Portus Magnus. Underwater archaeology in the Eastern Port of Alexandria in Egypt*. Oxford Centre for Maritime Archaeology: Monograph. Oxford, Oxford Centre for Maritime Archaeology.

Goiran, J. -P., Salomon, F., Tronchère, H., Carbonel, P., Djerbi, H. and Ognard, C. 2011 "Caractéristiques du Basin Portuaire de Claude: Nouvelles Données pour la Localisation des Ouvertures." pp. 31–45 in Keay and Paroli 2011.

Goldsworthy, H. and Zhu, M. 2009 "Mortar Studies Towards the Replication of Roman Concrete." *Archaeometry* 51.6: 932–46.

Gotti, E., Oleson, J. P., Bottalico, L., Brandon, C., Cucitore, R. and Hohlfelder, R. L. 2008 "A Comparison of the Chemical and Engineering Characteristics of Ancient Roman Hydraulic Concrete with a Modern Reproduction of Vitruvian Hydraulic Concrete." *Archaeometry* 50.4: 576–90.

Gourdin, W. H. and Kingery, W. D. 1975 "The Beginnings of Pyrotechnology: Neolithic and Egyptian Lime Plaster." *Journal of Field Archaeology* 2: 133–50.

Greene, K. 1992 "How was technology transferred in the western provinces?" pp. 101–5 in M. Wood and F. Queiroga, eds, *Current Research in the Romanization of the Western Provinces*. Oxford: Tempus Reparatum.

Greene, K. 2000 "Technological innovation and economic progress in the ancient world: M.I. Finley re-considered." *Economic History Review* 53: 29–59.

Gros, P., Corso, A. and Romano, E. 1997 *Vitruvius Pollio, De Architectura.* 2 vols Turin: Einaudi.

Günther, R. T. 1903a "The Submerged Greek and Roman Foreshore near Naples." *Archaeologia* 58.2: 499–560.

Günther, R. T. 1903b "Earth-Movements in the Bay of Naples. IV. The Phlegræan Shore-Line. (Continued)." *Geographical Journal* 22.3: 269–86.

Günther, R. T. 1913 *Pausilypon: The Imperial Villa near Naples*. Oxford: Oxford University Press.

Harrell, J. A. 2012 "Building Stones." 24 pp. in W. Wendrich, ed., *UCLA Encyclopedia of Egyptology*. Los Angeles: UCLA. Link: http://digital2.library.ucla.edu/viewItem.do?ark=21198/zz002c10gb.

Harris, W. V. 2011 "Introduction." pp. 9–20 in Harris and Iara, eds 2011.

Harris, W. V. and Iara, K., eds 2011 *Maritime Technology in the Ancient Economy: Ship-Design and Navigation*. Journal of Roman Archaeology, Suppl. Series, 84. Portsmouth, RI: JRA.

Haury, J. 1964 *Procopi Caesariensis Opera Omnia*, vol. 4. Rev. ed. Leipzig: Teubner.

Hay, R. L. and Sheppard, R. A. 2001 "Occurrences of zeolites in sedimentary rocks: An overview." pp. 217–34 in *Natural Zeolites: Occurences, Properties, Applications*. Reviews in Mineralogy and Geochemistry, 45. Blacksburg VA: Mineralogical Society of America.

Hay, R. L. and Guldman, S. 1987 "Diagenetic alteration of silicic ash in Searles Lake, California." *Clay and Clay Minerals* 35.6: 449–57.

Hay, R. L. and Iijima, A. 1968 "Nature and origin of palagonite tuffs of the Honolulu group on Oahu, Hawaii." *Geological Society of America, Memoir* 116: 331–76.

Healy, J. F. 1999 *Pliny the Elder on Science and Technology*. Oxford: Oxford University Press.

Hellman, M.-C. 2002 *L'Architecture grecque, 1: Les principes de la construction.* Paris: Picard.

Helm, R. 1868 *Apulei Platonici Madaurensis, Metamorphoseon Libri XI*. Leipzig: Teubner.

Hesnard, A. 1999 "Le Port de Marseille romaine: d'Auguste à la fin du IV siècle de notre ère." pp. 45–47 in A. Hesnard *et al.* 1999.

Hesnard, A. 2004 "Vitruve, *De architectura*, V, 12 et le port romain de Marseille." pp. 175–204 in A. Gallina and R. Turchetti, eds, *Le Strutture dei Porti e Degli Approdi Antichi.* II seminario, Roma-Ostia antica, 16–17 aprile 2004. Soveria Mannelli: Rubbettino.

Hesnard, A., Moliner, M., Conche, F. and Bouiron, M. 1999 *Parcours de Villes, Marseille: 10 Ans d'Archéologie, 2600 Ans d'Histoire.* Aix-en-Provence: Édisud.

Hewlett, P. C., ed. 1988 *Lea's Chemistry of Cement and Concrete.* 4th ed. Amsterdam: Elsevier.

Higginbotham, J. 1997 *Piscinae, Artificial Fishponds in Roman Italy*. Chapel Hill: University of North Carolina Press,

Hohlfelder, R. L. 1985 "The building of the Roman harbour at Kenchreai: Old technology in a new era." pp. 81–86 in A. Raban, ed., *Harbour Archaeology.* Oxford: BAR.

Hohlfelder, R. L. 1987 "Caesarea Maritima, Herod the Great's City on the Sea." *National Geographic Magazine* 171.2: 260–79.

Hohlfelder, R. L. 1988 "Procopius, *De Aedificiis*, 1.11.18–20: Caesarea Maritima and the Building of Harbours in Late Antiquity." pp. 54–62 in I. Malkin and R. L. Hohlfelder, eds, *Mediterranean cities. Historical perspectives*. London: Cass.

Hohlfelder, R. L. 1996 "Caesarea's master harbor builders: lessons learned, lessons applied?" pp. 77–101 in Raban and Holum 1996.

Hohlfelder, R. L. 1997 "Building Harbours in the Early Byzantine Era: The Persistence of Roman Technology." *Byzantinische Forschungen* 24: 367–80.

Hohlfelder, R. L. 1999 "Building Sebastos: the Cyprus Connection." *International Journal of Nautical Archaeology* 28: 154–63.

Hohlfelder, R. L. 2000a "Beyond Coincidence? Marcus Agrippa and King Herod's Harbor." *Journal of Near Eastern Studies* 59: 241–53.

Hohlfelder, R. L. 2000b "Anastasius I, Mud, and Foraminifera: Conflicting Views of Caesarea Maritima's Harbor in Late Antiquity." *Bulletin of the American Schools of Oriental Research* 317: 41–62.

Hohlfelder, R. L., ed. 2008 *The Maritime World of Ancient Rome*. Ann Arbor, University of Michigan Press.

Hohlfelder, R. L., Brandon, C. and Oleson, J. P. 1992 "The Changing Fortunes of Caesarea's Harbours in the Roman Period." pp. 75–78 in R. L. Vann ed., *Caesarea Papers Straton's Tower, Herod's Harbour, and Roman and Byzantine Caesarea.* Journal of Roman Archaeology Supplementary Series, 5. Ann Arbor: JRA

Hohlfelder, R. L., Brandon, C. and Oleson, J. P. 1996 "Caesarea's Master Harbor Builders: Lesson Learned, Lessons Applied?" pp. 75–101 in Raban and Holum 1996.

Hohlfelder, R. L., Brandon, C. and Oleson, J. P. 2005 "Building a Roman *pila* in the sea-experimental archaeology at Brindisi, Italy, September 2004." *International Journal of Nautical Archaeology* 34: 123–27.

Hohlfelder, R. L., Brandon, C. and Oleson, J. P. 2007 "Constructing the Harbour of Caesarea Palaestina, Israel: New Evidence From the ROMACONS Field Campaign of October 2005." *International Journal of Nautical Archaeology* 36: 409–15.

Hohlfelder, R. L., Brandon, C. and Oleson, J. P. 2008 "The Roman Maritime Concrete Study: Brief Summary of Fieldwork from 2002 to 2005." pp. 297–304 in Hohlfelder, ed., 2008.

Hohlfelder, R. L., Brandon, C. and Oleson, J. P. 2011 "Roman Hydraulic Concrete and the Roman Maritime Concrete Study (ROMACONS): A Summary of Recent Fieldwork 2005–2007." pp. 109–20 in Ringbom and Hohlfelder 2011.

Holum, K. G. 1992 "Hadrian and Caesarea: An Episode in the Romanization of Palestine." *Ancient World* 23: 51–61.

Holum, K. G., Hohlfelder, R. L., Bull, R. J. and Raban, A. 1988 *King Herod's Dream: Caesarea on the Sea*. New York: Abrams.

Holum, K. G., Raban, A. and Patrich, J., eds 1999 *Caesarea Papers 2 – Herod's Temple, The Provincial Governor's Praetorium and Granaries, The Late Harbor, A Gold Coin Hoard, and Other Studies.* Journal of Roman Archeology, Suppl. Series, 35. Portsmouth: JRA.

Holum, K. G., Stabler, J. A. and Reinhardt, E. G., eds 2008 *Caesarea Reports and Studies, Excavations 1995–2007 within the Old City and the Ancient Harbor.* Oxford, BAR International Series, S1784. Oxford: Archaeopress.

Humphrey, J., Oleson, J. P. and Sherwood, A. N. 1998 *Greek and Roman Technology: A Sourcebook*. London: Routledge.

Hurst, H. 1976 "Excavations at Carthage 1975: Second interim report." *Antiquaries Journal* 56: 177–97.

Ihm, M. 1908 *C. Suetoni Tranquilli Opera*, vol.1. Leipzig: Teubner.

Incitti, M. 1986 "Recenti scoperte lungo la costa dell'Alto Lazio." *Bollettino d'Arte, Supplemento* 3: 195–202.

Jackson, M. D., Chae, S. R., Taylor, R., Meral, C., Moon, J., Yoon, S., Li, P.; Emwas, A. M., Vola, G., Wenk, H.-R. and Monteiro P. J. M. 2013a "Unlocking the secrets of Al-tobermorite in Roman seawater concrete." *American Mineralogist* 98: 1669–87.

Jackson, M. D., Ciancio Rossetto, P., Kosso, C. K., Buonfiglio, M. and Marra, F. 2011 "Building materials of the Theater of Marcellus, Rome." *Archaeometry* 4.4: 728–42.

Jackson, M. D., Deocampo, D., Marra, F. and Scheetz, B. 2010 "Mid-Pleistocene Pozzolanic Volcanic Ash in Ancient Roman Concretes." *Geoarchaeology* 25: 36–74.

Jackson, M. D. and Kosso, C. K. 2013 "*Scientia* in republican era stone and concrete masonry." pp. 268–84 in J. D. Evans, ed., *A Companion to the Archaeology of the Roman Republican Period.* London: Wiley Blackwell.

Jackson, M. D., Logan, J. M., Scheetz, B. E., Deocampo, D. M., Cawood, C. G., Marra, F., Vitti, M. and Ungaro, L. 2009 "Assessment of material characteristics of ancient concretes, Grande Aula, Markets of Trajan, Rome." *Journal of Archaeological Science* 36: 2481–92.

Jackson M. D. and Marra F. 2006 "Roman Stone Masonry: Volcanic Foundations of the Ancient City." *American Journal of Archaelogy* 110: 403–36.

Jackson, M. D., Marra, F., Deocampo, D., Vella, A., Kosso, C. K. and Hay, R. L. 2007 "Geological observations of excavated sand (*harena fossicia*) used as fine aggregate in Roman pozzolanic mortars." *Journal of Roman Archaeology* 20: 25–52.

Jackson, M. D., Marra, F., Hay, R. L., Cawood, C. and Winkler, E. 2005 "The judicious selection and preservation of tuff and travertine building stone in ancient Rome." *Archaeometry* 47.3: 485–510.

Jackson, M. D., Moon, J., Gotti, E., Kunz, M., Taylor, R., A. Emwas, A., Meral, C., Guttmann, P., Levitz, P., Wenk, H.-R. and Monteiro,

P. J. M. 2013b “Material and elastic properties of Al-tobermorite in ancient Roman seawater concrete.” *Journal of the American Ceramic Society.* DOI: 10.1111/jace12407.

Jackson, M. D., Vola, G., Všiansky, D., Oleson J. P., Brandon C., Hohlfelder R. and Scheetz B. 2012 “Cement microstructures and durability in ancient Roman seawater concretes.” pp. 49–76 in J. Válek, C. Groot and J. Hughes, eds, *Historic Mortars: Characterization, Assessment, Conservation and Repair.* Berlin, New York: Springer-RILEM.

Jakobsson, S. and Moore, J. G. 1986 “Hydrothermal minerals and alteration rates at Surtsey volcano, Iceland.” *Geological Society of America, Bulletin* 97: 648–59.

Joncheray, A. and Joncheray, J.-P. 2002 “Chrétienne M, trois épaves distinctes, entre le cinquième siècle avant et le premier siècle après Jésus-Christ.” *Cahiers d’Archéologie Subaquatique* 14: 57–130.

Jüngst, E. and Thielscher, P. 1936 “Vitruv über Baugrube, Baugrund und Grundbau.” *Römische Mitteilungen* 51: 145–80.

Jüngst, E. and Thielscher, P. 1939 “Nachträgliches zu Vitruv V.12.” *Philoologische Wochenschrift* 59.6: 174–76.

Kaneko, T., Nakada, S., Yoshimoto, M., Fujii, T., Yasudam, A., Yoneda, M. and Aoyagi, M. 2005 “Determination of burial age of the ‘Augustus villa’ (Italy).” *Geochemical Journal* 39: 573–78.

Keay, S., ed. 2012 *Rome, Portus and the Mediterranean*. London: the British School at Rome.

Keay, S., Millett, M., Paroli, L. and Strutt, K. 2005 *Portus: An Archaeological survey of the Port of Imperial Rome.* Archaeological Monographs of the British School at Rome, 15. London: The British School at Rome.

Keay, S. and Paroli, L. 2011 *Portus and its Hinterland*. Archaeological Monographs of the British School at Rome, 18. Rome: British School at Rome.

Kiessling, T. 1826 *Ioannis Tzetzae Historiarum Variarum Chiliades.* Leipzig: Teubner.

Kingery, W. D., Vandiver, P. B. and Prickett, M. 1988 “The Beginnings of Pyrotechnology, Part II: Production and Use of Lime and Gypsum Plaster in the Pre-Pottery Neolithic Near East.” *Journal of Field Archaeology* 15: 219–44.

Kingsley, P. 1995 “Artillery and Prophecy: Sicily in the reign of Dionysius I.” *Prometheus* 21: 15–23.

Kleingünther, A. 1933 *“Prōtos heuretēs”; Untersuchungen zur Geschichte einer Fragestellung*. Leipzig: Dieterich.

Klitzsch, E., List, F. K. and Pohlmann, G. 1986 “*Geological map of Egypt, 1:500.000 scale, Alexandria*.” NH 35 NE sheet, Conoco Map Project. Cairo: Egyptian General Petroleum Corporation.

Klitzsch, E., List, F. K. and Pohlmann, G. 1987 “*Geological map of Egypt, 1:500.000 scale, Cairo.*” NH 36 NE sheet, Conoco Map Project. Cairo: Egyptian General Petroleum Corporation.

Knoblauch, P. 1977 *Die Hafenanlagen und die Anschliessenden Seemauern von Side*. Ankara: Türk Tarih Kurumu Basımevi.

Koui, M. and Ftikos, Ch. 1998 “The ancient Kamirian water storage tank: A proof of concrete technology and durability for three millenniums.” *Materials and Structures* 31 (Nov.): 623–27.

Kroes, R. 1990 “Woodwork in the foundations of stone-built Roman bridges.” *Bulletin Antieke Beschaving* 65: 97–105.

Kron, G. 2008a “Animal Husbandry, Hunting, and Fishing.” pp. 175–222 in J. P. Oleson, ed., *The Oxford Handbook of Engineering and Technology in the Classical World*. Rev. ed. New York: Oxford.

Kron, G. 2008b“Reconstructing the Techniques and Potential Productivity of Roman Aquaculture in the Light of Recent Research and Practice.” pp. 175–85 in E. Hermon, ed., *Vers une gestion intégrée de l’eau dans l’empire romain.* Rome: L’Erma de Bretschneider.

Krukowsky, S. T. 2010 “Lime.” pp. 561–80 in J. E. Kogel, N. C. Trivedi and J. M. Barker, eds, *Industrial Minerals and Rocks: Commodities, Markets, and Users*. Littleton CO: Society for Mining, Metallurgy, and Exploration, Inc.

Labelye, C. 1751 *A Description of Westminster Bridge*. London: Printed by W. Strahan, for the author.

Lafon, X. 1998 “*Piscinae* et pisciculture dans le basin occidental de la Méditerranée.” *Journal of Roman Archaeology* 11: 573–82.

Lafon, X. 2001 *Villa Maritima; recherches sur les villas littorales de l’Italie romaine (IIIe siècle av. J.-C. / IIIe siècle ap. J.-C.),* Rome: École françaises de Rome.

Lambeck, K., Anzidei, M., Antonioli, F., Benini, A. and Esposito, A. 2004 “Sea Level in Roman Time in the Central Mediterranean and Implications for Recent Change.” *Earth and Planetary Science Letters* 224: 564–75.

Lamprecht, H.-O. 1996 *Opus Caementitium. Bautechnik der Römer*, 5th edn. Düsseldorf: Beton-Verlag.

Lancaster, L. C. 2005a *Concrete Vaulted Construction in Imperial Rome: Innovations in Context.* Cambridge: Cambridge University Press

Lancaster, L. C. 2005b “The process of building the Colosseum.” *Journal of Roman Archaeology* 18, 57–82.

Lancaster, L. C. 2009 “Auguste Choisy and the Economics of Roman Construction.” pp. 307–28 in J. Girón and S. Huerta. eds, *August Choisy (1841–1909) l’architecture et l’art de bâtir*: (Actas del Simposio Internacional celebrado en Madrid, November 19–20, 2009). Madrid.

Lancaster, L. C. 2010 “Parthian Influence on Vaulting in Roman Greece? An Enquiry into Technological Exchange under Hadrian.” *American Journal of Archaeology* 114: 447–72.

Lancaster, L. C. 2011 “The Use of Lightweight Concrete in Rome, Cilicia, and Tunisia.” pp. 60–72 in Ringbom and Hohlfelder 2011.

Lancaster, L. C. 2012 “Ash Mortar and Vaulting Tubes: Agricultural Production and the Building Industry in North Africa.” pp. 145–60 in S. Camporeale, H. Dessales and A. Pizzo, eds, *Les chantiers de construction de l’Italie et des provinces romaines: 3e rencontre. L’économie des chantiers (Paris, École Normale Supérieure, 10–11 D*écembre 2009). Mérida: Instituto de Aqueología de Mérida. Madrid.

Lancaster, L. C., Sottili, G., Marra, F. and Ventura, G. 2010 “Provenancing of lightweight volcanic stones used in ancient Roman concrete vaulting: evidence from Turkey and Tunisia.” *Archaeometry* 52.6: 949–69.

Lancaster, L. C., Sottili, G., Marra, F. and Ventura, G. 2011 “Provenancing of lightweight volcanic stones used in ancient Roman concrete vaulting: evidence from Rome.” *Archaeometry* 53.4: 707–27.

Langton, C. and Roy, D. M. 1984 “Longevity of borehole and shaft sealing materials: characterization of ancient cement based building materials.” *Materials Research Society Symposium Proceedings* 26: 543–49.

Lea, F. M. and Desch, C. H. 1956 *The Chemistry of Cement and Concrete*. 2nd ed. London: Edward Arnold Ltd.

Leatham, J. and Hood, S. 1958/9 “Sub-marine Exploration in Crete, 1955.” *Annual of the British School at Athens* 53/34: 263–89.

Lechtman, H. N. and Hobbs, L. W. 1987 “Roman concrete and the Roman architectural revolution.” pp. 81–128 in W. D. Kingery, ed., *Ceramics and Civilization*, Vol. III. Westerville OH: American Ceramic Society.

Lehmann-Hartleben, K. 1923 *Die antiken Hafenlagen des Mitelmeeres: Beiträge zur Geschichte des Städtebaus im Altertum.* Klio, Beiheft 14. Leipzig: Dieterich.

Leitch, V. 2013 "Reconstructing history through pottery: the contribution of Roman N African cookwares." *Journal of Roman Archaeology* 26: 281–306

Lenoir, M. 1979 *Pseudo-Hygin: Des Fortifications du Camp.* Paris: Les Belles Lettres.

Lepper, F. and Frere, S. 1988 *Trajan's Column: A New Edition of the Cichorius Plates*. Gloucester: Alan Sutton.

Leslie, A. B. and Hughes, J. J. 2002 "Binder microstructure in lime mortars: implications for the interpretations of analysis results." *Quarterly Journal of Engineering Geology and Hydrogeology* 35: 257–63.

Leveau, P. 1984 *Caesarea de Maurértanie: une ville romaine et ses campagnes.* Collection de l'École française de Rome, 70. Rome: École française de Rome.

Lewis, M. 2000 "The Hellenistic Period." pp. 631–48 in Ö Wikander, ed., *Handbook of Ancient Water Technology*. Leiden: Brill.

Lézine, A. 1962 *Architecture romaine d'Afrique. Recherches et mises au point.* Paris: Presses Universitaires de France.

Lian, C., Zhuge, Y. and Beecham, S. 2011 "The relationship between porosity and strength for porous concrete." *Construction and Building Materials* 25: 4294–98.

Lindroos, A. *et al.* 2011 "Problems in Radiocarbon Dating of Roman Pozzolanic Mortars." pp. 214–30 in Ringbom and Hohlfelder 2011.

Liou, B. and Pomey, P. 1985 "Directions des recherches archéologiques sous-marines." *Gallia* 43: 547–76.

Lugli, G. 1957 *La tecnica edilizia romana, con particolare riguardo a Roma e Lazio*. 2 vols. Rome: Giovanni Bardi.

Lustrino, M., Duggen, S. and Rosenberg, C. L. 2011 "The central-western Mediterranean: Anomalous igneous activity in an anomalous collisional tectonic setting." *Earth Science Reviews* 304: 1–40.

Lustrino, M., Martuarano, A., Morra, V. and Ricci, G. 2002 "Volcanological and geochemical features of young pyroclastic levels (<12 Ka) in the urban area of Naples." *Periodico di Mineralogia* 71.3: 241–53.

MacDonald, W. L. 1982 *The Architecture of the Roman Empire, I: An Introductory Study*. Rev. ed. New Haven: Yale University Press.

Maffei, A. 1949 "Pozzolana." *Enciclopedia Italiana* 28: 141–42.

Mancini, M., Bellucci, L. and Petronio, C. 2008 "Il Pleistocene inferiore e medio di Nettuno (Lazio): Stratigrafia e mammalofauna." *Geologica Romana* 41: 71–85.

Mango, C. 1985 *Le développement urbain de Constantinople (IVe–VIIe siècles).* Paris: Diffusion de Boccard.

Marcari, G., Fabbrocino, G. and Lourenço, P. B. 2010 "Mechanical properties of tuff and calcarenite stone masonry panels under compression." pp. 1083–92 in W. Jäger and B. Haseltine, eds, *Proceedings of the 8th International Masonry Conference 2010.* Dresden: International Masonry Society.

Marchetti, D. 1891 "Di un antico molo per lo sbarco dei marmi riconosciuto sulla riva sinistra del Tevere." *Bulletino della Commissione Archeologica Communale di Roma* 19: 45–60.

Marchiori, A. 1989 "Aquileia: porto e 'sistema' portuale." *Aquileia Nostra* 60: 114–48.

Marcus, R. 1963 *Josephus, Jewish Antiquities Books XIV–XV*. Cambridge MA: Harvard University Press.

Margari, V., Pyle, D. M., Bryant, C. and Gibbard, P. L. 2007 "Mediterranean tephra stratigraphy revisited: Results from a long terrestrial sequence on Lesvos Island, Greece." *Journal of Volcanology and Geothermal Research* 163: 34–54.

Marra, F. and D'Ambrosio, E. 2013a "Trace Element Classification Diagrams of Pyroclastic Rocks from the Volcanic Districts of Central Italy: The Case Study of the Ancient Roman Ships of Pisa." *Archaeometry* 55.6: 993–1019.

Marra, F., D'Ambrosio, E., Sottili, G. and Ventura, G. 2013b "Geochemical fingerprints of volcanic material: Identification of a pumice trade route from Pompeii to Rome." *Geological Society of America Bulletin* 125.3–4: 556–77.

Marra, F., Deocampo, D., Jackson, M. and Ventura, G. 2011 "The Alban Hills and Monti Sabatini volcanic products used in ancient Roman masonry (Italy): An integrated stratigraphic, archaeological, environmental and geochemical approach." *Earth Science Reviews* 108: 115–36.

Marriner N. and Morhange, C. 2007 "Geoscience of Ancient Mediterranean Harbours." *Earth-Science Review* 80: 137–94.

Mart, Y. and Perecman, I. 1996 "Caesarea: Unique Evidence for Faulting and Sea Level Fluctuations in the Late Holocene." pp. 3–24 in Raban and Holum 1996.

Martelli, E. 2013 *Sulle spalle dei saccarii: Le rappresentazioni di facchini e il trasporto di derate nel porto di Ostia in epoca imperiale*. BAR Intl Ser S2467. Oxford: Archaeopress.

Martin, R. 1965 *Manuel d'architecture grecque, I: Matériaux et techniques*. Paris: Picard.

Marucchi, O. 1911 "L'ipogèo sepolcrale di Trebio Giusto, recentemente scoperto sulla Via Latina, e proposta di spiegazione gnostica delle due pitture." *Nuovo Bullettino di Archeologia Cristiana* 17: 209–35.

Marzano, A. 2011 "Snails, wine and winter navigation. pp. 179–87 in Harris and Iara 2011.

Marzano, A. 2013 *Harvesting the Sea. The Exploration of Marine Resources in the Roman Mediterranean*. Oxford: Oxford University Press.

Marzano, A. and Brizzi, G. 2009 "Costly display or economic investment?: A quantitative approach to the study of marine aquaculture." *Journal of Roman Archaeology* 22: 215–30.

Massazza, F. 1985 "Concrete resistance to seawater and marine environment." *Il Cemento* 1: 3–25.

Massazza, F. 1988 "Pozzolana and pozzolanic cements." pp. 471–632 in Hewlett, ed., *Lea's Chemistry of Cement and Concrete*, 4th ed., London: Arnold.

Massazza, F. 2002 "Properties and applications of natural pozzolanas." pp. 326–52 in J. Bensted and P. Barnes, eds, *Structure and Performance of Cements*, 2nd ed., London, Taylor and Francis.

Massazza, F. and Costa, U. 1979 "Aspects of the pozzolanic activity and properties of pozzolanic cements." *Il Cemento* 1979: 76–318.

Maura, G. 1996 "Dosaggio della calce in malte pozzolaniche recenti ed antiche." *Materiali e strutture* 6.2: 49–60.

Mayhoff, C. 1892 *C. Plini Secundi Naturalis Historiae Libri XXXVII.* Leipzig: Teubner.

Mazzarino, A. 1982 *M. Porcius Catonis De Agri Cultura*. Leipzig: Teubner.

McCann, A. M. 2002 T*he Roman Port and Fishery of Cosa: A Short Guide. Rome.* Rome: American Academy in Rome.

McCann, A. M. 2008 "Response to 'Cosa's Hydraulic Concrete: Towards a Revised Chronology,' by E. K. Gazda." pp. 291–95 in R. L. Hohlfelder, ed., 2008.

McCann, A. M., Bourgeois, J., Gazda, E. K., Oleson, J. P. and Will, E. L. 1987 *The Roman Port and Fishery of Cosa: A Center of Ancient Trade*. Princeton: Princeton University Press.

McCann, A. M. and Oleson, J. P. 1974 "Underwater Excavations at the Etruscan Ports of Populonia and Pyrgi." *Journal of Field Archaeology* 1: 398–402.

McCormick, M. 2001 *Origins of the European Economy: Communications and Commerce, A.D. 300–900.* Cambridge: Cambridge University Press.

McCoy, F. and Heiken, G. 2000 "Tsunami generated by the late Bronze Age eruption of Thera (Santorini), Greece." *Pure and Applied Geophysics*, 157: 1227–56.

McKenzie, J. 2003 "Glimpsing Alexandria from Archaeological Evidence." *Journal of Roman Archaeology* 16: 35–63.

Mehta, P. K. 1990 *Concrete in the marine environment*. Elsevier: Oxford.

Mehta, P. and Monteiro, P. J. M. 2006 *Concrete: Microstructure, Properties, and Materials.* 3rd ed. New York: McGraw-Hill.

Meiggs, R. 1973 *Roman Ostia.* 2nd ed. Oxford: Clarendon Press.

Meiggs, R. 1982 *Trees and Timber in the Ancient Mediterranean World*. Oxford: Oxford University Press.

Meineke, A. 1877 *Strabonis Geographica*. Leipzig: Teubner.

Merla G. and Ercoli, A. 1971 *Note Illustrative della Carta Geologica d'Italia alla scala 1:100.000 Foglio 190, Monopoli.* Roma: Libreria dello Stato.

Mertens, G., Snellings, R., Van Balen, K., Bicer-Simsir, B., Verlooy, P. and Elsen, J. 2009 "Pozzolanic reactions of common natural zeolites with lime and parameters affecting their reactivity." *Cement and Concrete Research* 39: 233–40.

Milne, G. 1982 "Recording timberwork on the London waterfront." pp. 7–23 in S. McGrail, ed., *Woodworking Techniques before A.D. 1500*. British Archaeological Reports, Intl. Ser., S129. Oxford: BAR.

Milne, G. 1985 *The Port of Roman London*. London: Batsford.

Miniero, P. 2001 "Baia: dallo Scavo Subacqueo, al Museo, al Parco Archeologico Sottomarino e le Prospettive di Tutela." pp. 29–35 in P. A. Gianfrotta and F. Maniscalco, eds, *Proceedings of the Forum Internazionale di Archeologica Subacquea, Pozzuoli, 22–24 September 1998, Forma Maris.* Naples: Massa.

Miniero, P. 2007 "Il parco sommerso di Baia: da sito archeologico ad area marina protetta." pp. 197–204 in F. Gravina, ed., *Communicare la memoria del Mediterraneo.* Collection du Centre Jean Bérard, 24. Naples: Centre Jean Bérard.

Miniero, P. 2010 "Baia sommersa e *Portus Iulius*: il rilievo con strumentazione integrata Multibeam." pp. 102–8 in D. J. Blackman and M. C. Lentini, eds, *Ricoveri per navi militari nei porti del mediterraneo antico e medievale*. Proceedings of the workshop held in Ravello, 4–5th November 2005. Bari: Edipuglia.

Miriello, D., Barca, D., Bloise, A., Ciarallo, A., Crisci, G. M., De Rose, T., Gattuso, C., Gazineo, F. and La Russa, M. F. 2010 "Characterization of archaeological mortars from Pompeii (Campania, Italy) and identification of construction phases by compositional data analysis." *Journal of Archaeological Science* 37: 2207–23.

Mocchegiani Carpano, C. 1999 "Il porto romano di Testaccio." *Forma Urbis: Itinerari nascosti di Roma antica.* 4.1: 4–17.

Morgan, N. J. 1996 "Pattern Book, Western, before *c.* 1440." Vol. 24 pp. 268–71 in J. Taylor, ed., *Dictionary of Art*. New York: MacMillan.

Morhange, C., Marriner, N., Laborel, J., Todesco, M. and Oberlin, C. 2006 "Rapid sea-level movements and noneruptive crustal deformations in the Phlegrean Fields caldera, Italy." *Geology* 34: 93–96.

Morley, N. 2007 "The Early Roman Empire: Distribution." pp. 570–91 in W. Schiedel, I. Morris and R. Saller, eds, *The Cambridge Economic History of the Greco-Roman World*. New York: Cambridge University Press.

Morra, V., Calcaterra, D., Cappelletti, P., Colella, A., Fedele, L., de' Gennaro, R., Langella, A. and Mercurio, M. 2010 "Urban geology: relationships between geological setting and architectural heritage of the Neapolitan area." pp. 1–66 in M. Beltrando, A. Peccerillo, M. Mattei, S. Conticelli, and C. Doglioni, "The Geology of Italy: Tectonics and Life along Plate Margins." *Journal of the Virtual Explorer 36.27* Electronic Edition, ISSN 1441-8142.

Mues-Schumacher, U. 1994 "Chemical variations of the A.D. 79 pumice deposits of Vesuvius." *European Journal of Mineralogy* 6: 987–59.

Müller-Wiener, W. 1994 *Die Häfen von Byzantion-Konstantinupolis-Istanbul*. Tübingen: Wasmuth.

Mynors, R. A. B. 1963 *C. Plini Caecili Secundi Epistularum Libri Decem.* Oxford: Oxford University Press.

Nappi, G., De Casa, G. and Volponi, E. 1979 "Geologia e caratteristiche tecniche del 'Tufo Giallo della Via Tiberina'." *Bolletino Società Geologica Italiano* 98: 431–45.

Nicolaou, K and Flinder, A. 1976 "Ancient Fish-Tanks at Lapithos, Cyprus." *International Journal of Nautical Archaeology* 5: 133–41.

Nieto, X., Revil, A., Morhange, C., Vivar, G., Rizzo, E. and Aguelo, X. 2005 "La Fachada Marítima de Ampurias. Estudios Geofísicos y Datos Arqueológicos." In *Forum Emporiae MMIV = El Fòrum romà d'Empúries, 2004 anys d'història.* Empúries: Museu d' Arqueologia de Catalunya-Empúries.

Oleson, J. P. 1976 "A Possible Physiological Basis for the Term *Urinator,* 'Diver'." *American Journal of Philology* 97: 22–29.

Oleson, J. P. 1977 "Underwater Survey and Excavation in the Port of Pyrgi (Santa Severa), 1974." *Journal of Field Archaeology* 4: 297–308.

Oleson, J. P. 1982 *Sources of Innovation in Later Etruscan Tomb Design (ca. 350–100 B.C.).* Rome: Giorgio Bretschneider.

Oleson, J. P. 1984 *Greek and Roman Mechanical Water-Lifting Devices*: *The History of a Technology*. Toronto: Toronto University Press.

Oleson, J. P. 1985 "Herod and Vitruvius: Preliminary Thoughts on Harbour Engineering at Sebastos: the Harbour of Caesarea Maritima." pp. 165–72 in A. Raban, ed., *Harbour Archaeology*. British Archaeological Reports, Intl. Ser., S257. Oxford: BAR.

Oleson, J. P. 1987 "The Spring House Complex." pp. 19–128 in McCann *et al.* 1987.

Oleson, J. P. 1988 "The technology of Roman Harbours." *International Journal of Nautical Archaeology* 17: 147–58.

Oleson, J. P. 1989a "Area G: Northwest Tip of Northern Breakwater and Adjacent Tower." pp. 127–30 in Raban, A., ed., *The Harbours of Caesarea Maritima Results of the Caesarea Ancient Harbour Excavation Project 1980–1985*. British Archaeological Reports, Intl. Series, S194. Oxford: BAR.

Oleson, J. P. 1989b "Area P: Piscina." pp. 160–67 in A. Raban, ed., *The Harbours of Caesarea Maritima, Volume 1: The Site and Excavations*, BAR International Series, S491. Oxford: BAR.

Oleson, J. P. 1992 "The Technology of King Herod's Harbour." pp. 49–67 in R. L. Vann, ed., *Caesarea Papers. Straton's Tower,* *Herod's Harbour, and Roman and Byzantine Caesarea.* Journal of Roman Archaeology, Suppl. Series, 5. Ann Arbor: JRA.

Oleson, J. P. 1996 "Artifactual Evidence for the History of the Harbors of Caesarea." pp. 359–77 in Raban and Holum 1996.

Oleson, J. P. 2000 "Water-Lifting." pp. 217–302 in Ö. Wikander, ed., *Handbook of Ancient Water Technology*. Leiden: Brill.

Oleson, J. P. 2004 "Well-Pumps for Dummies: Was there a Roman Tradition of Popular, Sub-Literary Engineering Manuals?" pp. 65–86 in F. Minonzio, ed., *Problemi di Macchinismo in Ambito Romano*. Como: Municipio di Como.

Oleson, J. P. 2005 "Design, Materials, and the Process of Innovation in Roman Force Pumps." pp. 311–31 in J. Pollini, ed., *Terra marique: Studies in Art History and Marine Archaeology in Honor of Anna Marguerite McCann*. Oxford: Oxbow Books.

Oleson, J. P. 2011 "*Harena sine calce*: Building Disasters, Incompetent Architects, and Construction Fraud in Ancient Rome." *Acta Instituti Romani Finlandiae* 128: 9–27.

Oleson, J. P., Bottalico, L., Brandon, C., Cucitore, R., Gotti, E. and Hohlfelder, R. L. 2006 "Reproducing a Roman Maritime Structure with Vitruvian pozzolanic concrete." *Journal of Roman Archaeology* 19: 31–52.

Oleson, J. P., Brandon, C., Cramer, S. M., Cucitore, R., Gotti, E. and Hohlfelder, R. L. 2004a "The ROMACONS Project: A Contribution to the Historical and Engineering Analysis of the Hydraulic Concrete in Roman Maritime Structures." *International Journal of Nautical Archaeology* 33.2: 199–229.

Oleson, J. P., Brandon, C. and Hohlfelder, R. L. 2004b "The Roman Maritime Concrete Study (ROMACONS): Fieldwork at Portus, Anzio, Santa Liberata, Cosa, 2002–2003." pp. 185–94 in F. Maniscalco, ed. *Mediterraneum. Tutela, Conservazione e Valorizzazionne del Patrimonio Culturale Subacqueo* 4. Naples: Massa Editore.

Oleson, J. P., Brandon, C. and Hohlfelder, R. L. 2008 "The Roman Maritime Concrete Study (ROMACONS): Activities to 2007." pp. 325–29 in J. P. Delgado, ed., "Nautical and Maritime Archaeology, 2006–2007 Seasons." *American Journal of Archaeology* 112: 307–35.

Oleson, J. P., Brandon, C. and Hohlfelder, R. L. 2011a "Technology, Innovation, and Trade: Research Into the Characteristics of Roman Maritime Concrete." pp. 107–19 in Robinson and Wilson, eds, 2011.

Oleson, J. P. and Branton, G. 1992 "The Technology of King Herod's Harbour." pp. 49–67 in Vann, R. L., ed., *Caesarea Papers Straton's Tower, Herod's Harbour, and Roman and Byzantine Caesarea.* Journal of Roman Archaeology, Supplementary Series 5. Ann Arbor: JRA.

Oleson, J. P., Fitzgerald, M. A., Sherwood, A. N. and Sidebotham, S. E. 1994 *The Harbours of Caesarea Maritima, Vol. II: The Finds and the Ship*. British Archaeological Reports, Intl. Series, S594. Oxford: BAR.

Oleson, J. P. and Hohlfelder, R. L. 2011 "Ancient Harbors in the Mediterranean." pp. 809–33 in A. Catsambis, B. Ford and D. L. Hamilton, eds, *Oxford Handbook of Maritime Archaeology*. Oxford, Oxford University Press.

Oleson, J. P. and Jackson, M. D. 2010 "How Did Expertise in Maritime Hydraulic Concrete Spread through the Roman Empire?" pp. 285–92 in J. Válek, C. Groot and J. J. Hughes, eds, *2nd Conference on Historic Mortars and RILEM TC 203-RHM Final Workshop: 22–24 September, 2010, Prague.* Bagneux: RILEM Publications.

Orsi, G., D'Antonio, M.,de Vita, S. and Gallo, G. 1992 "The Neapolitan Yellow Tuff, a large-magnitude trachytic phreatoplinian eruption: eruptive dynamics, magma withdrawal and caldera collapse." *Journal of Volcanology and Geothermal Research* 53: 275–87.

Orsi, G., de Vita, S. and Di Vito, M. 1996 "The restless, resurgent Campi Flegrei nested caldera (Italy): constraints on its evolution and configuration." *Journal of Volcanology and Geothermal Research* 74: 179–214.

Ostrow, S. E. 1979 "The Topography of Puteoli and Baiae on the Eight Glass Flasks." *Puteoli* 3: 77–140.

Ottaviani, M. 1988 "Proprietà geotecniche di tufi vulcanici italiani." *Rivista Italiana di Geotecnica* 3: 171–78.

Ousterhout, R. 1999 *Master Builders of Byzantium*. Princeton: Princeton University Press.

Özkaya, O. A. and Böke, H. 2009 "Properties of Roman bricks and mortars used in Serapis temple in the city of Pergamon." *Materials Characterization* 60: 995–1000.

Pabst, S., Wörner, G., Civetta, L. and Tesoro, R. 2008 "Magma chamber evolution prior to the Campanian Ignimbrite and Neapolitan Yellow Tuff eruptions (Campi Flegrei, Italy)." *Bulletin of Volcanology* 70: 961–76.

Paoli, P. A. 1768 *Avanzi delle antichità esistenti a Pozzuoli, Cuma e Baia.* Naples.

Paone, A. 2006 "The geochemical evolution of the Mt. Somma-Vesuvius volcano." *Mineralogy and Petrology* 87: 53–80.

Papageorgiou, S., Arnold, M., Laborel, J. and Stiros, S. 1993 "Seismic uplift of the harbour of ancient Aigeira, Central Greece." *International Journal of Nautical Archaeology* 22.3: 275–81.

Papakonstantinou, S., Pimentel, E. and Anagnostou, G. 2012 "Analysis of artificial ground freezing in the Pari-Duomo platform tunnel of the Naples metro." pp. 281–84 in T. Benz and S. Nordal, eds, *Numerical Methods in Geotechnical Engineering*. London: Taylor and Francis.

Parker, A. J. 1992a *Ancient Shipwrecks of the Mediterranean & the Roman Provinces.* BAR Intl. Ser., S580. Oxford: Tempus Reparatum.

Parker, A. J. 1992b "Cargoes, Containers and Stowage: the Ancient Mediterranean." *International Journal of Nautical Archaeology* 21.2: 89–100.

Parker, A. J. 1996 "Sea Transport and Trade in the Ancient Mediterranean." pp. 97–109, in E. E. Rice, ed., *The Sea and History*. Gloucester: Sutton Publishing.

Parker, R. J. 1989 "Geochemical and petrographic characteristics of potassium-rich pyroclastic and lava samples from Vulsini volcano, Roman magmatic region, Italy." *Journal of Volcanology and Geothermal Research* 39: 297–314.

Paroli, L. 2005 "The Last 50 Years." pp. 53–59 in Keay *et al.* 2005.

Patrice, J. 2011 *Studies in the Archaeology and History of Caesarea Maritima Caput Judaeae, Metropolis Palaestinae*. Leiden: Brill.

Pavía, S. and Caro, S. 2008 "An investigation of Roman mortar technology through the petrographic analysis of archaeological material." *Construction and Building Material* 22: 1807–11.

Peccerillo, A. 2005 "Plio-Quaternary volcanism in Italy: Petrology, Geochemistry, Geodynamics." Berlin: Springer-Verlag.

Pellandra, D. I. 1997 "Due poco note peschiere romane a Santa Severa e a Santa Marinella." *Archeologia subacquea* 2: 21–33.

Pellandra, D. I. 2002 "Ponza, 'Grotte di Pilato': la peschiera esterna." *Archeologia subacquea* 3: 101–5.

Pellegrino, A. 1967 "Proprietà fisico-meccaniche dei terreni vulcanici del Napoletano." *Atti del VII Convegno di Geotecnica.* Associazione Geotecnica Italiana. Rome: AGI.

Peluso, F. and Arienzo, I. 2007 "Experimental determination of permeability of Neapolitan Yellow Tuff." *Journal of Volcanology and Geothermal Research* 160: 125–36.

Perno, S. 1997 "Prove su elementi complessi componenti l'*opus caementicium." Materiale e strutture* 7.2–3: 109–21.

Pertusati, P. C., Musumeci, G., Bonini, L. and Trumpy, E. 2005 "*Carta Geologica della Toscana, 1:10,000*." No. 342160 Ansedonia, Pisa: Servizio Geologico Regionale.

Pesce, G. 1941 *I rilievi dell'anfiteatro Campano*. Rome.

Picozzi, S. 1974 "Il collettore del Colosseo." *Capitoleum* 12: 13–23.

Pike, S. and Soles, J. 2009 "Characterization of calcarenite quarries in east Crete" in Y. Maniatis, ed., *Proceedings of the 7th International Conference, Association for the Study of Marble and Other Stones used in Antiquity ASMOSIA VII, Thasos, Greece 15–20 September 2003*. Athens: École française d'Athènes.

Piromallo, M. 2004 "Puteoli, porto di Roma." pp. 267–78 in G. Zevi and R. Turchett, eds, *Le strutture dei porti e degli approdi antichi.* Soveria Manelli: Rubbettino.

Plommer, H. 1973 *Vitruvius and Later Roman Building Manuals.* Cambridge: Cambridge University Press.

Poggesi , G. and Rendini, P. 1998 *Memorie sommerse: archeologia subacquea in Toscana.* Grosseto: Amministrazione provinciale di Grosseto

Poidebard, A., Lauffray, J. and Mouterde, R. 1951 *Sidon: Aménagements Antiques du Port de Saida, Etudes aériennes, au sol, et sous-marines, 1946–50*. Beirut: Ministère des travaux publiques.

Pollitt, J. J. 1966 *The Art of Rome, c.753 B.C to 337 A.D.* Englewood Cliffs, N.J.

Pompilio, M. 2005 "Inerti di natura vulcanica nei calcestruzzi del ninfeo ovest press oil Calcidico di Leptis Magna." pp. 290–91 in F. Tomasello, *Fontane e ninfei minori di Leptis Magna.* Rome: "L'Erma" di Bretschneider.

Purcell, N. 1996 "The ports of Rome: evolution of a '*façade maritime*'." pp. 267–79 in A. Zevi and A. Claridge, eds, *'Roman Ostia' Revisited. Archaeological and Historical Papers in memory of Russell Meiggs*. London: British School at Rome.

Quilici, L. 2004 "Per il Restauro del Faro del Lazzaretto a Civitavecchia." pp. 111–18 in M. Giacobelli, ed., *Lezioni Fabio Faccenna, conference di archeologia subacquea* (III–V ciclo). Bari: Edipuglia.

Raban, A. 1989 *The Harbours of Caesarea Maritima, Vol. I: The Site and the Excavations*. J. P. Oleson, ed. British Archaeological Reports, Intl. Ser., S491. Oxford: BAR.

Raban, A. 1996 "The Inner Harbour Basin of Caesarea: Archeological Evidence for its Gradual Demise." pp. 628–66 in Raban and Holum 1996.

Raban, A. 1999a "Destruction of Herod the Great's Harbor at Caesarea Maritime, Israel – Geoarchaeological Evidence." *Geology* 27.9: 811–14.

Raban, A. 1999b "The Lead Ingots from the Wreck Site (Area K)." pp. 179–88 in Holum *et al.* 1999.

Raban, A. 2008 "Underwater Excavations in the Herodian Harbor Sebastos." pp. 129–42, in Holum *et al.* 2008.

Raban, A. 2009 *The Harbour of Sebastos (Caesarea Maritima) in its Roman Mediterranean Context,* in M. Artzy, B. Goodman and Z. Gal, eds. British Archaeological Reports Intl. Series, S1930. Oxford: BAR.

Raban, A. and Galili, E. 1985 "Recent maritime archaeological research in Israel." *International Journal of Nautical Archaeology* 14: 321–56.

Raban, A. and Holum, K., eds 1996 *Caesarea Maritima: A Retrospective after Two Millennia*. Leiden: Brill.

Rea, R. 2004 *L'Ipogeo di Trebio Giusto sulla Via Latina.* Vatican City: Pontificia commissione di archeologia sacra.

Reinhardt, E. G., Goodman, B. N., Boyce, J. I., Lopez, G., van Hengstum, P., Rink, W. R., Mart, Y. and Raban, A. 2006 "The Tsunami of 13 December A.D.115 and the Destruction of Herod the Great's Harbor at Caesarea Maritima." *Geology* 34.12: 1061–64.

Reinhardt, E. G. and Raban, A. 1999 "Destruction of Herod the Great's Harbor at Caesarea Maritima, Israel--Geoarcheological Evidence." *Geology* 27: 811–14.

Reinhardt, E. G. and Raban, A. 2008 "Site Formation and Stratigraphic Development of Caesarea's Ancient Harbor." pp. 155–81 in Holum *et al*. 2008.

Richardson, L., Jr. 1992 *A New Topographical Dictionary of Ancient Rome.* Baltimore: Johns Hopkins University Press..

Rickman, G. 1966 "Mare Nostrum." pp. 1–14 in E. E. Rice, ed., *The Sea and History*. Glouchester: Sutton Publishing.

Rickman, G. 1980 "The Grain Trade under the Roman Empire." *Memoirs of the American Academy in Rome* 36: 261–75.

Rickman, G. 2005 "Portus Romae?" pp. 232–37 in J. Pollini, ed., *Terra Marique*. Oxford, Oxbow Books.

Ringbom, Å., Heinemeier, J., Lindroos, A. and Brock, F. 2011 "Mortar Dating and Roman Pozzolana, Results and Interpretations." pp. 187–208 in Ringbom and Hohlfelder 2011.

Ringbom, Å. and Hohlfelder, R. L., eds 2011 *Building Roman Aeterna: Current research on Roman mortar and concrete. Commentationes Humanarum Litterarum,* 128. Helsinki: Societas Scientiarum Fennica.

Ringel, J. 1988 "Literary Sources and Numismatic Evidence of Maritime Activity in Caesarea During the Roman Period." pp. 63–73 in I. Malkin and R. L. Hohlfelder, eds, *Mediterranean Cities: Historical Perspectives*. London: Frank Cass & Co., Ltd.

Rispoli, C. 2011 "Il calcestruzzo dei porti Romani di Baia e Pompeiopolis: mix-design, composizione mineralogica e processi minerogenetici secondari." Tesi di Laurea, Università Federico II di Napoli.

Rivet, L., Brentchaloff, D., Roucole, S. and Saulnier, S. 2000 *Fréjus.* Revue Archéologique de Narbonnaise, Supplément 32. Montpellier.

Robinson, D. and Wilson, A., eds 2011 *Maritime Archaeology and Ancient Trade in the Mediterranean*. Oxford Centre for Maritime Archaeology, Monograph 6. Oxford: Oxford Centre for Maritime Archaeology.

Robinson, O. F. 1992 *Ancient Rome: City Planning and Admoinistration.* New York: Routledge.

Rose, V. and Müller-Strübing, H. 1867 *Vitruvii de Architectura Libri Decem.* Leipzig: Teubner.

Rowland, I., Howe, T. and Dewar, M. 1999 *Vitruvius: Ten Books on Architecture.* Cambridge: Harvard University Press.

Roy, D. M. and Langton, C. A. 1989 *Studies of ancient concrete as analogs of cementitious sealing materials for a repository in tuff.* Report LA-11527-MS, UC-721, prepared by the Materials Research Laboratory, Pennsylvania State University, for Los Alamos National Laboratory, New Mexico.

Rudd, N. 2004 *Horace. Odes and Epodes.* Cambridge MA: Harvard University Press.

Ruegg, S. D. 1988 "Minturnae: A Roman River Seaport on the Garigliano River, Italy." pp. 209–28 in A. Raban, ed., *Archaeology of Coastal Changes*. British Archaeological Reports, Intl. Series, S404. Oxford: BAR.

Russell, B. 2011 "*Lapis transmarinus*: Stone-carrying Ships and the Maritime Distribution of Stone in the Roman Empire." pp. 139–55 in Robinson and Wilson, eds 2011.

Rustico, L. 1999 "Peschiere romane." *Mélanges de l'École française de Rome* 111: 51–66.

Samuelli Ferretti, A. 1997 "Proposte per lo studio teorico-sperimentale della statica dei monumenti in *opus caementicium*." *Materiali e strutture* 7.2–3: 63–84.

Scarpati, C., Cole, P. and Perrotta, A. 1993 "The Neapolitan Yellow Tuff – A large volume multiphase eruption from Campi Flegrei, Southern Italy." *Bulletin of Volcanology* 55: 343–56.

Schäfer, J., *et al.* 1981 *Phaselis: Beiträge zur Topographie und Geschichte der Stadt und ihrer Häfen.* Instanbuler Mitterilungen, Beiheft 24. Tübingen: Wasmuth.

Schäfer, J. and Schläger, H. 1962 "Zur Seeseite von Kyme in der Aeolis." *Archäologischer Anzeiger* 1962: 40–57.

Scheidel, W. 2011 "A Comparative Perspective on the Determinants of the Scale and Productivity of Roman Maritime Trade in the Mediterranean." pp. 21–37 in Harris and Iara, eds 2011.

Schläger, H. 1971 "Die Texte Vitruvs im Lichte der Untersuchungen am Hafen von Side." *Bonner Jahrbücher* 171: 150–61.

Schläger, H., Blackman, D. J. and Schafer, J. 1968 "Der Hafen von Anthedon mit Beitragen zur Topographie und Geschichte der Stadt." *Archäologischer Anzeiger* 1968: 21–98.

Schmiedt, G. 1972 *Il livello antico del Mar Tirreno. Testimonianze dei resti archeologici.* Florence: Leo S. Olschki.

Schofield, R. and Tavernor, R. 2009 *Vitruvius on Architecture.* London: Penguin Books.

Schörle, K. 2011 "Constructing Port Hierarchies: Harbours of the Central Tyrrhenian Coast." pp. 93–106 in Robinson and Wilson eds, 2011.

Schramm, A. 1936 "Der Molenbau in Vitruvs Architectura." *Philologische Wochenschrift* 49/50: 1404–8.

Schramm, A. 1938 "Der Molenbau in Vitruvs Architectura V 12, 3–7." *Römische Mitteilungen* 53: 46–49.

Scicchitano, C., Monaco, C. and Tortorici, L. 2007 "Large boulder deposits by tsunami waves along the Ionian coast of south-eastern Sicily (Italy)." *Marine Geology* 238: 75–91.

Scognamiglio, E. 1997 "Aggiornamenti per la topografia di Baia sommersa." *Archeologia subacquea* 2, 35–45.

Scognamiglio, E. 2001 "Baia Sommersa: Gli Sviluppi di Ricerca." pp. 43–50 in P.A. Gianfrotta and F. Maniscalco, eds, *Proceedings of the Forum Internazionale di Archeologica Subacquea, Pozzuoli, 22–24 September 1998*. Forma Maris. Naples: Massa Editore.

Scognamiglio, E. 2002 "Nuovi date su Baia Sommersa." *Archeologia subacquea* 3: 47–55.

Scognamiglio, E. 2006 "Archeologia Subacquea a Miseno (Campi Flegrei)." *Archaeologia Maritima Mediterranea* 3: 65–77.

Scognamiglio, E. 2008 "Il molo semisommerso della villa romana di Sapri." *Archaeologia Maritima Mediterranea* 5: 139–49.

Scognamiglio, E. 2009a "Porto Giulio: nuovi dati." *Archaeologia Maritima Mediterranea* 6: 143–53.

Scognamiglio, E. 2009b "La rada di Baia, forma e frequentazione." *Archaeologia Maritima Mediterranea* 6: 155–65.

Scognamiglio, E. 2010 "Prime ricognizioni lungo la costa settentrionale dell'Isola di Capri." *Archaeologia Maritima Mediterranea* 7: 117–28.

Segev, A. 2009 "40Ar/ 39Ar and K–Ar geochronology of Berriasian–Hauterivian and Cenomanian tectonomagmatic events in northern Israel: implications for regional stratigraphy." *Cretaceous Research* 30: 810–28.

Segev, A., Sass, E., Ron, H., Lang, B., Kolodny, Y. and McWilliams, M. 2003 "Stratigraphic, geochronologic, and paleomagnetic constraints on Late Cretaceous volcanism in northern Israel." *Israel Journal of Earth Science* 51: 297–309.

Sersale, R. and Orsini, P. G. 1969 "Hydrated phases after reaction of lime with 'pozzolanic' materials or with blastfurnace slags." *Proceedings, Fifth International Symposium on the Chemistry of Cement*, Tokyo, 1968. 4,: 114–21. Tokyo: Cement Association of Japan.

Shackleton Bailey, D. R. 2003 *Statius, Silvae.* Cambridge MA: Harvard University Press.

Shaw, J. W. 1969 "A Foundation in the Inner Harbour at Lechaeum." *American Journal of Archaeology* 73: 370–72.

Shaw, J. W. 2009 *Minoan Architecture: Materials and Techniques, 2nd ed*. Studi di archeologia cretese. Padova: Bottega d'Erasmo.

Sherwin-White, A. N. 1966 *The Letters of Pliny: A Historical and Social Commentary.* Oxford: Clarendon Press.

Siddall, R. 2000 "The use of volcaniclastic material in Roman hydraulic concretes: a brief review." pp. 339–44 in W. J. McGuire *et al.*, eds, *The Archaeology of Geological Catastrophes*. London: Geological Society.

Signorini, R. 1967 "*Note Illustrative della Carta Geologica d'Italia alla scala 1:100,000*." Ercolano, Napoli: Poligrafica Cortevalori.

Simplício, M. C. and Barros, P. 2006 "'Quarteira Submersa', um sito romano de vocação maritima no litoral algarvio (Loulé)." In *V Jornadas Internacionales de Arqueología Subacuática, Comercio, Redistribución y Fondeaderos. La Navegación a Vela en el Mediterráneo,* Valência. Gandia.

Sneh, A. 2000 "Faulting in the Coastal Plain of Israel During the Later Quaternary, Reexamined." *Israel Journal of Earth Sciences* 49: 21–9.

Sneh, A., Bartov, Y., Weissbrod, T. and Rosensaft, M. 1998 "*Geological Map of Israel, 1:200.000 scale, Carmel.*" Alit (3-III), Nazerat (3-IV), Hadera (5-I), Umm El Fahm (5-II) 1:50.000 sheets. Jerusalem: Geological Survey of Israel.

Snellings, R., Mertens, G. and Elsen, J. 2012 "Supplementary Cementitious Materials." *Reviews in Mineralogy and Geochemistry* 74: 211–78.

Soltan, A. M., Awad, S. A. and El-Ansary, G. M. 2010 "Applicability of Egyptian limestones for calcination." *Applied Earth Science* (Transactions of the Institute for Mineralogy and Metallurgy B) 119.4: 236–42.

Somma, R., Ayuso, R. A., De Vivo, B. and Rolandi, G. 2001 "Major, trace element and isotope geochemistry (Sr-Nd-Pb) of interplinian magmas from Mt. Somma-Vesuvius (Southern Italy)." *Mineralogy and Petrology* 73: 121–43.

Stamatopoulos, A. C. and Kotzias, P. C. 1991 "Volcanic Ash in Ancient and Modern Construction." pp. 491–501 in D. A. Hardy, ed., *Thera and the Aegean World III, vol. 1: Archaeology.* London: The Thera Foundation.

Stanislao, C. 2011 "Il calcestruzzo dei porti Romani di Egnazia, Chersonissos ed Alessandria d'Egitto: mix-design, composizione mineralogica e processi minerogenetici secondari." Tesi di Laurea, Università Federico II di Napoli.

Stanislao, C., Rispoli, C., Vola, G., Cappelletti, P., Morra, V. and de' Gennaro, M. 2011 "Contribution to the knowledge of ancient Roman seawater concretes: Phlegrean pozzolan adopted in the construction of the harbour at Soli-Pompeiopolis (Mersin, Turkey)." *Periodico di Minerologia* 80.3: 471–88.

Steinhauser, G., Sterba, J. H., Oren, E., Foster, M. and Bichler, M. 2010 "Provenancing of archeological pumice finds from North Sinai." *Naturwissenschaften* 97: 403–10.

Sterba, J. H., Polinger Foster, K., Steinhauser, G. and Bichler, M. 2009 "New light on old pumice: the origins of Mediterranean volcanic material from ancient Egypt." *Journal of Archaeological Science* 36: 1738–44.

Stiros, S. 2001 "The ancient harbour at Mavra Litharia Korinthias, Construction, history and conclusions for the reasons of ancient Aigeira's decline." In V. Mitsopoulos-Leon, C. Schauer and W. Gauss, eds, *Forschungen in der Peloponnese, Akten des Symposions anlässlich der Feier "100 Jahre Österreichisches Archäologisches Institut Athen." Athen 5.3.–7.3.1998.* Athens: Österreichisches Archäologisches Institut.

Stiros, S., Pirazzoli, P., Rothaus, R., Papageorgiou, S., Laborel J. and Arnold, M. 1996 "On the Date of Construction of Lechaion Western Harbour of Ancient Corinth, Greece." *Geoarchaeology* 11.3: 251–63.

Stoll, O. 1993 "Der Transfer von Technologie in der römischen Antike." *Münstersche Beiträge zur Antiken Handelsgeschichte* 12.2: 93–118.

Sulpizio, R., Cioni, R., Di Vito, M. A., Mele, D., Bonasia, R. and Dellino, P. 2010 "The Pomici di Avellino eruption of Somma-Vesuvius (3.9 ka BP). Part I: stratigraphy, compositional variability and eruptive dynamics." *Bulletin of Volcanology* 72: 539–58.

Taylor, H. F. W. 1992 "Tobermorite, jennite, and cement gel." *Zeitschrift fur Kristallographie* 202: 41–50.

Taylor, H. F. W. 2004 *Cement Chemistry*. London: Thomas Telford Publishing.

Taylor, R. 2003 *Roman Builders: A Study in Architectural Process*. Cambridge: Cambridge University Press.

Testaguzza, O. 1970 *Portus: Illustrazione dei Porti di Claudio e Traiano e della Città di Porto a Fiumicino.* Rome: Julia Editrice.

Thackeray, H. St. J. 1927 *Josephus, The Jewish War Books I–II.* Cambridge MA: Harvard University Press.

Thomas, M. D. A., Bremner, T. and Scott, A. C. N. 2011 "Actual and modelled performance in a tidal zone." *Concrete International* 33: 23–28.

Thornton, M. K. and Thornton, R. L. 1989 *Julio-Claudian building programs. A quantitative study in political management.* Wauconda, IL: Bolchazy-Carducci.

Tonarini, S., D'Antonio, M., Di Vito, M. A., Orsi, G. and Carandente, A. 2009 "Geochemical and B-Sr-Nd isotopic evidence for mingling and mixing processes in the magmatic system that fed the Astroni volcano (4.1–3.8 ka) within the Campi Flegrei caldera (southern Italy)." *Lithos* 107: 135–51.

Trigila, R. 1987 "The provenance of some tuff samples." pp. 313–14 in McCann *et al.* 1987.

Trigila, R., Ferrini, F. and Cozzupoli, D. 1971 "Studio geopetrografico del complesso vulcanico di Latera (Vulcani Volsinii) nota II: la serie piroclastica di Stenzano fra F. Olpeta e la Selva del Lamone." *Periodico di Mineralogia* 40.1: 125–69.

Tucci, P. L. 2012 "La controversa storia della Porticus Aemilia." *Archeologia Classica* 63: 575–91.

Turbeville, B. N. 1993 "Petrology and Petrogenesis of the Latera Caldera, Central Italy." *Journal of Petrology* 34.1: 77–123.

Turriziani, R. 1964 "Chap. 14: Aspects of the Chemistry of Pozzolanas." pp. 69–86 in H. F. W. Taylor, ed., *Chemistry of Cements.*, vol. II. London: Academic Press.

Ucelli, G. 1952 *Le Navi di Nemi.* 2nd ed. Rome: Libreria dello Stato.

Válek, J. and Matas, T. 2012 "Experimental Study of Hot Mixed Mortars in Comparison with Lime Putty and Hydrate Mortars. Historic Mortars, Characteristics and Tests." pp. 269–81 in J. Válek, C. Groot and J. Hughes, eds, *Historic Mortars: Characterization, Assessment, Conservation and Repair.* Berlin, New York: Springer-RILEM.

Van Deman, E. B. 1912a "Methods of determining the date of Roman concrete monuments (First paper)." *American Journal of Archaeology* 16: 230–51.

Van Deman, E. B. 1912b "Methods of determining the date of Roman concrete monuments (Second paper)." *American Journal of Archaeology* 16: 387–432.

Van Driel-Murray, C. 1985 "The Production and Supply of Military Leatherwork in the First and Second Centuries A.D." pp. 43–81 in M. C. Bishop, ed., *The Production and Distribution of Roman Military Equipment, Proceedings of the Second Roman Military Equipment Research Seminar*. Oxford: BAR.

Vann, R. L. 1994 "Cilician Harbor Survey: 1993 Season at Soli-Pompeiopolis." pp. 68–73 in R. P. Woodward and C. D. Moore, eds, *Underwater Archaeology Proceedings from the Society for Historical Archaeology Conference: Vancouver British Columbia, 1994*. Uniontown PA: Society for Historical Archaeology.

Verduchi, P. A. 2004 "Notizie e riflessioni sul porto di Roma." pp. 233–46 in A. G. Zevi and R. Turchetti, eds, *Le Strutture dei Porti e Degli Approdi Antichi. Seminar held in Ostia Antica, Rome 16–17 April 2004*. Rubbettino: Soveria Mannelli.

Verduchi, P. A. 2005 "South West Corner of the Darsena Basin in Portus." pp. 255–57 in Keay *et al.* 2005.

Viaene, W., Waelkens, M., Ottenburghs, R. and Callebaut, K. 1997 "An Archaeometric Study of Mortars Used at Sagalassos." pp. 405–21 in M. Waelkens and J. Poblome, eds, *Sagalassos IV: Report on the Survey and Excavation Campaigns of 1994 and 1995*. Leuven: Leuven University Press.

Vidakis, M. and Meulenkamp, J. E. 1996 "*Geological Map of Greece, 1:50.000 scale, Heraklion, Mochos*." Athens: Institute of Geology and Mineral Exploration.

Vinci, A. 1984 "Chemical differences between the island and submarine pumice layers of Thera." *Marine Geology* 55: 487–91.

Vinci, A. 1985 "Distribution and chemical composition of tephra layers from Eastern Mediterranean abyssal sediments." *Marine Geology* 64: 143–55.

Vitaliano, C. J. and Vitaliano, D. 1974 "Volcanic tephra on Crete." *American Journal of Archaeology* 78: 19–24.

Vola, G., Gotti, E., Brandon, C., Oleson, J. P. and Hohlfelder, R. L. 2011a "Chemical, mineralogical and petrographic characterization of Roman ancient hydraulic concretes cores from Santa Liberata, Italy, and Caesarea Palestinae, Israel." *Periodico di Mineralogia* 80: 317–38.

Vola, G., Jackson, M., Oleson, J. P., Brandon, C. and Hohlfelder, R. L. 2010b "Mineralogical and Petrographic characterization of Ancient Roman Maritime Concretes from Mediterranean Harbours." pp. 381–88 in *Proceedings of the 2nd Historic Mortars Conference (HMC2010), 22–24th September 2010, Prague, Czech Republi.* Prague: RILEM.

Vola, G., Stanislao, C., Rispoli, C., Morra ,V. and de' Gennaro, M. 2010a "Petrographic quantitative analysis of pozzolanic mortars from ancient Roman marine concrete cores, drilled by Romacons team (2006–2009). *Rendiconti Online della Società Geologica Italiana* 11:2: 561–62.

Vola, G., Stanislao, C., Rispoli, C., Morra ,V. and de' Gennaro, M. 2011b "Analisi petrografica quantitativa di malte pozzolaniche provenienti da antichi calcestruzzi marini di età romana, campionati dal ROMACONS team (2006–2009)." *Rocce e Minerali Industriali* 6: 29–41.

Votruba, G. 2007 "Imported Building Materials of Sebastos Harbour, Israel." *International Journal of Nautical Archaeology* 36; 325–35.

Waelkens, M. 1987 "The Adoption of Roman Building Techniques in the Architecture of Asia Minor." pp. 94–105 in S. Macready and F. H. Thompson, eds, *Roman Architecture in the Greek World*. The Society of Antiquaries Occasional Papers, 10. London: Society of Antiquaries.

Warren, P. M. and Puchelt, H. 1990 "Stratified pumice from Bronze Age Knossos." pp. 71–81 in D. A. Hardy and A. C. Renfrew, eds, *Thera and the Aegean World III. Volume 3: Chronology*. London: The Thera Foundation.

Wasserman, I. n.d. "The durability of two natural stones intended for the conservation of the historical masonry sea wall in the old town of Acre."

White, K. D. 1967 *Agricultural Implements of the Roman World*. Cambridge: Cambridge University Press.

White, K. D. 1975 *Farm Equipment of the Roman World*. Cambridge University Press.

Wiegand, T. 1894 *Die puteolanische Bauinschrift, Sachlich erläutert.* Leipzig: Teubner.

Wilby, C. B. 1977 *Concrete for Structural Engineers*. London and Boston : Newnes-Butterworths.

Will, E. L. 1987 "Chapter IX. The Roman Amphoras." pp. 171–220 in McCann *et al.*, 1987.

Williams, R. 2004 *Lime Kilns and Lime Burning*, 2nd ed. Buckinghampshire; Shire Publications.

Wilski, P. 1909 *Klimatologische Beobachtungen aus Thera.* Thera, vol. 4. Berlin: Reimer.

Wilson, A. 2002 "Machines, Power, and the Ancient Economy." *Journal of Roman Studies* 2002: 1–32.

Wilson, A. 2006 "The economic impact of technological advances in the Roman construction industry." pp. 225–36 in E. Lo Cascio, ed., *Innovazione technica e progresso economico nel mondo romano.* Bari: Edipuglia.

Wilson, A. 2011a "Developments in Mediterranean Shipping and Maritime Trade from the Hellenistic Period to AD 100." pp. 33–55 in D. Robinson and Wilson, eds 2011.

Wilson, A. 2011b "The Economic Influence of Developments in Maritime Technology." pp. 211–33 in Harris and Iara, eds 2011.

Wilson, A., Schörle, K. and Rice, C. 2012 "Roman Ports and Mediterranean Connectivity." S. Keay, ed. 2012: 367–91.

Wilson Jones, M. 2000 *Principles of Roman Architecture.* New Haven: Yale University Press.

Ximenes, S. and Moerman, M. 1988 "The Roman Harbour of Laurons: Buildings and Structures." pp. 229–52 in A. Raban, ed., *Archaeology of Coastal Changes*. British Archaeological Reports, Intl. Series, S404. Oxford: BAR.

Yorke, R. A. 1966 "Cambridge Expedition to Sabratha 1966, Report." Unpublished Report Submitted to the Royal Geographical Society. Available for download: http://www.societies.cam.ac.uk/cuueg/Archives/Sabratha1966.pdf.

Yorke, R. A. 1976 "Search for Submerged Carthage." *Geographical Magazine* 49.1: 24–30.

Yorke, R. A. 1986 "The Harbour." pp. 243–45 in P. M. Kenrick, ed., *Excavations at Sabratha, 1948–1951.* Journal of Roman Studies, Monograph No. 2. London: Society for the Promotion of Roman Studies.

Yorke, R. A. and Davidson, D. P. 1969 "Roman harbours of Algeria." *Underwater Archaeology Report*. 1969: 8–21.

Yorke, R. A. and Davidson, D. P. 1985 "Survey of Building techniques at the Roman Harbours of Carthage and Some Other North African Ports." pp. 157–64 in A. Raban, ed., *Harbour Archaeology; Proceedings of the First International Workshop on Ancient Mediterranean Harbours, Caesarea Maritima, 24–28th June 1983.* BAR Intl. Series, S257. Oxford: BAR.

Yorke, R. A. and Little, J. H. 1975 "Offshore survey at Carthage, Tunisia, 1973." *International Journal of Nautical Archaeology* 4: 85–101.

Yule, B. and Barham, A. J. 1999 "Caesarea's Inner Harbour: the Potential of Harbour Sediments." pp. 262–84 in Holum *et al.* 1999.

Zarattini, A., Trigona, S. L., Bartoli, D. G. and Atauz, A. D. 2010 "The Roman fishpond of Ventotene (Latina, Italy)." *Fasti Online,* Folder-it-2010-191.

Zellmer, G., Turner, S. and Hawkesworth, C. 2000 "Timescales of destructive plate margin magmatism: new insights from Santorini, Aegean volcanic arc." *Earth and Planetary Science Letters* 174: 265–81.

# Index