PALAEOPORTOLOGY, ANCIENT HARBOURS AND COASTAL GEOMORPHOLOGY: WHAT CAN WE LEARN?

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This presentation aims to analyse ancient port structures, hoping that the ancient can tell us something useful for the modern, with special focus on breakwaters and quay walls. Archaic ships and the oldest known port structures are briefly presented. Vertical breakwaters and quays, large concrete blocks called *pilae*, arched breakwaters and rubble mound breakwaters are described in the ancient world. Some geomorphological aspects of a few coastal harbours are also reviewed. It is concluded that the Romans mainly used natural coastal shelters, but some major ports were built in places without any natural shelter, for strategic or economic reasons. Most of today's concepts for maritime structures were already existing in Roman times and it seems that little progress was made until the 18th c. when large maritime structures started to be built again. The combination of concrete and steel enables modern engineers to build higher, deeper, and larger than Roman engineers could dream of, but some modern structures may not last as long as some Roman structures, especially in salt water …

Keywords: ancient port structures, ancient breakwaters, Roman hydraulic concrete, Subsidence, Portus Augusti, Tyre, Narbo Martius, Caesarea Maritima.

1. INTRODUCTION

Building sustainable ports along coastlines is a difficult endeavour because coastlines are among the most rapidly changing landscapes on Earth. This challenge is faced worldwide today. Besides, the erection of coastal structures alters coastal dynamics in such a way that new structures tend to affect earlier constructions. The study of ancient harbours shows that it has been a nagging problem in coastal management since Antiquity. Investigating ancient cases is interesting because it provides more time depth into these changes than the modern cases, owing to the centuries of coastal changes that have elapsed since the structures started to alter their environment.

From a more economic point of view, a denser network of safe harbours around the Mediterranean Sea drastically improved the safety of sailing (Robinson, 2020). The present work collects data on about 3900 ports and shelters around the Mediterranean Sea between Gibraltar and Tangiers (excluding the Black and Red Seas) (de Graauw, 2024). With the length of the Mediterranean coast being around 25 000 nautical miles, this leads to an average density of one harbour every 6.4 nautical miles (12 km), as an order of magnitude. Hence, even though they could sail 50 to 100 nautical miles in a day, ancient ships could find a safe shelter within two hours of navigation, and this provided an important feeling of safety to the sailor who could be facing sudden weather changes at any time.

The main structures of a port are its *breakwater(s)* to reduce wave action inside a protected *basin*, where *quays* and *jetties*[2], with some mooring devices and warehouses, are available for loading/unloading ships. In addition, a port may include shipyards with slipways, shipsheds, canals for navigation and/or flushing, defensive chains, various types of beacons and a lighthouse. It should be noted that structures have been changed and repaired almost continuously inside ports to keep pace with the changing needs of users. This obviously leaves archaeologists with a giant space-time puzzle! The question is what can we learn from them today?

This paper is a synthetic summary of work undertaken by the author since 2010 (de Graauw, 2024, for more details and for location maps). Chapter 2 hereafter will present a brief historical overview of our Mediterranean civilisations, concentrating on the periods before the Roman era. Chapter 3 will analyse the physical conditions encountered when building ancient maritime structures. Chapter 4 will review several typical ancient port structures; finally, chapter 5 will describe some geomorphological aspects of a few ancient ports.

2. HISTORICAL OVERVIEW

The broad context is provided by a brief chronology of civilisations adapted from Inman who presented it 40 years ago at the 1974 ICCE conference in Copenhagen. It shows successive

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[2] A quay allows berthing on one side, a jetty allows berthing on its two sides and both can be on piles (wharf) or be a massive structure. We shall use the word "pier" only for a bridge pier or a *pila*. The word "mole" may refer to a jetty or a breakwater. A breakwater, in the sense of "wave-breaker", is usually connected to the shore, but may be detached from it.

Mediterranean civilisations since the dawn of Mediterranean history around 3000 BCE (Before Current Era) (Fig. 1).

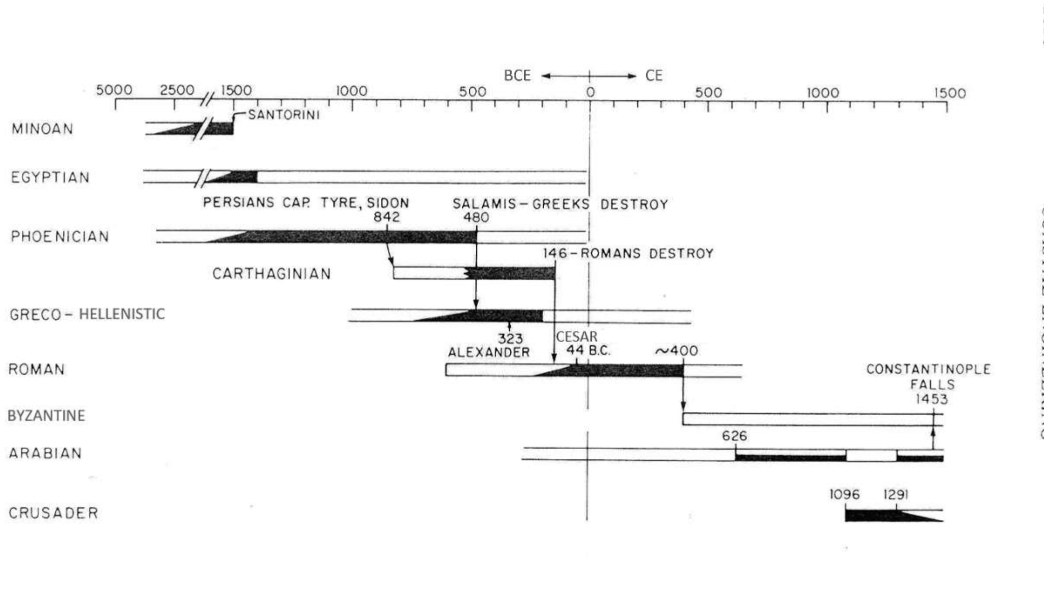

Figure 1. Chronology of civilizations' influence on Mediterranean harbors and ships.

Figure 1. Chronology of civilisations adapted from Inman (1974)

Ancient port structures

Many Palaeolithic (< 10 000 BCE), Mesolithic (10 000-5000 BCE) and Neolithic (5000-3300 BCE) sites have been identified in coastal areas (Dawson, 2013), but they did not have any port structures. A few testimonies are provided by log boat wrecks in northern Europe, Gibraltar, Turkey, Cyprus, Israel. A submerged probable seawall dated ca. 5500-5000 BCE was found at Hreiz (Israel) (Galili, 2019).

The *oldest known seaport structure* (in 2024) is the wadi al-Jarf breakwater in the Gulf of Suez (ca. 2600 BCE, King Khufu-Chéops). This structure is ca. 405 m long and ca. 6 m wide. It is made of cobbles and lime (Tallet, 2021). Khufu-Chéops is therefore a precursor, not only for his Great Pyramid, but also for his maritime and fluvial works. The port of Byblos (Lebanon) was built in the same period, but it is located inside natural coves with no known port structures (Carayon, 2012a). Further south, Ashkelon (Israel) and Gaza were also active trade centres during that period, but no remains of archaic port structures have yet been found (Galili, 2021b). Between 2400 and 2000 BCE, a 4 m deep basin of 215 x 35 m was built with fired mudbrick at Lothal near River Sabarmati (Gujarat, India), but this may have been a water reservoir (Blackman, 1982). The smaller basins of Ur (Iraq) were probably also built in this period (Woolley, 1974; Oleson, 2015). Further coastal settlements are found in the Gulf at Susa, Uruk (Iraq) and Rishir (Iran).

The very large port on Pharos Island (Ras el-Tin, Alexandria, Egypt) might also date from this period and its more than 2 km long main breakwater might be seen as an ancestor of the typical Phoenician breakwater structure with two vertical walls made of large, quarried blocks and interspace filled with rubble. Many more places were found in the Nile delta, e.g., Avaris (dated 1700 BCE) with a 450 x 400 m basin excavated near the Pelusiac Nile branch. A series of Minoan ports were found on the north coast of Crete, which are usually quite small (Frost, 1963). Natural shelters were used in the 2nd millennium BCE on the Turkish west coast, and anchorages, more or less sheltered by offshore ridges, were used as natural shelters on the Levantine coast. In Yavne-Yam (Israel) a 100 m x 50 m stone rampart may have been built to improve the shelter (Galili, 1993).

Early Phoenicians gradually improved their natural shelters by adding breakwater structures on top of the offshore ridges, like the massive 1800 BCE stone structure found at Dor (Love Bay, Israel) (Raban, 1995) and at Sidon (Saida, Lebanon). Corings show that Sidon's inner port was already existing in the 17-15th c. BCE thanks to this artificially improved reef (Carayon, 2012b; Marriner, 2009). At Kommos (Crete) a shipshed located near the coast, and including 6 galleries of 37 x 5.60 m, is dated Late Minoan (ca. 1400 BCE) (Blackman, 2013). At Dor (Israel), a 50 x 10 m quay-platform made of stone slabs is dated around 1300 BCE (Raban, 1995). A possible Minoan slipway with two galleries of ca. 5 x 40 m is located at Nirou Khani (Crete). A slipway was also found at Sounion (Attica, Greece) and shipsheds were found at Kition (Cyprus). Mycenaean ports on the Peloponnesus also date from this period (Mauro, 2019). The heyday of Greek slipways and shipsheds came when triremes (170 rowers, in say 500 BCE) based at Zea and Munychia (Piraeus, Greece) became Athens' powerful weapon for controlling the seas.

The first true breakwaters were all built in ancient Phoenicia between 1000 BCE and 600 BCE (Tabbat al-Hammam, Sidon, Tyre, Atlit) and consisted of two ashlar vertical walls with the interspace filled with rubble. The vertical walls all included oblong ashlar headers[3].

A major evolution was the introduction of '*Puteolanus pulvis'* ('pozzolana') for hardening concrete under water. This enabled large blocks of hundreds of cubic meters of concrete to be constructed under water by pouring concrete into wooden caissons, as described by Vitruvius around 20 BCE (Coulon & Golvin, 2020). The first known uses for vertical concrete breakwaters are at Agrippa's naval base of Portus Iulius, near Pozzuoli (Italy) in 37 BCE and at Cosa (Italy). The most famous is at Caesarea Maritima (Israel) built between 21 and 10 BCE (Raban, 2009; Galili, 2017; Oleson, 2014). The largest was built as from 42 CE at Portus Claudius (Rome, Italy) (Testaguzza, 1970; Noli & Franco, 2009; Oleson, 2014).

The first rubble mound breakwater was possibly built on Delos Island in the 8th c. BCE (Flemming, 1980), but the Samos breakwater (ca. 530 BCE) described by Herodotos (Hist, 3, 44-60) is more famous. This type of structure was widely used for breakwaters in water deeper than a few meters where dumping loose rock over-board barges was easier than positioning ashlar headers with divers. This construction method was described in 103 CE by Pliny the Younger (Letters, 6, 31) at Centumcellae (Civitavecchia).

As a general historical trend, it may be noted that the oldest harbours were limited to natural shelters. After that, natural shelters were improved and enlarged by man-made breakwaters. Finally, harbours were built on straight coasts without any natural shelter (Amathus, in Cyprus, Caesarea Maritima in Israel, Portus near Rome).

Ancient trade networks

After the conquests by Julius Cesar and his successors, the Roman empire encompassed the whole Mediterranean area. Rome had around one million inhabitants to be fed and a Mediterranean trade network emerged where 'all roads led to Rome'.

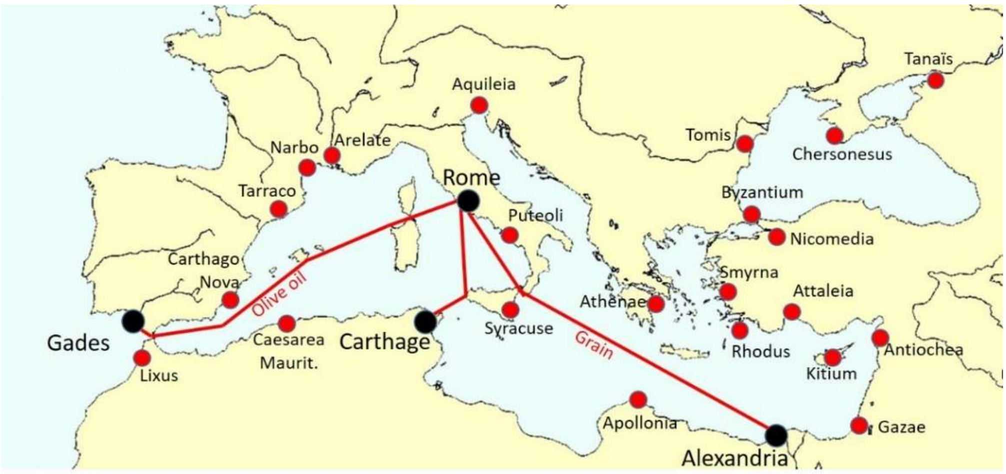

Figure 2. Trade networks in the Roman Mediterranean Sea. (map by de Graauw)

Figure 2 is a snapshot of the Roman period trade network, and other cities may have been main trade hubs at other times, e.g., Athens previously, and Constantinople subsequently. Alexandria was a major hub of the Roman economy. Other nodes of a large-mesh Roman trade network included Gades (Cadiz in Baetica, for garum, salted fish, olive oil) and Carthage (Proconsular Africa, for grain, salted fish, olive

[3] 'Ashlar headers' are parallelepipedal blocks of quarried stone placed in such a way as to face the waves with their smallest section. When placed with their largest section to the waves, they are called 'ashlar stretchers'.

oil). This coarse network shows three lines converging to Rome for imports. Finer-mesh networks might be added to the coarse one by including nodal points of lesser importance (Arnaud, 2005).

It is perhaps useful to remember that 'imports, not exports, are the purpose of trade' (P. Krugman, 1993). After unloading their cargo at the ports of Rome, foreign merchants could export Roman goods as a return cargo when sailing back to their home country, but what could Rome really export? The Roman state could provide the 'service' of military protection of provinces within the area of 'Pax Romana', receiving a tribute for this service. However, the main Roman export was gold and silver bullion (mined *inter alia* in Spain and Romania) used for payment of imported goods!

Egyptian grain was transported in sacks of one Ptolemaic artaba (ca. 39 litres) with a unit weight of ca. 30 kg, but we have no remains of them and limited iconography (Ostia mosaic in the Aula dei Mensores, and the fresco of the river boat Isis Giminiana). Liquid bulk (wine, olive oil) was moved in amphorae the weight of which was around 40 to 50 kg (i.e., 25 litres plus 15 to 25 kg tare). Amphorae were made of fired earthenware ceramic and cheaply produced in vast quantities. They were handled by one or two individuals.

Ancient ships

Like today, ancient trade relied much on shipping, but we have little information about the details of ancient ships: some shipwrecks (sometimes in deep waters), some pictures on vases and some reliefs (Fig. 3).

Figure 3. Lenormant relief with oar arrangement on a trireme warship (ca. 410 BCE). (Acropolis Mus. Athens)

What we call 'experimental archaeology' was used to build replicas of these ships to better understand ancient sailing (Katzev, 1987; Rankov, 2012). Many books have been devoted to ancient ships (e.g., Davis, 2009; Whitewright, 2011), and it is worth recalling here that rowing was a main propulsion system on Bronze Age ships (3300-1200 BCE), much more than sails which could be used only in favourable conditions. Even later on, sailing ships were not allowed under full sail inside harbours (this is still so today), hence they used oars to row ships near the harbour entrance, or hired oared tugboats. This is why a double entrance like those at Portus (Rome) and Centumcellae (Civitavecchia), with a central island, was popular with sailors. As modern sailing boats have motorisation, this layout with a detached breakwater is now abandoned.

As a general order of magnitude for the Roman empire (1^{st} to 3^{rd} c. CE), we may say that ancient freighters had a draught of 1.5 to 3.5 m, with exceptional ships having a draught up to 4.5 m (Casson, 1971; Boetto, 2010 & 2012). Ships carried grain in bags, and olive oil and wine in amphorae, but also many other commodities like large blocks of marble, many kinds of ceramics, raw metals, precious exotic goods, etc. A large 40 m ancient ship could carry 100 million Euros' worth of pepper (De Romanis, 2012). This may be compared to a large modern 400 m-long container ship carrying a value of around one billion euros.

Table 1. Schematic average sizes of ancient freighters (1st – 3rd c. CE)

Type	Deadweight (t)	Length (m)	Beam (m)	Draught (m)
10 000 amphorae	400-500	40	9	3.5
2 000 amphorae.	100	20	7	2.5
400 amphorae	15-20	15-17	4.5-5.5	1.5

The largest ships were sailing for the *Annona* grain transport between Alexandria and Rome. The famous Roman shipwreck 'Madrague de Giens' was a 7 000-amphorae ship of ca. 30-35 x 9 m. The famous 4th c. BCE 'Kyrenia' shipwreck that was rebuilt as a replica in the 1980s (ca. 15 x 4.5 m) belongs to the group of 400-amphorae ships in the table above (Katzev, 2008). The much later ships of the Byzantine period (4th – 6th c. CE) tended to be smaller than Roman ships, even for long distance sailing. In reality, ship size did not vary much until the 15th century.

Let us now investigate how ports were built to meet the needs for loading and unloading these ships.

3. PHYSICAL CONDITIONS

Ancient winds

By comparing ancient winds as described by Aristotle and Theoprastos with modern wind data, it was shown by Murray (1987) that 'the winds of classical Antiquity were essentially the same as they are today'. And as waves follow the same trend as wind, and littoral drift the same trend as waves, we are very fortunate to be able to use modern wave statistics to conduct geomorphological studies spanning several millennia.

Ancient sea levels

The eustatic sea level started to rise around 20 000 years ago, at the end of the last glaciation period, opening the Holocene era. The following sequence of Sea Level Rise (SLR) was observed (Fleming, 1998, Morhange, 2013) in round figures:

- Observed between 15 000 and 7000 Before Present (BP): around *14 mm/year*, resulting in ca. 110 m SLR over this period.
- Observed between 7000 and 2000 BP: around *0.7 mm/year*, resulting in ca. 3.50 m SLR over this period.
- Observed in the past 2000 years: around *0.25 mm/year*, resulting in ca. 0.50 m SLR over this period.
- Observed in the 20th c.: around *1 to 2 mm/year*.
- Observed in the 21st c.: around *3 to 4 mm/year…*

Over the last 2000 years, the eustatic sea level rose less than 1 m, but local crustal movements must be added, leading to a so-called Relative Sea Level Rise (RSLR) which is a discontinuous process because of earthquakes. It is obviously difficult to differentiate eustatic SLR from crustal movements of the Earth as our measuring instruments stand on Earth. A rough first approximation would be to consider that both water and Earth crust are moving independently, so that the average of all measured sea level movements on the entire Mediterranean basin would reflect the eustatic SLR, while local deviations from this average would reflect the local crust movements (e.g., Crete). This approach is theoretically incorrect as we know that when the sea level rises, water comes onto dry land which will subside due to the new load of water, depending on the underlying geology. The Earth's crust and mantle are reacting like a mattress, on which some areas have been relieved of the weight of ice layers, and others have been loaded with an additional layer of meltwater. RSLR therefore consists of a rise in sea level interacting with ground subsidence. This process is part of the Glacial Isostatic Adjustment (GIA). Hence, water and land are *not* moving independently, and we need more complex modelling of the interactions between the two (Spada & Melini, 2023). It might then possibly be found that most, if not all, of the RSLR over the last 2000 years is due to crustal movements (Nic Flemming, pers. com. 2024).

Ancient tsunamis

A list of 'all' known historical earthquakes and tsunamis recorded in the Mediterranean area before 1500 CE, was compiled (de Graauw, 2024) and it shows the following:

- A total number of around 465 earthquakes was reported from 2000 BCE to 1500 CE. Around 135 of these earthquakes generated a tsunami that was reported (29%).
- Earthquakes are fairly well distributed in time and in magnitude, although some concentrations in time are found in 0-150 CE, 300-600 CE, 850-1000 CE.

- The largest earthquake was reported on 21/7/365 CE in Crete, with an intensity evaluated at X-XI on the European Macroseismic Scale.

Obviously, each coastal earthquake did not necessarily induce a tsunami, and only few tsunamis were reported by ancient writers, but at least one ancient author made the intellectual connection between earthquakes and tsunamis: Thucydides (Hist. 3, 89), in Greece around 425 BCE.

It has been shown that it can be really hard to distinguish ancient tsunami deposits from other deposits induced by storms and major floods (Delile & Salomon, 2020), which is why we favour the term 'high-energy event' on Fig. 4, although the occurrence of a tsunami is fairly certain in this case.

Figure 4. High-energy deposit in the Byzantine harbour of Yenikapı, Istanbul (6th c. CE). (D. Perincek, 2010)

4. ANCIENT PORT STRUCTURES

A catalogue of 'all' known ancient ports, harbours and coastal settlements founded before 500 CE, was compiled (de Graauw, 2024). It includes around 6000 places from Iceland to Sri Lanka, and it was shown that only around 15% of them include some kind of port structure such as a breakwater, a quay, a slipway, a lighthouse or a warehouse. See also de la Pena's monumental work on ancient ports (2021).

No port structures

The most common case was thus the case with 'no structures' at all. For loading and unloading cargo, this meant ship-to-ship transfer on deep water, or beaching on sandy beaches (Fig. 5). As drinking water was a vital need, estuaries were favoured.

The Latin word *ripa* was used for what we might call a 'beach market' where business was conducted on an urban beach without any port infrastructures (e.g., Vicus Lartidianus at Puteoli, Italy).

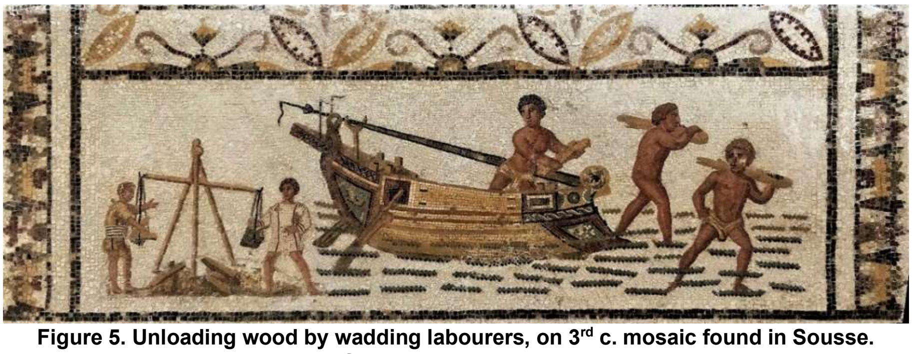

Figure 5. Unloading wood by wadding labourers, on 3rd c. mosaic found in Sousse. (Photo de Graauw, 2018, Bardo Mus, Tunis)

As the beach slope depends on its grain size, the very fine sands (or silts) found in large deltas yield a very flat slope which keeps ships far from land. Conversely, a shingle beach has a steep slope that is dangerous for landing ships on. Homer repeatedly mentioned beaching ships (e.g., Odyssey, 13, 113-115). In Odysseus' time (say 1200 BCE), the ships may have been of the *eikosoros* type, with two files of 10 rowers. This oared ship is the ancestor of what would later be called a 'triaconter' (*triakontoros*) with two files of 15 rowers, a length of around 20 m and a weight of less than 10 tons. Unloading fish from 10 to 20 m Senegalese fishing boats is still practised today, but hauling such a ship on the beach is a very heavy task. Boris Rankov (2012) explains that it was possible to haul a 25-ton light-ship trireme on a slipway in a harbour, provided the slipway had the correct slope (not steeper than 1:10) and was adequately greased. However, he considers that 'it is hard to see that triremes would have been beached except from necessity'. Greg Votruba (2017) provided convincing argumentation that cargo ships did not habitually beach and concluded that 'from the Classical period at the latest, the standard practice was to remain afloat at anchor'. Hence, with increasing ship sizes (and weights), beaching became impractical, if not unfeasible, and places for safe anchorage were sought.

Figure 6. Ship-to-ship transfer (Mosaic at Piazza delle Corporazioni N° 25, Ostia).

Figure 6 shows transfer of amphorae from a large seagoing ship staying offshore at anchor, to a smaller river ship. This option was chosen in places where the river bar would not allow sailing without danger as mentioned by Strabo (Geogr. 5, 3, 5) at Ostia (Italy) before the construction of the large harbour of Portus. A similar case was mentioned by Pliny the Elder for Muziris (India) (NH, 6, 26, 10) and modern underwater archaeology has possibly found such a place at Ashkelon (Israel) dated 4^{th}-6^{th} c. CE where ships were moored offshore on wooden posts (Galili, 2021b).

Jetties

It was obviously easier to moor at some kind of wooden jetty built out from the coastline. Like today, many wooden jetties must have existed in sheltered areas and inside harbours to load/unload ships, but most of them have disappeared, eaten away by nature. The Byzantine Port of Theodosius (Yenikapi, Istanbul) was built just before 400 CE and it features some of the very few recovered wooden jetties, such as this large one, apparently repaired over time by adding wooden posts (Fig. 7).

Figure 7. Remains of wooden jetty at Yenikapi (Istanbul).

Another wooden jetty in the same harbour basin was wiped out by a tsunami in the 6th c. and the base of the piles survived under a thick layer of sediment (Perincek, 2010). A stone jetty was also recovered in this same basin (Ginalis, 2024 and 2022). Other stone jetties perpendicular to the coast were found in Tunisia (Stone, 2016). All of these jetties had the same purpose of reaching sufficiently deep water to berth seagoing freighters with a draught of 1.5 to 3.5 m (Table 1).

Vertical breakwaters

As mentioned in our historical overview above, the first true breakwaters were made in ancient Phoenicia with oblong quarried blocks of ca. 0.5 to 1 m x 0.5 to 1 m x 1 to 5 m (Fig. 8). In Thasos, the same double wall technique was used around 500 BCE with large slabs used as ashlar headers, up to 0.5 m x 1.5 m x 2 m (Empereur, 1993). Oblong headers were still used much later around 300 BCE at Amathus (Cyprus) with 0.7 x 0.7 x 3 m headers backing a rubble mound facing the sea (Empereur, 2017) and at Acre (Akko, Israel) with 0.8 x 0.8 x 3 m headers on 4-5 m water depth at the 60 x 13 m Tower of Flies. Large headers were also used in 10 BCE for the quay wall on the lee side of the main breakwater at Caesarea Maritima (0.6 x 0.6 x 2.3 m headers) (Raban, 1995). At Arados (Arwad, Syria) large ashlar blocks were used to build seawalls parallel to the coastline (Viret, 2005).

Figure 8. North breakwater of Tyre (Lebanon) built with ashlar headers, (800 BCE). (Photo Goiran, 2019)

Around 20 BCE, Vitruvius described three methods based on the use of Roman concrete for marine works. One consisted of preparing large concrete blocks on shore that were aimed to fall into the sea after erosion undermined them, but no practical application of this method is known. Another method required a watertight enclosure (a cofferdam) allowing water to be pumped out to enable work in the dry. This method was mainly used to build bridge piers in rivers.

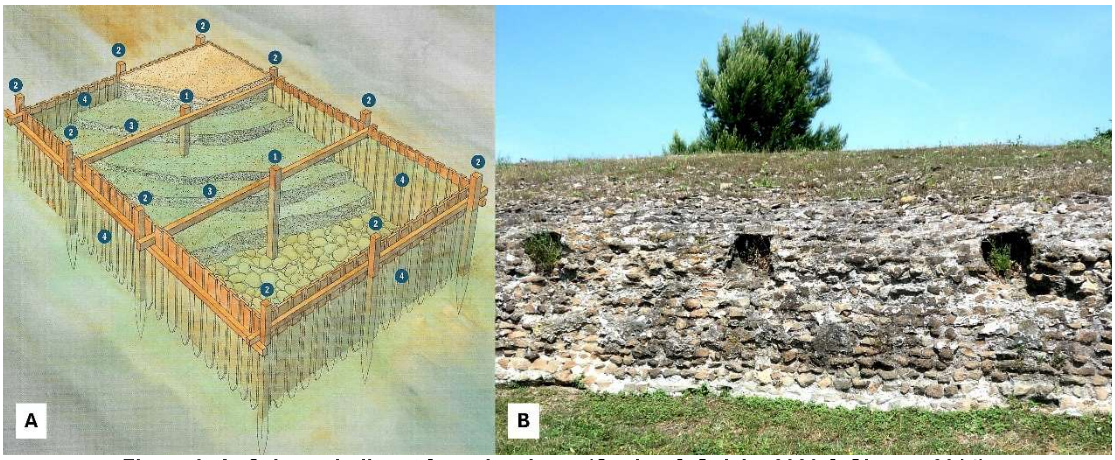

Figure 9. A: Caisson built out from the shore. (Coulon & Golvin, 2020 & Oleson, 2014).
B: Portus' north concrete breakwater showing imprints of transverse caisson beams.
(Photo de Graauw, 2011)

The most interesting method described by Vitruvius for coastal works consisted of pouring Roman hydraulic concrete with pozzolana into fixed wooden formworks that were built out from the coast into the sea. It included an enclosure made of posts (*stipites*) that were driven into the subsoil. If needed, tie rods could be inserted between opposite faces of the enclosure. Such tie rods were made of wooden beams (*catenae*) which have disappeared with time, leaving transversal cavities inside the concrete structure (Fig. 9).

An alternative to this method consisted of *prefabricating* a rigid wooden enclosure, with or without a bottom, which was then floated to the desired location before being filled with hydraulic concrete or stones (Fig. 10). This alternative method was well suited for hard (rocky) seabeds where piles could not be driven. It is similar to sinking an old ship to build a man-made island like those of Portus Claudius (Rome, Italy) (Pliny, NH, 36, 14, 9) and several other sites (e.g., Lilybaion, Sicily; Thonis-Heracleion, Egypt; Marseille & Narbonne, France). Underwater excavations at Caesarea Maritima (Israel) and Antirhodos (Alexandria, Egypt) showed imprints *inside and under* the concrete mound, proving that the structure consisted of wooden caissons used as lost formworks for concrete to be poured in situ. This method was also used in the Byzantine period (ca. 500 CE) at Hiereia and Eutropion (respectively Fenerbahce and Moda Pier, Istanbul, Turkey) where caissons (*kibotoi*) were placed on top of each other on two alignments to build both breakwaters (Procopius, Aedif., 1, 11).

Figure 10. Roman wooden floating caisson with divers, tugs and heavy hoisting equipment, at Caesarea Maritima. (Aquarelle by Robert Teringo, 1987, National Geographic, 171-2)

A variant of this method which was used only on the northern breakwater at Caesarea Maritima consisted of a large *double-walled caisson without floor* constructed on shore and towed into position (Fig. 10). Once on location, the space between the twin peripheral walls was filled with mortar until the whole formwork sank to the bottom. Only then was it filled with concrete. The size of the block recovered is 15 x 11.5 x 2.4 m, or over 400 m^3 (Oleson, 2014). It is just a pity that these caissons were placed on loosely packed sand 2000 years ago. A subsidence of around 5-6 m (!) of the whole breakwater structure resulted from the combined effects of undermining of the foundation due to bad filter-layer design, liquefaction during earthquakes and/or compaction of the underground due to wave impacts.

An additional rubble mound was sometimes placed in front of the vertical structure (Amathus, Cyprus, and Hiereia/Eutropion, Istanbul, and possibly Thapsus, Bekalta, Tunisia) in order to absorb wave energy and thus reduce wave reflection and horizontal wave pressure on the vertical wall. Such a design improves the caisson stability, but it may increase wave overtopping.

Roman hydraulic concrete

Crushed ceramics (pots, tiles, bricks) were used for many centuries to obtain waterproof plasters for cistern and aqueduct linings, called *opus signinum*, but the crushing of potsherds was much more labour-intensive than just mining river sand. Around 200 BCE, crushed ceramics were replaced by *Puteolanis pulvis* (pozzolana sands mined from the Phlegraean Fields near Pozzuoli) for the construction of coastal fish tanks (*piscinae*), as it allowed mortar to *cure under water*, which is why it is called 'hydraulic mortar'. Roman hydraulic concrete is the combination of this hydraulic mortar with layers of aggregates (Vitruvius, De Arch., 2, 6 and Pliny, Nat. Hist., 35, 47 & 36, 52-54). The resulting structure is now called *opus caementicium*, and is 'neither particularly hard nor strong' but provides an 'extraordinary longevity in sea-water' (Oleson, 2014).

Indeed, in a marine environment, salt water and associated chlorides (Cl^- ions), sulphates (SO_4^{--} ions), carbon dioxide (CO_2), oxygen (O_2), water (H_2O) and other chemicals penetrate the concrete by capillarity and diffusion and by convection through the micro cracks. These micro cracks are a problem because they allow penetration of the elements inside the concrete, eventually reaching the steel rebar of modern reinforced concrete (note that Roman concrete was *not* steel reinforced). Obviously, the compaction quality and thickness of the cover layer between the lower rebar and the under face of the beam (around 50 mm) is important, but micro cracks *must* exist in order to have the steel rebar working. The result is that a significant number of Reinforced Concrete (RCC) marine structures built in the past decades are already in bad condition and need very expansive repair works. Some coastal structures were supposed to last many decades but are showing serious deficiencies after only 10-15 years! This is usually visible by traces of corrosion of the steel rebars embedded in the RCC structure. Hence, although the compressive strength of Roman hydraulic concrete is smaller than that of modern concrete[4], its longevity, especially in marine conditions, is still a matter of surprise and debate for today's civil engineers. Modern research is still ongoing to better understand why, and it shows that the presence of lime clasts generates a process of long-term self-healing of micro cracks by filling them with calcite (Seymour, 2023).

A good question would be to ask whether concrete may be reinforced by courses of bonding tiles acting as a horizontal chaining like modern rebars (A. de Graauw, 2024). As this concerns tensile strength, we must first compare the tensile strengths of limestone or sandstone to that of fired bricks or tiles, and that turns out to be in favour of tiles. Second, we must compare the adherence, or bond strength, of lime mortars on tiles and natural stone, and that again turns out to be in favour of tiles. Hence, it seems that we may validate the hypothesis that courses of bonding tiles located in the lower sections of massive structures like bulwarks and donjons increase the internal cohesion of the structure. More generally, they may be assimilated to a horizontal chaining system.

True Roman hydraulic concrete with pozzolana was forgotten during the Byzantine period when it was replaced by crushed ceramics (this type of concrete was later called *horasan* by the Turks and *cocciopesto* in Italy). This hydraulic concrete proved efficient for foundation works for buildings, but not for marine works in sea water. As an example, the eastern breakwater of Akko connecting the Tower of Flies to the mainland, built by the Arab architect Abu Bakr in the 9th c., using concrete poured into wooden caissons, has been destroyed by the sea to its current state as a reef (Gertwagen, 2024).

Hydraulic cement was finally reinvented by John Smeaton in 1756, followed by James Parker (1796), Louis Vicat (1818-1828) and Joseph Aspdin (1824) who named it 'Portland cement'. Reinforced concrete was invented by Joseph Monier (1867) and prestressed concrete by Eugène Freyssinet (1928).

Rubble mound breakwaters

Rubble mound breakwaters have been around for over 2500 years and modern coastal engineers still build them to create harbours sheltered from wave penetration. They were used in water deeper than a few meters where positioning of ashlar headers by divers was difficult. The largest ancient breakwaters are at Portus Claudius (Rome, Italy), Alexandria (Ras el-Tin, Egypt) and Thapsus (Bekalta, Tunisia).

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[4] Compressive strength of Roman hydraulic concrete ranges between 2.5 and 8.5 MPa, while modern concrete reaches 50 MPa and even up to 150 MPa for modern ultra-high-performance concrete.

Most of them are now submerged as a normal consequence of 2000 years of storms (and possible tsunamis). If a rubble mound on deep water is not oversized, sooner or later a storm will occur that is able to move the armour layer. Boulders, usually 0.5 to 1 m in ancient times, will then be moved downwards on the seaside and pushed over the crest into the lee side. A study was carried out to find some simple relation between the governing parameters (water depth, structure height, stone size) and the equilibrium position of the crest of rubble mound breakwaters subject to long term wave attack. It was concluded that undersized emerging rubble mound breakwaters reduce to submerged breakwaters and that, for a given stone size, submerged breakwaters stabilise to a predictable crest level after long term wave attack in breaking wave conditions (de Graauw, 2014).

Figure 11. Rubble-mound breakwater at Kissamos (Crete). (Photo de Graauw, 2022)

Fortunately, we have one exceptional case at Kissamos (Crete) where the underground was uplifted around 6 m during an earthquake. The Kissamos armour layer consists of ca. 1 m rock boulders, or around 1 to 1.5 ton, reaching ca. 4 m above today's Mean Sea Level (MSL) (Fig. 11). As far as can be seen on site without excavation, the whole structure was made of the 1 m boulders still visible at its surface. Further analysis of the internal structure of this breakwater would be very interesting indeed.

The rubble mound breakwater at Pythagoreion on the isle of Samos (Greece) was probably built by Polycrates around 530 BCE and has a length of 480 m, while Herodotos (Hist., 3, 60) estimated it at 'more than two stadia' (370 m) when he saw it. Its largest water depth is presently ca. 14 m, but some sedimentation is likely to have occurred since Herodotos estimated it at 'twenty fathoms' (37 m) which may have been somewhat exaggerated.

Leptis Magna's north coast is protected by what would be called today a 'berm breakwater' consisting of rock that is intentionally unstable under wave action. Rubble was dumped on the beach and in the sea down to a depth of ca. 5 m, at around 50 m from the shore. It is rounded on the beach and angular on the upper beach. Quarry blocks smaller than 500 kg (decommissioned building blocks?) seem to have been used as a coastal protection. As their weight is not sufficient, they have been rolling in the wave-breaking area during storms, which may explain their rounded shape due to abrasion.

We must also remember the sea level rise of about 0.5 m since antiquity, so that breakwaters that were stable at that time in shallow water (a few meters water depth) may have become unstable because larger waves can reach them nowadays. In tidal areas, the worst conditions for stability are when the largest waves occur together with the highest water level. The probability of occurrence of this happening is smaller than for a fixed water level, but that does not change the final result for stability in the long term.

Arched breakwaters

Several 'arched breakwaters', built on top of *pilae*, are known to have been built in Roman times, but no ancient literary evidence is available. A *pila* is a large block of Roman hydraulic concrete cast under water as described by Vitruvius' methods mentioned above. It was tested by Oleson (2014) in Brindisi (see also the brilliant drawings by Coulon & Golvin, 2020). Many sites with *pilae* were found around Naples (25 out of 50 sites) and can even be seen on Google Earth, but only three are proven arched breakwaters: Nisida and Pozzuoli near Naples (Italy), and Civitavecchia (Italy) which is the only one surviving today (Fig. 12).

Figure 12. Molo del Lazzaretto at Civitavecchia (Italy). (Photo de Graauw, 2022)

An arched breakwater looks like the upper tier of the Pont du Gard aqueduct (France). 'Maritime *pilae*' have a smaller opening over *pila*-width ratio than aqueducts because of their completely different aim which is not to support some kind of road or canal, but to stop wave penetration into the port while providing limited opening for water circulation inside the port, supposed to reduce pollution and sedimentation in the harbour basin, or at least in its entrance channel.

The average horizontal dimensions of the measured *pilae* are 9 m x 7 m, nearly square. The largest *pila* was found at Nisida: 14.5 x 14.5 x 8 m (1700 m^3) (Mattei, 2018). Various types of alignments can be distinguished:

- single isolated structures, possibly a foundation for some heavy structure such as a tower or a lighthouse,
- rather continuous structures in the open sea, probably part of a vertical breakwater,
- rather continuous structures in a sheltered area, perhaps forming a massive jetty or quay platform inside a harbour basin protected by a breakwater,
- *pilae* spaced with regular intervals (of say 0.5 to 1.0 *pila*-width), perhaps the base of arched breakwaters or wooden decks, or intervals meant to be filled with rubble dumped into wooden formworks placed between the *pilae*.

The north breakwater of Portus Claudius (Rome) was probably an arched breakwater as shown on Nero's coins of one sestertius (64 CE) where water is even seen flowing between piers on the right side of the coin (see *infra*).

Quay walls

As mentioned earlier, Roman imperial period freighter had a draught of 1.5 to 3.5 m. Hence, quay walls (or 'docks' in American English[5]) were 2.5 to 5.5 m high structures if we consider that they would provide a functional height of 0.5 to 1.5 m above MSL, and a 0.5 m under-keel clearance. The smaller quay walls were made of wooden sheet piling (e.g., Alexandria, de Graauw, 2000), and the larger ones of quarried blocks (e.g., Marseille, France). In Rezé (south of Nantes, France) the river port had a heavy-duty quay wall with piles attached to a lower beam and with flat stones placed between the piles. Similar but less sophisticated constructions have been found at Bordeaux, Irun, and London (Gerber, 2005).

A Hellenistic quay (say 300 BCE) was found in Cyprus on the harbour side of the main breakwater made of oblong blocks around 0.50 x 0.50 x 2 m (Fig. 13). At Carthage, a quay wall was completely dug out and three layers were found: Punic[6] (ca. 200 BCE), Roman (around 300 CE) and Byzantine (around

[5] To bring in a ship into the port to its allotted place for mooring, is to berth (GB) or to dock (US) a ship.
[6] 'Punic' is the Latin word for the Greek 'Phoenician' meaning the purple/crimson colour dye prepared in Tyre (Lebanon) from murex shells. The term Punic is exclusively used to refer to Phoenicians in the western Mediterranean, including Carthage and many other places in North Africa, Sicily, Sardinia, Baleares, southern Spain.

500 CE) (Ennabli, 1992). Raising of the quay wall was needed because of the combined effects of sea level rise *and* underground subsidence.

A rather unique structure of nine adjacent quays for loading/unloading small, oared warships like triaconters, was found at Apollonia (Libya) by Nic Flemming (2021).

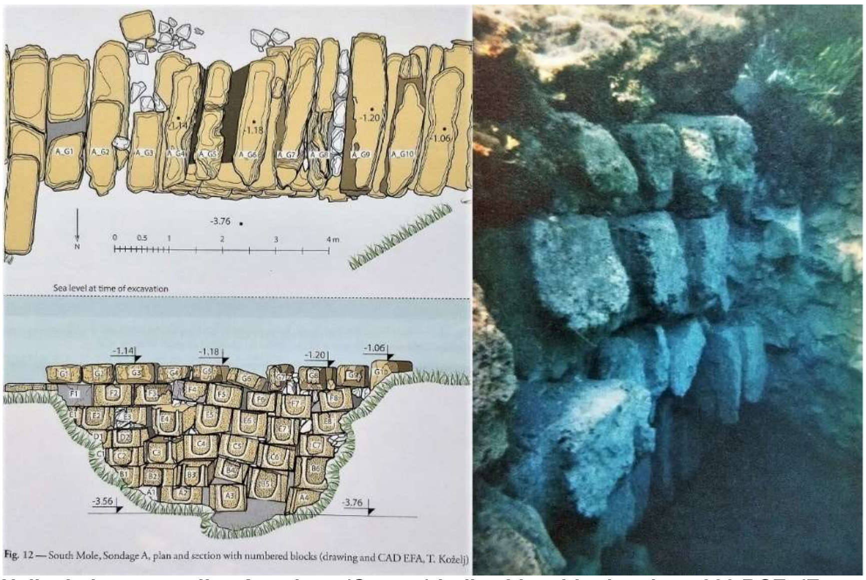

Figure 13. Hellenistic quay wall at Amathus, (Cyprus) built with ashlar headers, 300 BCE. (Empereur, 2017)

Moorings

Moorings were usually made of pierced stones with a horizontal or a vertical hole (Fig. 14). Homer himself mentions them (Odyssey, 13, 78). In addition, wooden posts must have been used in many places for mooring lines, but they did not survive. The famous Torlonia relief clearly shows a mooring ring with horizontal piercing and a mooring line. The unloading footbridge with a man carrying an amphora is also clearly pictured.

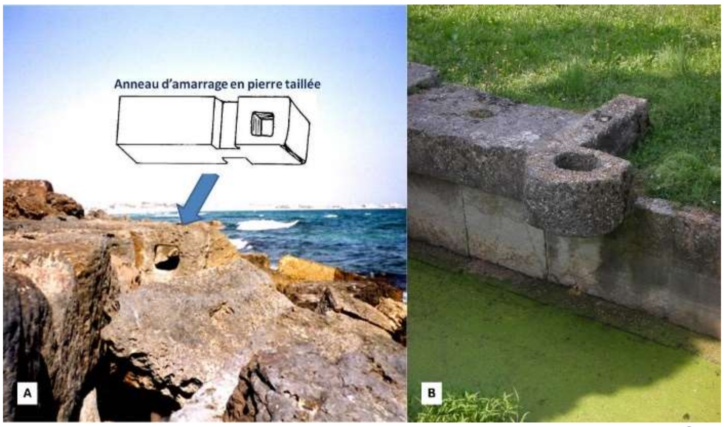

Figure 14. A: Mooring stone at Leptis Magna's north coast (Libya). (Photo de Graauw, 2000)
B: Possible foot-hole of a derrick mast at Aquileia (Italy). (Photo de Graauw, 2010)

A derrick is an obvious concept for any sailor used to handle mast, boom and topping lift. Its main interest is that it can turn the load laterally by means of the lateral lines. The vertical force is taken over by the vertical mast resting on a strong support. The horizontal force induced by the cantilever is taken over by two guy lines placed on the land side behind the mast in order not to hinder the lateral movement of the load. We suggest that the heavy-duty pierced stones found in Aquileia (Fig. 14B), might have hosted the foot of a derrick mast (and perhaps also those in Leptis Magna where the semi-circular shape is still a bit mysterious). Very similar arrangements were used to support the 'velum' in theatres and amphitheatres in Nîmes and Orange (France) and at the Colosseum (Rome, Italy) (Madeleine, 2010).

Canals

Flushing canals were used as sedimentation of harbour basins has always been a problem, but with limited success (Fig. 15).

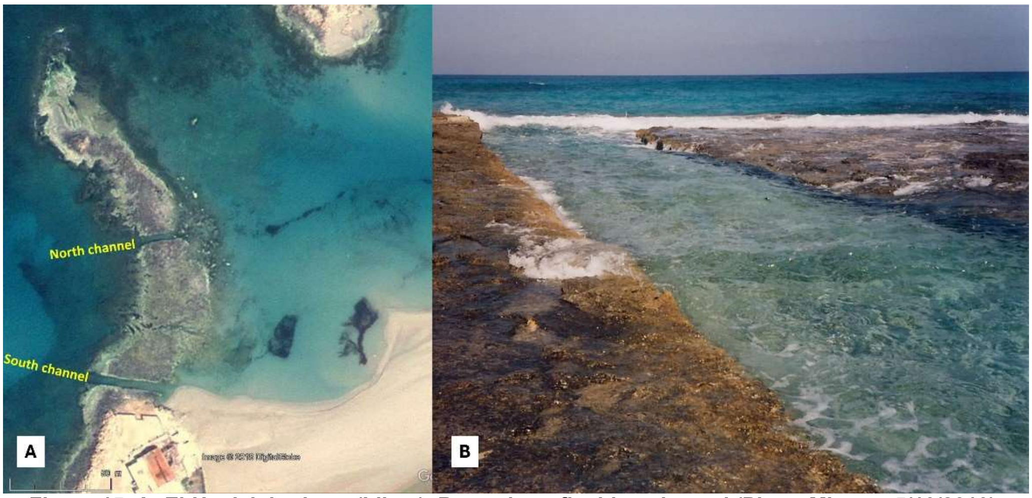

Figure 15. A: El-Hanieh harbour (Libya). B: northern flushing channel (Photo Misson, 5/10/2010).

On Ventotene Island (ancient Pandataria), the port is still used today in its original form. The port layout has a narrow entrance, in front of a horseshoe cove with a gently sloping beach that absorbs waves and allows the hauling of small boats. Right of the entrance, there is a well-protected elongated rectangular mooring basin. In 'sculpting' the coastal rocky bank, the Roman engineers shaped the natural reef near the sea surface with a rough and gently sloping profile to attenuate the runup of breaking waves and collect the overflowing water in a suitable drainage channel (Fig. 16). Large bollards were carved into the rock to favour ship manœuvring and to close the entrance at night with a chain.

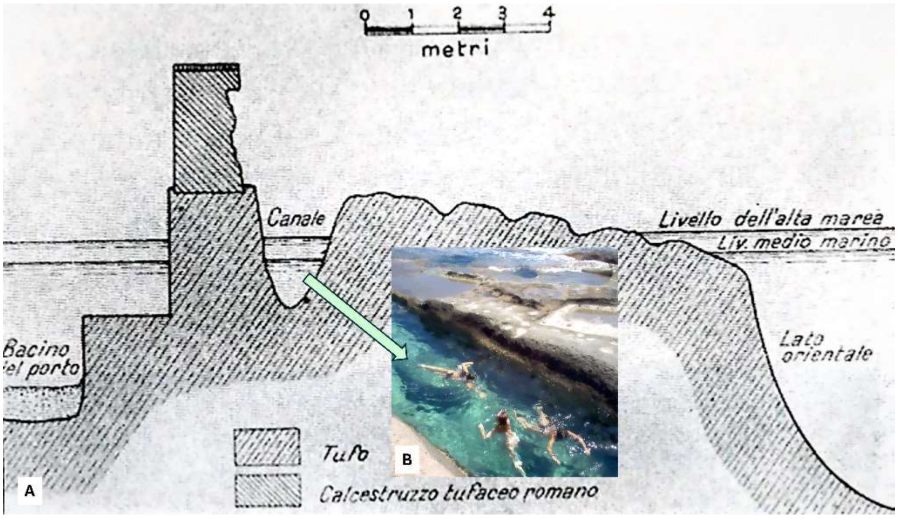

Figure 16. Ventotene (Italy) canal in front of breakwater.

Many other canals were dug for irrigation purposes and for river-flow diversions. At Ansedonia (Italy), an impressive canal called 'Tagliata Etrusca' was dug into the rock to feed sea-water fish-tanks and to reduce port siltation with water flushing controlled by sluice gates. Local navigation canals were dug for port operations (e.g., Portus, Italy; Narbo, France; Ephesus, Turkey) and many canals were used for inland navigation in the Nile Delta, and in the Tigris and Euphrates plains. Some coastal navigation canals were also dug by the Romans, e.g., Marius canal in the Rhône delta (France) and the Corbulo canal in the Rhine delta (the Netherlands) (Werther, 2018).

A most important canal was dug in the archaic Tjekou valley for navigation between the (eastern) Pelusiac Nile branch and the Red Sea via the Bitter lakes, in today's wadi Tumilat (Egypt). The so-called *Nekou Diorux*, was initiated by Pharaoh Necho II around 600 BCE, even if it was Darius who built it about a century later (Aubert, 2004; Cooper, 2009). We should remember this pharaoh who was very interested in maritime expeditions, as he was the one who launched a circumnavigation of Africa. As reported by Strabo (Geog. 17.1.25), we can understand fears to jeopardise the water quality of the (then freshwater) Bitter lakes, the Nile to Red Sea canal and even the Nile Delta, but we can confirm today that a lock near Suez preventing the risk of inundating the Nile Delta during high Red Sea water levels was not required: the Red Sea Mean Sea Level (MSL) is only 10 to 20 centimeters higher than the Mediterranean Sea MSL, and the highest water level near Suez resulting from high tide combined with, rare, southern wind, does not exceed say 1 or 2 m above its MSL. However, the risk of changing the existing freshwater Bitter lakes into saltwater lakes was real when creating a connection with the Red Sea, and this justified a lock[7]. When both Bitter lakes were freshwater lakes, they were not considered as a marine area, and Clysma (Suez, Egypt) at the southern end of the canal, must therefore have been the only true seaport at the northern end of the Red Sea since archaic times. Cargo was most probably transhipped there on/from large seagoing ships onto smaller vessels sailing on the Nile to Red Sea canal (de Graauw, 2024).

Dredging

If we compare Trajan's hexagonal basin at Fiumicino near Rome with Carthage's circular basin at the same scale (Fig. 17), we see that Rome's basin (33 ha x 7 m = ca. 2 million m^3) required over 10 times more dredging than Carthage's basin (5 ha x 3 m = ca. 0.15 million m^3). Note that Trajan's dredging works are to be added to Claudius' 4 million m^3 dredged 50 years earlier and realise that dredging millions of cubic meters 'by hand' without any mechanical equipment other than wicker baskets was an enormous task! No less impressive was the digging out of thousands of cubic meters of tuff rock at Ventotene where the harbour basin, the storage cellars and the fish tank required 60 000 m^3 of digging.

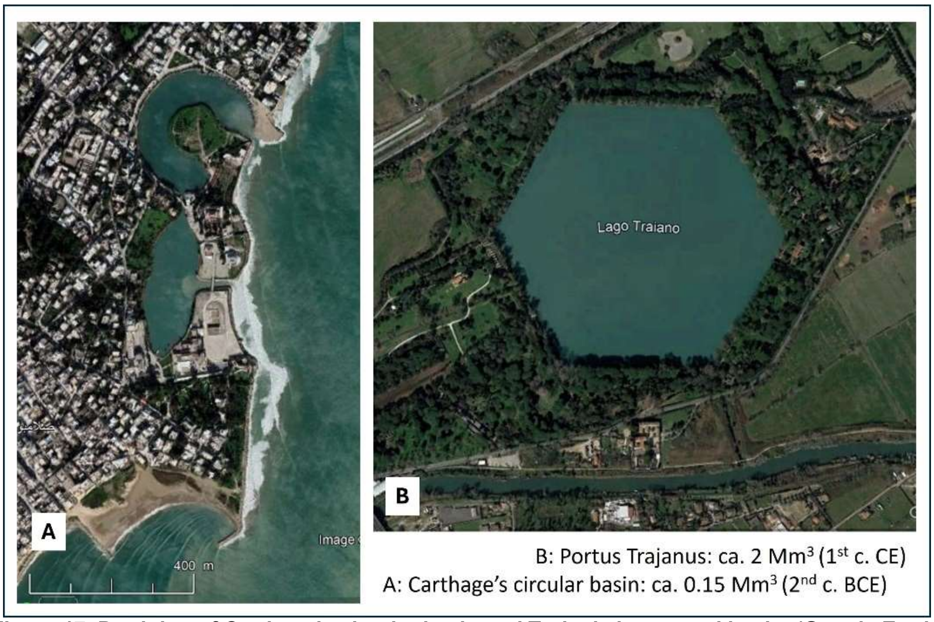

Figure 17. Dredging of Carthage's circular basin and Trajan's hexagonal basin. (Google Earth)

As silting up of harbour basins was a recurring problem, special barges were designed to clean the bottom of harbour basins. Three wrecks dating from the 2nd - 3rd century CE with a central well housing the bucket on a pole have been found below Place Jules Verne (Marseille) (Pomey, 1995). Remains of significant mechanical dredging were found on the bottom of the harbour basin at Naples (Italy)

[7] The modern Suez Canal (opened in 1869, initially 8 m deep, now 24 m) changed this situation completely as no locks were included and salt water could flow freely into the Bitter lakes, and due to evaporation, the Bitter lakes are now even more saline than the Red Sea.

(Giampaola & Carsana, 2023). Dredging of the harbour basin was also conducted at Ephesus (Turkey) (Tacitus, 16, 23) and at Sidé (Turkey) (Diogenianus, prov. 252). At Tyre north harbour (Lebanon) and at Ostia (Italy) a sediment hiatus was found which was interpreted as a proof for dredging (Marriner, 2005; Goiran, 2014). The Port of Julian, one of the harbours of Constantinople was even dredged after being emptied of all its water in the 6th c. CE! (Marcellinus, Chronicle, 509).

Defensive chains

A '*limen kleistos*' is a port whose access was restrained by a closing device, usually with a narrow entrance (Arnaud, 2023). Around 90 of them were identified in the catalogue of ancient ports (de Graauw, 2024). This closing device, consisting of a gate system (*kleithron, kleithra*) or a chain system (*alyseis*) (Fig. 18), could be used both to stop the enemy from entering the port and to trap the enemy once inside the port, as mentioned by Dio Cassius (Hist, 51, 9) at Paraetonium (Marsa Matruh, Egypt).

Figure 18. Portion of harbour chain at La Rochelle (France). (Photo de Graauw, 2024)

Ancient authors mention at least eight harbours with chains at the entrance. Chains stretching across a harbour entrance are also mentioned by Vitruvius (Arch, 5, 12). In order to install a chain (or gates) to close the entrance to a harbour, the width has to be limited. The smallest entrance width known is at Phalasarna (Crete) (around 10 m). Other narrow entrances range between 10 and 30 m and up to 75 to 100 m, as far as we can see from today's remains on Google Earth.

Considering a unit weight of 25 kg per meter for a modern chain with 10 cm shackles, a length of 10 m (250 kg) is not a problem to be lifted by capstans. A 40 m-chain weighs around one ton and can also be lifted, but a sag will be generated, and it is interesting to know how much this sag is, depending on the traction force.

The mathematical formulation was written down by Leibniz in 1691, after some discussions among authors such as Galileo, Bernoulli and Huygens, showing it was not an easy matter. Anyhow, this formulation can now be used to compute the horizontal force needed on a chain stretching between the lateral banks of a canal. If the chain is fastened 3 m above the water level with a sag of 2.5 m, it will hang half a meter above water, meaning that a trireme cannot pass over or under it.

The computation shows that the required chain length is 40.4 m, just a little more than the canal width of 40 m. The required horizontal traction force is about 2 tons, i.e., about twice the mass of the chain, on each side of the canal. This should not be a problem with Roman capstans located on both lateral quays of the canal at 3 m above the water level.

A smaller traction force would induce a longer chain with a greater sag. With a sag of 5 m, the height of fastening the chain on the banks would increase from 3 m to 5.5 m, requiring towers on both lateral quays of the canal. A wider canal, e.g., 150 m, would require a heavier chain (3.75 tons) and more traction from both banks (14 tons) in order to have a 5 m sag.

Our computations show that a chain can be stretched between the sides of a canal with a traction force not exceeding 10-15 tons, which may be considered feasible with Roman equipment like capstans and treadwheels.

It has been suggested that the chain closing a harbour entrance would need to be supported by floating pontoons, but although so-called 'booms' have been used in the Middle Ages with wider entrances of 300 m and more, our computations do not confirm the need for such an arrangement for entrances smaller than 100 to 150 m.

Slipways & shipsheds

Around 140 ancient slipways and 90 shipsheds were identified in the catalogue of ancient ports (de Graauw, 2024). They are mentioned here for the sake of completeness as they are detailed in Blackman's very complete work (2013). They are often part of a shipyard where ships were built and/or repaired[8].

Figure 19. One of Carthage's slipways with shipshed. (Photo de Graauw, 2018)

Figure 20. Farum Brigantum lighthouse Tower of Hercules, A Coruna (Spain). (Photo Wikipedia, 2023)

Slipways and shipsheds were used to take ancient warships with a draught of 1 to 2 m out of the water. Most famous are those at Carthage and at Piraeus where hundreds of them were available.

On figure 19, imagine the transverse wooden beams on which ships would slip and see the lateral pillars supporting the roofing. It is noteworthy that some ancient slipways at Zea (Piraeus, Greece) were rightly preserved under a modern building.

Lighthouses and warehouses

Around 180 ancient lighthouses and 100 ancient warehouses were identified in the catalogue of ancient ports (de Graauw, 2024). They are included here for completeness, as other studies have already been devoted to them. Lighthouses are detailed in Trethewey's work (2018), and warehouses are detailed in Chankowski's work (2018).

The Tower of Hercules dated ca. 100 CE, at A Coruna (Galicia, Spain) deserves special attention as it is the oldest still working lighthouse (Fig. 20). It is 55 m high and reaches 112 m above the sea level. A major restoration was completed in 1791 (Trethewey, 2018) and you can still visit the Roman part inside. The famous lighthouse at Pharos (Ras-el-Tin, Alexandria, Egypt) was one of the seven wonders of the ancient world. Its construction was initiated around 300 BCE by the first Hellenistic King Ptolemy I and completed by his son Ptolemy II around 280 BCE. It was 120 to 130 m above the sea level and its light of fire could be seen from more than 40 km at sea, or around 6 hours' sailing. This ancient world's highest building designed by Sostrato of Cnidos lasted over 15 centuries before being destroyed by earthquakes. Remains of the lighthouse at Leptis Magna (Libya) can still be seen today. It is interesting to note that reconstruction of the lighthouse of Patara (Gelemis, Turkey) has recently been undertaken.

Most ancient *horrea* (warehouses) have probably been lost during successive rearrangements of port areas and we know about them through a limited number of examples. By far the largest complex was found in Rome, both downtown and at Ostia and Portus. Most warehouses were built as from 100 BCE to store commodities like grain, pepper, olive oil, and so on. In order to avoid humidity spoiling perishables, the ground floor was raised on a series of small parallel walls a few decimetres high above the ground level.

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[8] Another facility in a modern shipyard is a dry-dock which is an enclosed basin in which a ship can be dried-out for maintenance. A modern tidal dock is an enclosed basin with sluice gates where ships are kept afloat at low water of the tide. Both types of dock are unheard of in ancient times.

5. GEOMORPHOLOGY OF A FEW ANCIENT PORTS

Around 50% of the known ancient Mediterranean harbour locations are not used any longer today (within a radius of 1500 m around the location of the ancient harbour). Around 15% of the ancient Mediterranean harbours are now silted up, of which ca. 75% are not used anymore today, like Sharm Yanbu on the Red Sea (Saudi Arabia) which might be the ancient Charmotas (de Graauw, 2024). This shows that when siltation occurs, ports are often finally abandoned, which does not mean that many dredging efforts have not been spent for years before giving up the battle against Nature.

Portus (Italy)

Portus Augusti, the port of Rome, was initiated in 42 CE by emperor Claudius at ca. 3 km NW of the older harbour of Ostia Antica on the Tiber estuary where a sand bar made access for seagoing ships dangerous. As a matter of fact, the emperor needed a safe and reliable port to feed the people of Rome that could easily rebel when hungry[9]. This port was built on a straight coastline without any natural shelter. With its 4 km breakwaters, 4 to 5 million m^3 dredging works and 200 ha basin providing anchorage for several hundred Roman size ships, the harbour basin is now completely buried under Fiumicino Airport after 2000 years of sedimentation from the river Tiber, but quay walls, warehouses and breakwater remains are still visible in the Portus archaeological area. The only harbour basin still visible today is the hexagonal basin built by emperor Trajan between 106 and 113 CE.

Waves in this area are dominant from SE to SW which explains a resulting longshore sediment transport towards North (Noli & Franco, 2009). The finer fraction (silt) flows offshore and only the coarse fraction (sand) stays in the coastal area (estimated at 50 000 to 100 000 cubic meters/year over the past centuries) inducing a 10 m/year progradation beside the south breakwater of Portus Claudius. Considering a seaward extension of 1000 m for this breakwater (BW), it can be understood (in a very simplified reasoning) that sediment would start to get around the toe of the BW after 100 years. This left many more years for the harbour to be still (partly) operational, as long as the water depth was at least 3 to 4 m inside the harbour. It would, however, not be surprising that Claudius' engineers anticipated this, at least in a qualitative way, and this would then explain why they built such an expensive, long and deep, south breakwater, since they did not need a 10 m water depth for contemporary ancient ships, but *they had to create a large sedimentation trap south of the harbour*. In the same line of thought, Claudius' engineers may also have decided to use the concept of an arched breakwater on the northern side of the port, as this concept had already been in use for nearly one century. Such an arched BW was supposed to allow currents to flow through the BW, providing some flushing which would help reducing siltation of the harbour basin, even if today we have serious doubts about its efficiency.

If Claudius' engineers realised that sediment coming from the Tiber was flowing north as littoral drift along the coastline, they must have thought that they had to build the south BW *first* in order to stop this material from settling inside the future harbour area against the northern BW, if that one had been built first. They may have realised also that if sedimentation were to occur on the south side of the south BW, then erosion would occur on its north side, i.e., inside the future harbour (Fig. 21A). This was quite a neat opportunity to let nature do the work of cleaning up the area that would have to be dredged anyway… After some time, they would start building the north BW and the coastline would readjust with some erosion near the northern side of the south BW combined with some sedimentation near the southern side of the north BW. The coastline between both breakwaters would then be stabilised (Fig. 21B).

The erosion area observed north of the north BW on Fig. 21B may be an explanation for the somewhat hectic layout of the north BW near Monte Arena (Felici, 2013), where several structure designs are used, *possibly showing repair actions*. A northern access channel for ships (Goiran, 2008) may not have been anticipated from the onset by Claudius' engineers, but the opportunity provided by this local erosion may have been taken to use it, and even to enhance it artificially for transit of ships from Portus Claudius through the northern canal system leading to the Tiber.

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[9] Like today: '*Panem et circenses*', bread and games to ensure social peace… (Juvenal, *Satires*, 10.81).

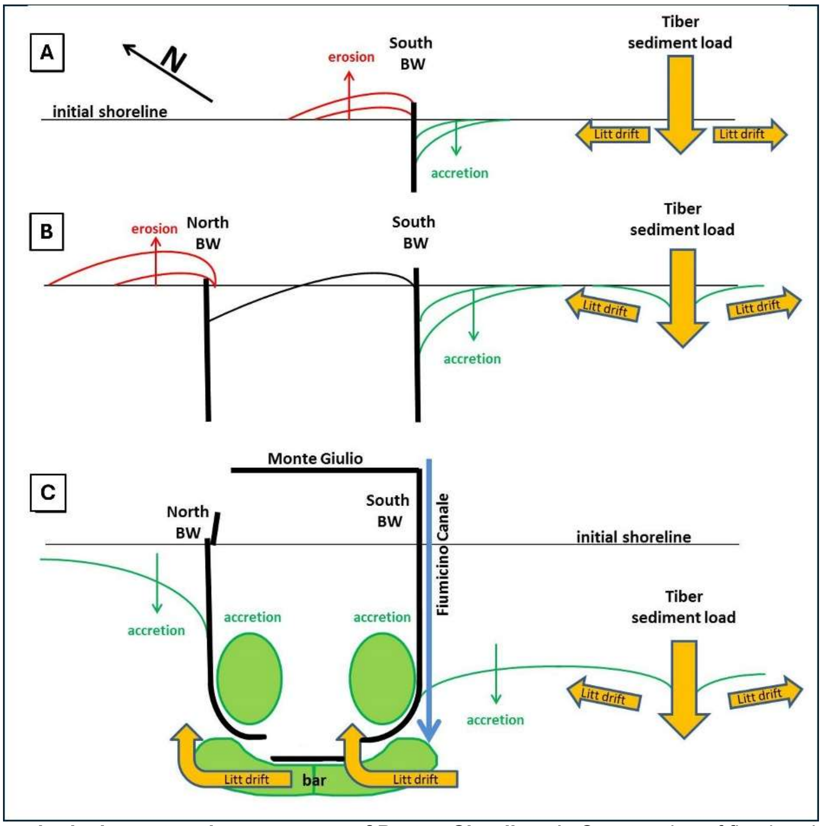

Figure 21. Hypothetical construction sequence of Portus Claudius. A: Construction of first breakwater (south), B: Construction of second breakwater (north), C: Coastal progradation and harbour sedimentation. (Pictures de Graauw)

We usually distinguish vertical breakwaters and rubble mound BWs. The first are built with caissons filled with hydraulic concrete (e.g., Caesarea Maritima, Israel). The latter are built by dumping stones from a lorry or a cart, and concrete can possibly be found on top of the rubble mound (near the sea level where it is easier to pour). Morelli's report on corings at Portus (2011) shows that the crest of the deep section of the breakwaters are at approx. 4 m below the Roman Sea Water Level (SWL) with a total remaining structure height of around 10 m reaching approx. 14 m below Roman SWL. The initial BW may thus have been a 15 to 20 m high structure which sunk several metres into the original silty clay seabed.

We now have two options: it could have been built higher and been partly destroyed by long-term wave action or have been built as a low-crested BW from the onset. The first option is usually built as an emerging BW, built out from land with carts, involving considerable logistics (carts meeting each other on top of the BW, etc.). The deep section of the north BW includes a rubble mound of roughly one million m^3, with an average stone diameter of 0.50 m (typically a 50 to 300 kg class of rock). This material is clearly not stable on the BW crest with waves larger than only 1 m, which occur many times a year. It is expected that this material placed on a water depth of 10 to 15 m should suffer frequent damage during storms, especially at the roundheads and at the lighthouse island which are both subjected to frontal wave attack. The structure would thus be lowered by repeated wave attack until it was no more than a submerged breakwater.

As corings show that this did not happen, the second option is favoured. It seems likely, at this moment, that the north BW was not made entirely of rubble, but that another structure (concrete poured into wooden formworks or ashlar? massive or arched?) was built out from land on top of a rubble mound having its crest about 3 meters below Roman SWL (Fig 22). This is however not (yet?!) confirmed by archaeology… nor have large blocks of hydraulic concrete been found (yet!)… If this structure was not destroyed by wave action, ashlar blocks could have been dismantled during the Renaissance. In any case, the upper level of the Portus breakwaters seems to have been lost over the years.

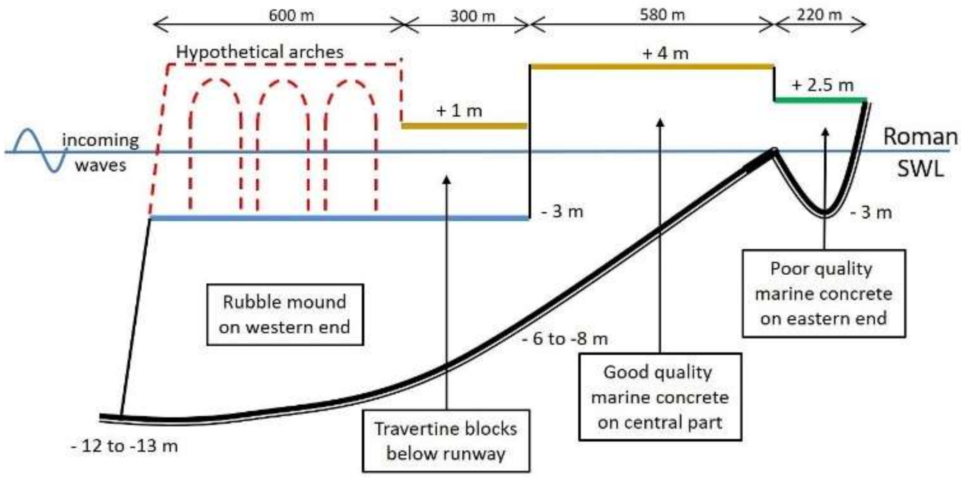

Figure 22. Hypothetical longitudinal section of Portus' north breakwater. Beware the 1:50 distorted scale! Note the Roman Sea Water Level is ca. 0.8 m below the present one. (Picture de Graauw)

When building the new airport at Fiumicino, Testaguzza (1970) identified the three emerging parts of the ancient north breakwater, but he did not find the submerged western section that was buried deeper than he could excavate at that time.

Tyre (Lebanon)

The city of Tyre started as a small offshore outpost of the city of Ushu, or Palaeotyre (Old Tyre), from where it resisted invasions and sieges for many centuries. In 332 BCE, Alexander the Great eventually succeeded in seizing the city after building a causeway 750 m long and 60 m wide, which was laid in water depths reaching 5.4 m, according to the ancient authors. The causeway interrupted longshore sand transport, forcing sand to pile-up against and on top of the causeway, thus creating a sandy isthmus that has connected Tyre to the mainland ever since. A lot of corings were made to understand the geomorphological evolution over the past 3500 years (Brocard et al., 2024).

The isthmus profoundly altered the layout of Tyre and its harbours. Ancient authors Strabo (16, 2) and Arrian (2, 7), living in the first and second centuries CE, report that the Phoenician city had two harbours, one opening towards the north, and the other opening to the south. The ancient northern harbour is filled with Hellenistic to Byzantine sediments and is clearly documented below the modern harbour of Tyre (Marriner, 2005). The southern harbour no longer exists and several hypotheses for its location have been put forward over the past two centuries.

A breakwater similar in style to the Phoenician breakwater, with oblong headers built in the 6th to 4th centuries BCE along the north coast (Nourredine, 2019), was discovered in 2019 along the south coast in water 2 metres deep by a team of French researchers (Goiran, et al., 2021). Cores collected onshore by the team revealed the presence of sediments typically deposited inside a harbour basin, behind the newly identified breakwater (Brocard et al., 2024) and samples of these Phoenician sediments have been radiocarbon dated to the Phoenician period. As the depth of this stratigraphic unit is similar to that of the submerged structure, these two elements (structure and sediment) confirm the presence of the lost Phoenician southern harbour.

The newly identified breakwater is therefore regarded as protecting the southern harbour of Tyre (‘M’ on Fig. 23). Its basin (‘10’ on Fig. 23) would have covered an area of up to one hectare (100 x 100 m), south of the Roman baths complex (de Graauw et al., 2024). The port structures of the southern Phoenician harbour of Tyre appear to have been buried during the Hellenistic and Roman periods, allowing the south-east corner of the island to be used by the Romans for the development of monumental baths. The team suggested that the southern harbour had to be abandoned owing to the rapid growth of a massive sandy isthmus during the centuries which followed the erection of Alexander’s causeway. The area of this southern harbour was then repurposed, with the building of monumental baths, and the development of an urban district protected by Roman-style seawalls. However, early Byzantine tomb stones of ‘murex fishermen of the Egyptian’s port’ prove that the southern harbour was still operational around say 300 CE (Aliquot, 2020).

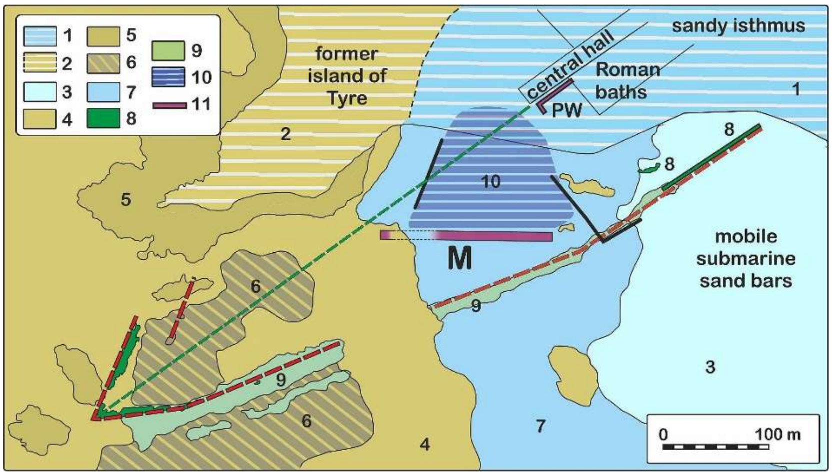

Figure 23. Distribution of man-made structures, bedrock, and sediments around the southern harbour of Tyre. Red dashed line: Poidebard (1939)’s southern harbour enclosure. Green dashed line: axis of the monumental Roman baths. Black lines: Roman quays. Geology: 1: emerged part of the sandy isthmus, 2: emerged land over calcarenite bedrock (wherever bedrock is above -2.5 m), 3: submarine part of the sandy isthmus, 4: submerged outcrops of calcarenite, 5: shore platform cut into calcarenite (mostly man-made), 6: natural block pavement over calcarenite, 7: natural block pavement over marine sediments, 8: roman concrete (*opus caementicium*), 9: rubble mound dike, 10: proposed southern harbour-basin, 11 (M): east-west Phoenician-like breakwater. Top is north (drawing by Brocard, 2024).

In addition, coring also revealed the presence of harbour sediments likely deposited in another basin, at an earlier location of the northern harbour of Tyre. This northern proto harbour would also have been abandoned to give way to the growing sandy isthmus, and relocated to its Hellenistic-Byzantine location, under the modern harbour of Tyre (Fig. 24).

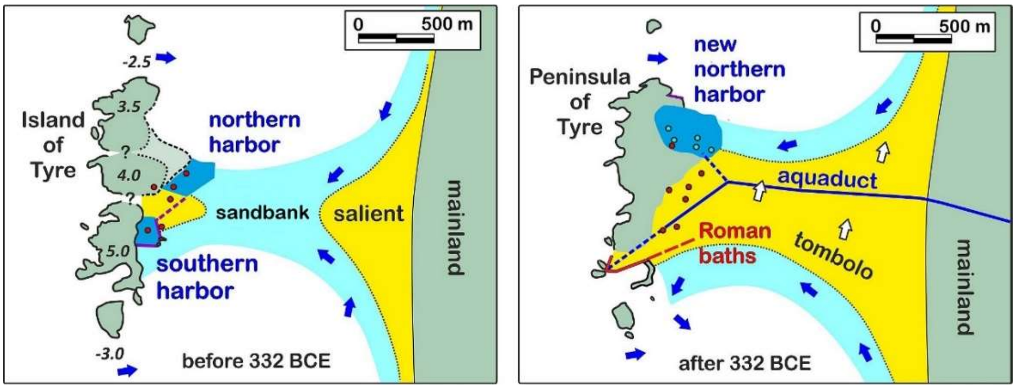

Figure 24. Schematic paleogeographic maps of Tyre, highlighting the effect of the formation of the sandy isthmus on its two Phoenician harbours, the displacement of the northern harbour further north, and the repurposing of the southern harbour into a Roman baths area. Red & blue dots: corings. Arrows: net sand flux (blue: marine, white: terrestrial). Numbers on left panel refer to the minimum, currently constrained elevation of the calcarenitic bedrock relative to the ancient sea level at -2.5 m which is the supposed archaic sea level (drawing by Brocard, 2024).

Tyre’s urban and port development really started on the island after 1500 BCE. Some islets were then probably interconnected, enlarging the original island, and improving shelter from sea waves to such an extent that by 1350 BCE, the Tyrian king Abimilky reportedly stationed battleships in a proto harbour in the lee of Tyre Island (Amarna Letter EA 153). As sedimentation in the lee of Tyre Island further progressed, a submarine sand bank formed, built by the refraction and diffraction of waves around the island. A large harbour was still present in the lee of the island by around 1200 BCE (Anastasi 1 papyrus), but the accumulation of sand over the sand bank had led to its partial emergence, creating a coastal 'salient' attached to the lee of the island. Around 950 BCE, the famous Tyrian king Hiram I, friend of King David and King Solomon, connected one more islet to the main island, and reclaimed the area in-between, which was called *Eurychoros* (wide space, agora). Hiram I obviously used the naturally formed salient and extended it through additional land reclamation. By then, the initial single harbour in the lee of the island had probably been largely occupied by the sand bank, and a new layout with two harbours had to be implemented, with a northern harbour and a southern harbour, set astride the growing sandbank. At that time, the southern harbour could have been the main one, as a north-south reef aligned with Tyre Island better protected the whole southern bay, which therefore could have been used as a summer anchorage area.

Both harbours were probably used for several centuries, while the city remained an island, as documented by the bronze bands of Balawat (858 BCE) and by Esarhaddon's Annals (671 BCE). During that time the city prospered and resisted several important sieges, also weathering earthquakes and tsunamis. After Alexander the Great built his causeway, the tombolos formed, and the harbours were once again threatened by sand accumulation. The northern harbour was moved away from the tombolo, at its current location, below the modern harbour. The southern harbour, on the other hand, was gradually abandoned. When the Romans arrived in the area in 64 BCE, they probably used sand removed during the levelling of the tombolo for further land reclamation and built the monumental Roman baths and an urban district starting in the 1st century CE. The French research team suggested that the structures described by Poidebard (1939) are the Roman seawalls that protected this urban area from sea waves.

Sand flux and sand volume calculations were carried out to provide a rough estimate of the time required for coastal processes to accumulate the sand volume currently contained in the peninsula that connects the former island of Tyre to the mainland.

At Haifa, around 50 km south of Tyre, modern longshore drift moves 50 000-80 000 m^3/yr of sand northwards (Zviely, 2007) for a mean incidence angle of waves of $\theta = 10°$. Assuming this sand transport capacity at Haifa, the decrease in the incidence angle to $\theta = 6°$ at Tyre implies that longshore transport capacity at Tyre is reduced by a factor 0.6 to 30-50 000 m^3/yr following the CERC formulation (1984). The total volume of sand accumulated behind Tyre Island was calculated as the difference between the elevation of the modern onshore and offshore surface of the sandy isthmus and the elevation of the substrate over which the sands were deposited. The resulting volume of sand accumulated behind Tyre Island *before* 332 BCE was estimated to 10 million m^3, and the volume accumulated *after* 332 BCE, to 30 million m^3 (Brocard et al., 2024). This volume required 6 to 10 centuries to accumulate at a rate of 30 000 to 50 000 m^3/yr, which means that the isthmus would have been able to reach its current size between the 3rd and the 7th century CE.

An estimated 2.5 m relative sea level rise affected the site, submerging the southern harbour structures. The age of this submergence is still poorly constrained, possibly in Hellenistic and/or Roman-Byzantine times (between say 500 BCE and 500 CE). The sea then overtook the seawalls of the southern district and gutted the Roman landfill. Wave action unearthed the Phoenician quay and breakwater structures that were buried, exposing them on the seafloor.

Concluding, the harbour history of Tyre, spanning a period of 3500 years, is one of abandonment and relocation of infrastructures, resulting in a complex pattern of structures, often superimposed one on top of the other. Development of many ancient ports was hampered at some point by a geological process of some sort, such as tectonic uplift or subsidence, soil settlement in deltas and estuaries, and, most commonly, by coastal progradation, either by direct ingress of fluvial sediments in estuaries and deltas, or by coastal accretion downdrift of river mouths. Tyre, in southern Lebanon, constitutes a remarkable case of the large amplitude of changes imparted by man-built structures. The only other case of such an amplitude is Alexandria (Egypt), and in both cases, the most important changes were caused by… Alexander the Great.

Narbo Martius (France)

Thanks to recent excavations by French archaeologists (Sanchez, 2024), the main Roman port of ancient Narbonne (1st c. BCE) is now believed to be located at Mandirac - Le Castelou (near Narbonne, France). This location is inside a series of coastal lakes that were more widely open to the sea in ancient times. The strong dominant NW wind in this area makes sailing difficult and generates local waves. The port was located at the ancient outlet of the river Aude (ancient river Atax) and this proved to be another problem, as sedimentation had to be kept outside the port that was therefore built as a canal that had to be extended periodically.

Figure 25. Coastal cell from Leucate to Agde (ca. 55 km) with 3 main river outlets. (Google Earth)

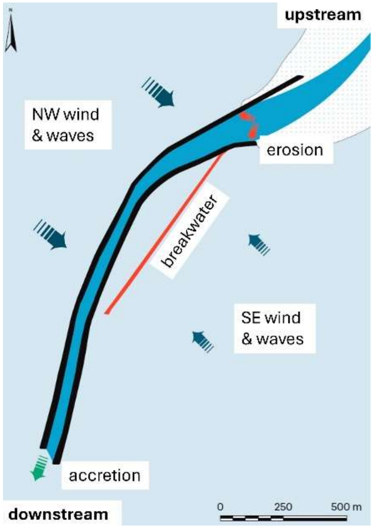

Figure 26. Canal-harbour at Mandirac – Le Castélou. (Picture Cavero)

Wave incidence induces a littoral drift towards SW between Agde and Gruissan and conversely, a littoral drift towards NE is induced between Leucate and Port-La-Nouvelle (Fig. 25). At the meeting place of both littoral drifts (at Grau de la Vieille Nouvelle), the mean wave incidence on the coastline is nil (Larue, 2009; Kulling, 2017). On the other hand, fluvial sediment transport is generated mainly during river floods, i.e., rather unsteady: one or several hundreds of thousand m^3 may be brought in in a few days, while littoral drift, which is steadier, does not exceed a few tens of thousands m^3 per year. This means that most of the river sediment is carried offshore: that is the finer fraction of sediment brought in by the river. The coarser fraction of river sediment (i.e., sand) settles near the river outlet where the flow velocity is reducing. This sediment gathers as a 'bar' located at the place where river and marine currents meet and which is under influence of both, depending on their relative strength.

It is usually considered that the river sediment discharge is *proportional* to the water discharge (Malavoi, 2011). Hence, a flood will temporarily increase the sediment discharge by eroding the riverbed. The order of magnitude of the sediment discharge of the river Aude was formerly in the millions of m^3/year (but modern river works reduced this by a factor 10). Similarly, if a structure locally increases the flow velocity, erosion will occur to satisfy the locally increased transport capacity of the flow. As an example, longitudinal dikes ('levees' or 'training walls') aimed at constraining the flow, induce a flow acceleration and thus local riverbed erosion. Hence, the upstream flow must be guided towards the canal intake, including during floods, and this may require quite extensive funnelling guide walls ('wing walls') to avoid water flows wandering around during floods. At the downstream outlet of the canal, accretion must be expected because of the local decrease of flow velocity. The outlet must therefore be at a water depth allowing some sedimentation before navigation is hampered. Once the minimum water depth for navigation is reached, the outlet must be dredged... or the canal length extended, but this cannot go on indefinitely.

Figure 26 shows the 50 m wide canal-port stretching over ca. 1.5 km. It was initially built during the 1st century CE and gradually extended until the 5th century. It consisted of two jetties, each made of a double line of vertical wooden sheet-piling filled with rubble (Roman hydraulic concrete was not used here). Ships could moor on either side of the canal-port, and the jetties served as land routes. Erosion occurred at the upstream end inducing repair works with a shipwreck filled with rubble. Damage probably occurred also on the western side where local wind waves hit the vertical wooden sheet-piling structure.

In order not to be facing the wind in this area, sailing ships must 'tack', reaching an angle with the wind direction of not less than around 60°. However, this tacking sailing technique is very uncomfortable for both ship and crew, and it was used only if there was no other choice. Access was probably also possible through the Grau de Gruissan and/or the Grau de Grazel, and ships sailed on the the Etang de Gruissan at the toe of the hilltop village of Gruissan. After sailing past Gruissan, ships had to cross two narrows with a minimum width of 250 to 350 m between the hills. Passing both narrows was difficult with head winds from west to NW, and in this area, ships probably required the assistance of land-based hauling. Nevertheless, sailing this route was easier than the southern route via the Grau de la Vieille Nouvelle and Bages, and it was obviously even easier with the rather infrequent easterlies. Moreover, a group of around ten shipwrecks was found near Gruissan, perhaps showing the sailors' preference for that access to Narbo.

Subsidence

Before entering the subject of subsidence, we must distinguish it from breakwater destruction by wave action. The latter yields spreading of materials on the sea floor resulting in a complete destruction of the breakwater superstructure which can then barely be recognised as such under water. This is not (or less) the case with subsidence yielding a vertical movement, possibly combined with tilting, of the structures.

Subsidence must also be distinguished from *wave-induced local scour* near the toe of the structure, mostly occurring at wave rundown, when breaking of waves coming in obliquely induces a longshore current that might yield erosion of the sandy bed in front of the structure. This may undermine the offshore toe of the structure and cause tumbling of the large capping blocks towards the sea, but not a uniform subsidence of the whole structure.

Repeated storms have sometimes been put forward as a possible explanation for the breakwater subsidence due to *wave-induced liquefaction*. From a hydraulic point of view, we must visualise a wave travelling towards the coast with a crest parallel to the breakwater. This wave is reflected by the offshore side of the breakwater, inducing a nearly double wave height in front of it. Large waves might indeed induce local liquefaction of the sandy seabed on the offshore side of the breakwater (Zen, 1990 & 1991). This induces a subsidence larger at that side than at the inner side of the breakwater and tumbling of large concrete blocks towards the offshore side would be observed rather than a uniform vertical subsidence.

A different mechanism is that of *wave-induced compaction* of the sub-soil underneath the structure. Before breakwaters are built, the seabed often consists of more or less loosely packed sand provided by longshore sediment transport. Adding the weight of the breakwaters and subjecting them to long-term vibrations due to wave action and to seismic action, will induce *compaction* of the sub-soil. In addition, *consolidation* of clayey materials (if any) and long-term deformation called *creep* may also play a role in coastal areas at a centennial or millennial timescale. Modern engineers always dredge away these layers of loosely packed and clayey materials before building any structure, but ancient builders did not, because they did not have the necessary heavy-duty dredging equipment; the first mechanical dredger was invented by a Genoese engineer and by Leonardo da Vinci in 15th c. CE.

Because of the long waves acting on the outer side of the breakwater, a cyclic hydraulic gradient is generated between both sides of the porous breakwater. This induces a strong flow inside the rubble mound or at the interface between the large concrete blocks and the unprotected sandy seabed. In order to avoid irreversible problems with the foundation of large marine structures due to *piping and undermining*, a foundation layer consisting of a 'granular filter' must be installed in accordance with strict requirements (de Graauw, 1984). As a matter of fact, foundation layers consisting of fine granular material (say 2 to 50 mm) placed underneath large blocks made of Roman concrete should be an essential part of their foundation. However, they have not been mentioned by many excavators so far, except in Caesarea Maritima and Atlit, where a 40-cm thick layer of rounded cobbles (up to 350 mm diameter) was found underneath a large concrete block of the Caesarea Maritima western breakwater (Votruba, 2007), and in Thasos where a 1 m layer consisting of 2 to 5 kg rubble was found (Empereur, 1993). This very porous foundation method allowed a strong alternate flow due to wave action within the foundation layer, eroding sand underneath and thus undermining the whole structure.

Other explanations of subsidence include earthquakes inducing *tsunamis*. The tsunami wave(s) first encounters the outer face of the breakwater, where part of its energy is reflected back to the open sea. At this stage, the tsunami might push large blocks of Roman concrete placed on top of the breakwater into the port, rather than generating a uniform vertical subsidence. Then, depending on the size of the tsunami, a substantial part of the energy would overflow the breakwater and submerge the whole harbour area, taking away all loose blocks, pavements, warehouses, ships, etc. The tsunami wave would then enter the city and would finally flow back to sea, taking much waste into the harbour (Fig. 4).

Earthquake-generated liquefaction is a convenient explanation for subsidence, as it is likely to affect large areas covered with cohesionless water-saturated sand provided by longshore sediment transport.

The potential for liquefaction depends on the subsoil properties (Idriss & Boulanger, 2008; Hettler, 2014): sand must be loosely packed (less than 70% relative density) and may include a small fraction of fine silts or clay, so-called 'silty sand' (less than 20% with a diameter below 74 microns). Longshore transport of sediment often provides this kind of sand in the nearshore area down to a water depth of ca. 10 m. During an earthquake, sand with a large porosity (say 40% for a loose packing) will tend to re-arrange its packing and reduce its porosity (to say 30% for a dense packing). This will require some pore water to seep out of the sub-soil, but that flow may be delayed by low-permeability materials. Any load resting on this sub-soil would then be floating on water instead of resting on a solid skeleton of sand grains, and as water would gradually flow out, the load would gradually sink into the sub-soil until it would rest on the re-arranged sand skeleton (Aachen University video). This liquefaction is a short-term process occurring within minutes during and shortly after the earthquake, and according to this process, liquefaction can only occur once in a given area. This is of course an idealised and simplified scenario, and many complications may occur in reality with superimposed layers of various materials, including impermeable layers, etc.

Such liquefaction was probably mentioned by Aelius Aristides (Oration 19) who witnessed the 178 CE earthquake in Smyrna (Turkey): 'some of the temples have *fallen*, some *sunk* beneath the ground'. Liquefaction probably occurred also at Thonis-Heracleion (Brocard, 2024). At the outer harbour at Caesarea Maritima, liquefaction, perhaps combined with compaction of the subsoil due to wave loads on the vertical western breakwater is probably a major explanation for the subsidence observed at the quays and breakwaters (Galili, 2021a). A few bore holes through the breakwater would confirm its present stratigraphy down to its foundation base and materials underneath.

This scenario would explain how the breakwaters subsided into the underground, allowing offshore waves to penetrate the Caesarea harbour, inducing its sedimentation, i.e., the port authorities witnessed meters of subsidence after one of the earthquakes (possibly 127-130 CE, 303 CE with tsunami, 363 CE, 419 CE, 425 CE) and refrained from further maintenance that would have been too costly, such as adding new layers of hydraulic concrete on top of the subsided breakwater. The port of Caesarea lost its importance, as mentioned by Procopius of Gaza (Anast. 19) just before 500 CE and the much older port of Akko, which did not suffer from subsidence, took over (Gertwagen, 2024).

Finally, there is *tectonic subsidence*. This involves crustal movements of the earth which may be horizontal, vertical, or combined. This also involves faults along which such crustal movements appear during earthquakes. It must be recalled that a meters-high subsidence due to tectonic movements is a major and catastrophic event with many casualties that is usually reported even in ancient literature.

With a better understanding of the phenomena involved, we will now take a closer look at places where subsidence was observed (Flemming, 1978, Pavlopoulos, 2011, Kolaiti, 2023). A few preliminary notes on the available data are to be considered:

- Subsidence (and uplift) may be a continuous process (e.g., consolidation) or a sudden process (e.g., liquefaction). Average rates of subsidence in mm/year really make sense only in case of continuous processes.
- As mentioned above in the section on ancient sea levels, the Relative Sea Level Rise (RSLR or Submergence) of around 0.25 mm/year over the past 2000 years may be due for a large part (maybe even totally) to crustal subsidence. Hence, places that were submerged more 0.5 m over the past 2000 years must have been subject to some kind of subsidence (as Submergence = Subsidence + eustatic Sea Level Rise).
- Over the 5000 years before that, RSLR was higher (around 0.7 mm/year) and therefore, we selected data with an age less than 5000 years (from now to 3000 BCE).
- If the eustatic SLR amounted to ca. 0.5 m in the past 2000 years, any uplift greater than 0.5 m will be visible on land without underwater exploration.

Sites with *more than 1 m submergence* in 2000 years (0.50 mm/yr) were selected from our data base, yielding 264 sites (including Atlantis!).

Figure 27 shows that submerged sites are found in the Rhône delta, the Tyrrhenian coast, the Po delta (Ravenna and Aquileia), several sites around the Peloponnesus and on Paros Island in the Cyclades, eastern Crete, many places on the SW Turkish coast between Izmir and Antalya, southern Cyprus, the Nile delta (Thonis-Heracleion, Alexandria), Cyrenaica (Apollonia), Sabratha and Carthage. The bay of Naples with 'bradyseism' linked to volcanic activity shows alternating uplift and subsidence.

Figure 27. Coastal sites submerged by more than 1 m in the last 2000 years. (Google Earth)

A similar exercise showed 108 sites uplifted in the last 2000 years. Some of them are located in Calabria, northern Peloponnesus, Samos, Rhodes, western Cilicia and northern Levant, but most are located in western Crete as a result of the tilting of the island during the 21/7/365 CE earthquake. During this event, the ancient port of Phalasarna and the ancient Kissamos breakwater were uplifted by ca. 6 m. A similar event occurred on 1/1/2024 on the Noto Peninsula (Japan) when the coastline was uplifted by 4 m, leaving Monzenmachi Kuroshima fishing harbour completely dry.

One more case was investigated for sites stable within ± 0.5 m in the last 2000 years, which yielded 127 sites. It showed good stability in southern France between Narbonne and Antibes (except for the Rhône delta), on the western Sicilian coast, in many places along the southern Turkish coast, in the Southern Levant, on the east Tunisian coasts (perhaps extending to Leptis Magna), and around Tangiers.

Field investigations conducted by geoarchaeologists are still ongoing to get a better overall view of these Mediterranean crustal movements (Kolaiti, 2023; Caporizzo, 2024).

6. SUMMARY & CONCLUSIONS

We may consider that most natural coastal shelters were used in Roman times and that around 50% of ancient ports persist today within 1500 m of their ancient location. However, only few shelters provided real port facilities (ca. 15%) and in most places a sheltered sandy beach sufficed. Some major ancient ports have been built in places without any natural shelter, for strategic or economic reasons (Portus Claudius, Caesarea Maritima, Amathus) and this is the common rule for new modern ports. It might even be said that any excellent natural shelter that has not yet been identified as an ancient port should be searched by archaeologists!

Vertical structures are the oldest maritime structures. They were made of ashlar headers in water depths of less than 5 m that were easily reachable by divers (Levantine coast). Inside harbours and on rivers, vertical quay walls were made of wood (Marseille, Bordeaux, Rezé). Piled jetties were also made of wood (Marseille, Istanbul).

Pilae are among the vertical structures that could be erected with hydraulic concrete poured into a wooden formwork. Remains have been found in southern Italy sometimes showing a dotted line of defence against wave action, possibly arched breakwaters.

Sloping rubble mound breakwaters have been around for 2500 years and most of them are now submerged because of wave action and relative sea-level rise. They were used in deeper waters and were sometimes used by the Romans as a base for *pilae* used as a crest structure.

Harbours show a general trend to silting up because they provide shelter not only for ships but also for sediment. Ports built on sandy coasts receive sand from the littoral drift activated by obliquely incoming waves. Ports in estuaries receive sediment from the river. Oceanic tides and even small Mediterranean water level fluctuations due to wind friction on the water surface – inducing its tilting with displacement of considerable volumes of water – provide fine marine materials to harbour basins acting as sediment traps. Structural solutions have not been very efficient (arches, flushing canals) and dredging was the only way… before abandoning the port. Around 15% of the ancient Mediterranean harbours are now silted up, of which ca. 75% are no longer used today. Fortunately, this silting upholds essential information for today's geo-archaeologists.

Geo-archaeologists have a vertical view of coastal morphology, because they use corings: the deeper, the older. Coastal engineers usually oversee geomorphology over less than 100 years but checking the last 1000 years with a geological approach may be useful.

Subsidence has sometimes been a problem because of liquefaction affecting cohesionless water-saturated sand and because of compaction due to wave loads on vertical structures. Some Mediterranean areas are prone to subsidence, while other areas have been uplifted, and others remained stable.

At least 5 to 10 tsunamis/century occurred in the Mediterranean area between 500 BCE and 1500 CE, mainly in its eastern part.

Today's port technology comes from our ancestors up to 5000 years ago, sometimes partly lost and reinvented (use of pozzolana). Most of today's concepts for maritime structures were already existing in Roman times and it seems that little progress was made until the 18th c. when large maritime structures started to be built again (Allsop, 2020).

The combination of concrete and steel enables modern engineers to build higher, deeper and larger than Roman engineers could dream of, but some modern structures may not last as long as some Roman structures, especially in salt water…

Please respect ancient cultural heritage when implementing new infrastructures, as we can still learn from them…

Geomorphology, Geoarchaeology, Palaeoportology… I hope these words mean more to you after reading this presentation. Our coastlines are constantly reshaped by the sea and by the earth. Ancient ports survive (or not) in a world under constant transformation.

ACKNOWLEDGEMENTS

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