Buried and Submerged Greek Archaeological Coastal Structures and Artifacts as Gauges to Measure Late Holocene Seafloor Subsidence off Calabria, Italy

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This synthesis integrates recently acquired archaeological and geological data with earlier documented observations to shed light on the subsidence of ancient Greek coastal facilities in southern Italy. These are now positioned between former shorelines and inner shelf sectors at five Calabrian margin localities. Submergence of coastal to inner shelf facilities has resulted in part from sea-level rise by about 2 m associated with glacio-hydro-isostatic factors since archaic to classic Greek time. This phenomenon alone, however, does not explain the wide variation of measured subsidence rates from site-to-site. The marked lowering of coastal site substrates by seismo-tectonic activity (including extensional fault motion), stratal readjustments at depth, and compaction of underlying sediment sequences is significant. Four of the subsided facilities are positioned near emerged Calabrian areas where prevailing Holocene average annual land uplift rates range to ∼1.0 mm/yr; at the fifth, near Hipponion, terrains have risen by nearly 2 mm/yr. In marked contrast, submerged and/or buried structures record the following late Holocene long-term average rates of coastal margin subsidence: Sybaris-Thuri on the Taranto Gulf margin (∼0.5–1.0 mm/yr); Hipponion-Vibo Valentia along the Tyrrhenian coast (∼0.8 to ∼3.2 mm/yr); and Locri-Epizefiri, Kaulonia, and Capo Colonna on Calabria's Ionian margin (∼1.6, ∼1.6–2.4, and ∼4.0 mm/yr, respectively).

INTRODUCTION

The ancient Greeks who colonized southern Italy (*Magna Graecia*) and established important settlements along coastal margins of Calabria actively pursued nautical activities, including aquaculture, commercial exchange, and maritime trade. To date, however, only a limited number of coastal facilities constructed there as ship landing sites, harbors, and shipyards have been discovered and detailed since some are now buried and others submerged offshore. Consequently, important aspects of the archaeological and historical records pertaining to this coastal region remain to be deciphered.

The major purpose of the present synthesis is to provide an approach using archaeological features as geoarchaeological proxies to help measure rates of late Holocene lowering of the coastal and seafloor surfaces in sectors between the present Calabrian coastline and inner shelf. These areas comprise integral parts of the highly active seismo-tectonic Calabrian arc. For such measurements, attention is paid to integrating new data with existing information available on Greek to early Roman archaeological structures and artifacts associated with the five coastal sites selected on the margin (Figure 1; cf. Schmiedt, 1975; Cerchiai, Jannelli, & Longo, 2004). One of these localities is presently buried by sediment landward of the coast (Sybaris-Thuri), while the four others are submerged near the coast or on the seafloor seaward of known ancient Greek sites (off Hipponion-Vibo Valentia, Locri-Epizefiri, Kaulonia, and Capo Colonna south of Crotone). Attention is paid here primarily to features of an estimated time span from about 2800 to 2300 yr B.P., that is, comprising Archaic to Hellenistic Greek and early Roman times. Rates of subsidence are mainly determined

Figure 1 Map of the study area showing locations of five discussed buried and submerged coastal facilities off Calabria, southern Italy.

on the basis of a vestige's depth and archaeologically estimated age at each offshore locality examined. It is anticipated that the results of the investigation will assist archaeologists and geographers in evaluating changes of coastal position and physiography over time and that, in some cases, likely altered the maritime activities of populations centered at the five settlements. In addition, the study will provide new data for geologists and engineers conducting coastal protection studies on presently evolving shorelines in this geodynamically, highly mobile region.

Hundreds of geological studies published during the past century have described the stratigraphic framework and tectonic complexities of terrains that form the Calabrian land mass in southern Italy. The general consensus of these works is that strata forming emerged terrains in this region constitute an integral part of the Calabrian arc, one of the Mediterranean's highly active tectonic regions (Berkhemner & Hsü, 1982; Finetti, 1985; Livermore & Smith, 1985; Udias, 1985; Doglioni, 1991; Gvirtzmann & Nur, 1999; Wortel & Sparkman, 2000; Goes et al., 2004; Molin, Pazzaglia, & Dramis, 2004; Woodward, 2009). Geological entities throughout this region have been subject to diverse forms of deformation, including large-scale folding of strata, fault offset, and land uplift during the Quaternary. Summaries of recent geological, geophysical, and seismological analyses document in ever increasing detail the manner of how and to what extent terrains have risen, especially since the end of the early Pleistocene until the present (Ferranti et al., 2006, 2009; Antonioli et al., 2009).

Deep penetration seismic surveys, other geophysical prospection, and coring for hydrocarbon exploration have also provided evidence of geologically recent (Pliocene to Holocene) and diverse styles of structural displacement offshore. Observations made seaward of Calabrian coasts in the Ionian and Tyrrhenian seas and Gulf of Taranto record the presence of extensional, compressional, and some strike-slip fault offsets, with large-scale anticlinal and synclinal folds. Some are associated with mechanisms of active transpression of Middle Pleistocene and younger depositional sequences that form the continental shelf (Ferranti et al., 2009). However, in contrast to work on land, there have been few actual measurements of late Holocene rates of seafloor motion offshore, especially on the inner part of the Calabrian shelf. Thus, aspects of seafloor displacement in this region—be it by uplift, susbsidence, and/or lateral shifts—and rates of such motion during the recent short time span of several thousand years since Greek colonization remain, for the most part, poorly defined.

BACKGROUND CONSIDERATIONS

Interpretations of Calabrian land uplift and offshore stratal displacement at the five study areas are based largely on the results of detailed litho- and chronostratigraphic, tectonic, and seismological analyses. Calculated rates of land surface displacement have recently been enhanced by more precise measurements of short-term elevation and sea-level changes obtained by Global Positioning System (GPS) positioning and leveling, satellite altimeter data, and tide-gauge records (Antonioli et al., 2009; Calafat & Gomis, 2009). This entails improved lithological and fossil age dating techniques such as optically stimulated luminescence, amino acid racemization, U/Th, and other (Cucci, 2004; Bianca et al., 2011). The progressively more robust databases serve to enhance an understanding of the effects of southern European-North African plate contact and associated seismotectonically induced motion of variable scale in the Calabrian arc. These include regionally significant phenomena such as subduction and deep-seated crustal delamination that have affected the crust and overlying to surficial strata in both Tyrrhenian and Ionian sectors of Calabria (Westaway, 1993; Miyauchi, Dai Pra, & Labini, 1994; Giunchi et al., 1996; Ferranti et al., 2006).

Useful for measuring geologically recent land uplift in proximity to Calabrian shorelines are distinct, superposed coastal terraces of Quaternary age. These raised step-like structures, that in some profiles are oriented perpendicular to the coast and resemble flights of stairs, are interpreted as markers of raised former wave-cut backshore, beach, and marine shoreface sections. A number of distinct terraces have been dated and traced laterally for considerable distances along Calabria's landward margin. Of the numerous investigations focusing on such terraces, many have paid attention to one formed during the last interglacial period when global sea level rose to elevations somewhat higher than at present. This terrace is usually designated as geochronological subunit MIS 5.5 inferred to have formed when sea level was about 6 ± 3 m above the present stand (Lambeck et al., 2004) and is dated to about 124 ka (Cucci & Cinti, 1998; Bianca et al., 2011). In Calabria, the MIS 5.5 terrace locally reaches elevations ∼100 m above mean sea level (msl) (Dumas et al., 1991, 1995; Ferranti et al., 2006). The elevation of this feature, determined by increasingly refined leveling techniques and supplemented by an ever larger set of dated coastal sections, has provided a means to more reliably measure long-term (late Pleistocene to Holocene) average rates of uplift landward of the coast. Estimated rates ranging to about 1.0 mm/yr are measured in northeast and southwest Calabria and, more locally, have at times even reached uplift values of nearly 2.0 mm/yr at the northern Strait of Sicily-Tyrrhenian margin (Ferranti et al., 2006; Antonioli et al., 2009; Bianca et al., 2011).

In offshore sectors surrounding Calabria, the very narrow width of the shelf platforms (commonly <3 km between shore and shelf-edge), variable depths of the outer shelf-to-slope break, and generally steep nature (>5°) of upper continental slopes characterize the tectonically modified nature of the shelf margins. In addition, the upper part of deep penetration seismic reflection profiles collected seaward of coasts record deformed strata of Pleistocene age (Ferranti et al., 2009). However, the resolution of the uppermost seafloor strata on such seismic records is poor. The acoustic signal at the base of the water column-subbottom strata interface tends to mask and preclude clear definition of late Holocene to on-going displacement affecting the upper seafloor surface.

There is, nevertheless, widespread evidence of distinct recent to contemporary displacement of seafloor surfaces as recorded by high-resolution, shallow penetration seismic, and multibeam sonar profiles. These techniques clearly indicate the presence of numerous, sharply defined, linear relief features on shelf platforms where such surveys have been obtained around Calabria. Some of these young neotectonic structures closely resemble horst-like ridges and graben depressions, while others depict near-vertical, low-relief, criss-crossed, and sharply angular seafloor offsets of low relief (1 m or less) that record several prevailing fault directions (Stanley et al., 2012). There have been relatively few attempts until now, however, to obtain actual measurements of late Holocene rates of vertical seafloor motion offshore, including on the inner shelf. The amounts of displacement, whether by uplift or susbsidence and/or lateral motion, and rates at which these have occurred during this recent short time span, have remained mostly undefined. It has been generalized that among the fastest geodynamic movements affecting the Mediterranean shores, those that determine the emergence or subsidence of coastline stretches, are those that occur at rates of 1–2 mm/yr vertically and at rates of 30–40 mm/yr horizontally (Milliman, 1992; Stewart & Morhange, 2009).

A series of geoarchaeological studies were initiated by us in 2003 to measure vertical and lateral coastline changes during the past ∼3000 years at the five Greek coastal localities on the Calabria margin, coded 1–5 in Figure 1. The focus has been on archaeological vestiges, those buried nearshore and facilities now submerged offshore. The study areas are shown in Figures 2–6: Sybaris-Thuri (site 1) in northeastern Calabria on the Gulf of Taranto margin; Hipponion-Vibo Valentia (site 2) along the Tyrrhenian coast of southwestern Calabria; and Locri-Epizefiri (site 3), Kaulonia (site 4), and off Capo Colonna south of Crotone (site 5) on southern Calabria's Ionian Sea margin. The geology, physical geography, nearshore oceanography, and coastal archaeology of features at each sector, which have been discussed by other workers in earlier studies, are an integral part of the present synthesis.

Our investigations have primarily involved recovery of drill cores, radiocarbon dating, petrological and biological analyses of sediment core sections, subbottom surveys by high-resolution seismic profiling techniques, and examination of the seafloor surface by multibeam sonar. Data from these studies are supplemented by direct examination of submerged areas by diving archaeologists. Investigations in this region continue under auspices of the Cities Under the Sea Program (CUSP) at the U.S. National Museum of Natural History, Smithsonian Institution in Washington, D.C., in close collaboration with the Department of Earth Sciences at the University of Calabria, Cosenza. This work has been coordinated with authorization, advice, and encouragement of the Soprintendenza Archeologica della Calabria in Reggio Calabria and its staff at the five examined sites.

MEASUREMENT OF SUBSIDENCE

To measure the subsidence rate at each of the localities requires that the original elevation of a studied

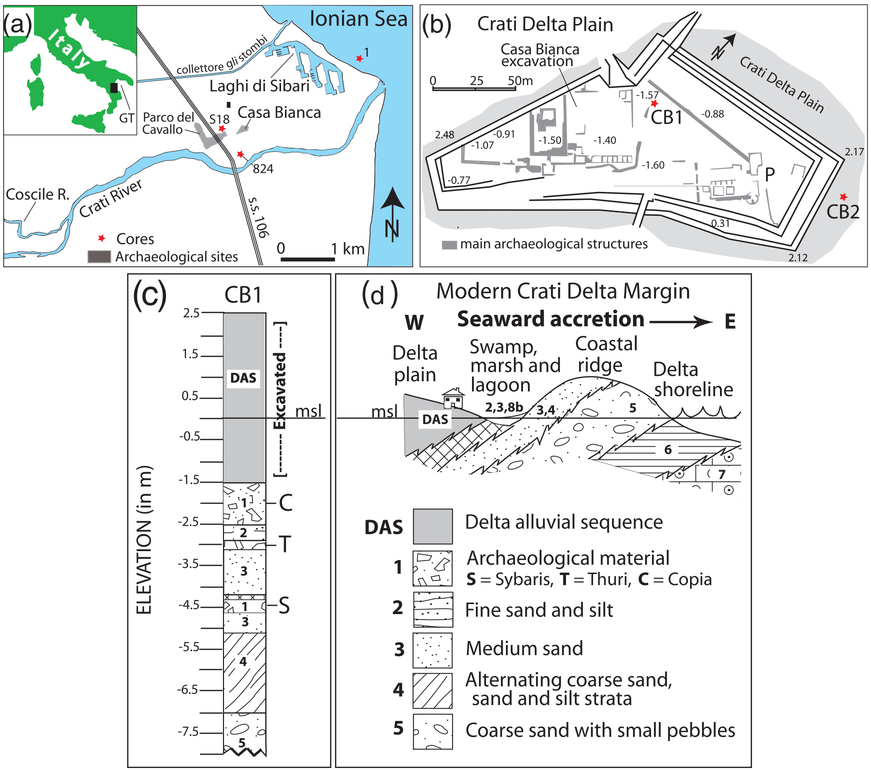

Figure 2 (a, b) Sybaris-Thuri-Copia study area, including the Casa Bianca excavation, Sybaris archaeological park in NE Calabria, showing port and ship slip facilities (P) and core sites CB1 and CB2. (c) Stratigraphic log of upper portion of core CB1 with its three buried archaeological levels (S, T, C). (d) Sediment facies sequence from W to E: delta alluvial plain, to wetland behind sandy coastal ridge, and to shallow marine in the Gulf of Taranto (GT, shown in inset a). Modified after Stanley and Bernasconi (2009) and Bernasconi, Stanley, and Caruso (2010).

anthropogenic feature, whether it be small (such as a ceramic or metal fragment) or large (seawall or port structure), be determined relative to present msl stand. The elevation of a part of the archaeological feature with respect to estimated msl at the time of its formation and use is referred to as ″functional height″ (Antonioli et al., 2009). In some cases, the functional height can be former sea level such as at a ship-landing site along the coast where structures and artifacts were originally positioned close to or at a wetland shoreline margin (example at site 1). In others, the functional height is the top of observed constructed feature or structure that was originally positioned at least ∼1 m above sea level in order to be effective under the Mediterranean's microtidal conditions. Examples of the latter include artifacts that were deposited at site 4 (near Kaulonia) that accumulated on a once broad subaerially exposed coastline formed in part of beachrock strata that are now submerged, and the tops of breakwaters at sites 2, 3, and 5 originally constructed to an elevation positioned somewhat above sea level. The materials at the five sites considered here are of Greek to early Roman age. The original elevations at time of use are then compared to elevations on estimated sea-level curves for the period 2800–2300 yr B.P. as compiled by geophysical modeling for this Mediterranean region. While several curves that comprise this time span are available (Pirazzoli, 1991), herein we use the curve compiled by Lambeck et al. (2004) as a measure of sea-level stands and their rise and change through mid- and late Holocene time to the present (Figure 7).

As a hypothetical example, let us consider submerged archaeological material such as the top of a linear breakwater that now lies at a depth of 7 m below present sea level. To the depth of 7 m, a value of 1 m is added to account for the elevation of the top of the original breakwater that once, in order to function properly, was likely positioned about 1 m above sea level. This provides a total lowering amount of 8 m since time of construction. For this example, the date of the structure is estimated at ∼2500 yr B.P. At that time, the elevation of sea level on the selected curve was positioned at just under 2.0 m below the present sea-level stand (Figure 7). Thus, 2 m is

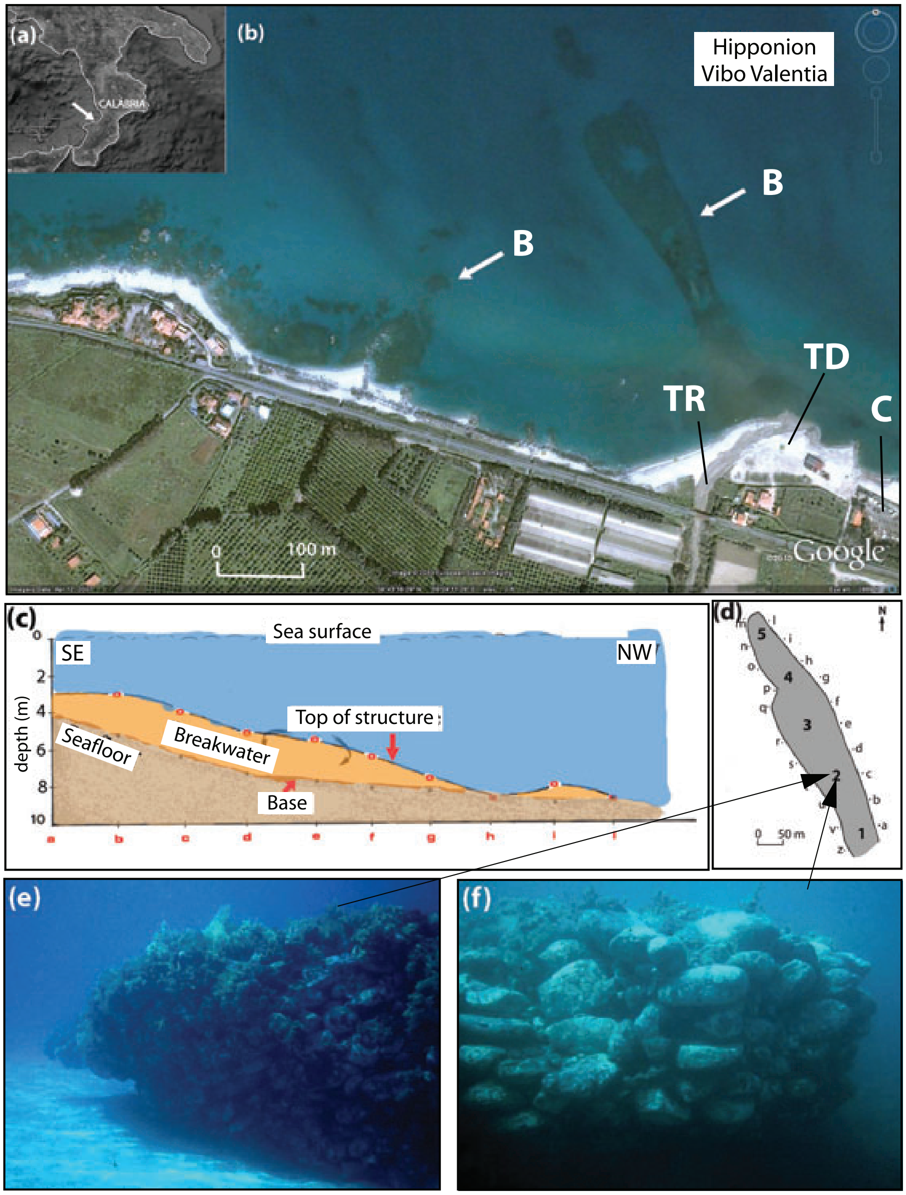

Figure 3 (a) Location of the Hipponion-Vibo Valentia (arrow) study area on the Tyrrhenian margin in southwest Calabria. (b) Google Earth image (2010) of the Hipponion coast showing the Trainiti River (TR), Trainiti Delta (TD), coring location (C), and 2 submerged breakwaters (B, arrows). (c, d) Profile and plan view of northwest-trending breakwater in (b). (e, f) Diver photographs of northwest-trending breakwater show formation by stacked rocks, encrusting vegetation and undercutting by wave erosion (courtesy of S. Mariottini).

subtracted from the total lowered depth of 8 m of the top of the now-submerged structure, recording a vertical displacement value of 6 m. An estimated long-term average annual rate of subsidence is then obtained by dividing the total lowered amount (6 m, or 6000 mm) by the age of the constructed artifact, that is, 2500 years in the case of this example. In this manner, an average rate of lowering of ~2.4 mm/yr since time of emplacement is determined in the case of this example.

SUBSIDENCE AT EXAMINED LOCALITIES

Sybaris-Thuri

Coastal facility

Although known from historic documentation, the northeast Calabrian Greek coastal towns of Sybaris (720–510 B.C.) and Thuri (444–285 B.C.), and Roman Copia (~282 B.C. – 3rd century A.D.), remained poorly defined

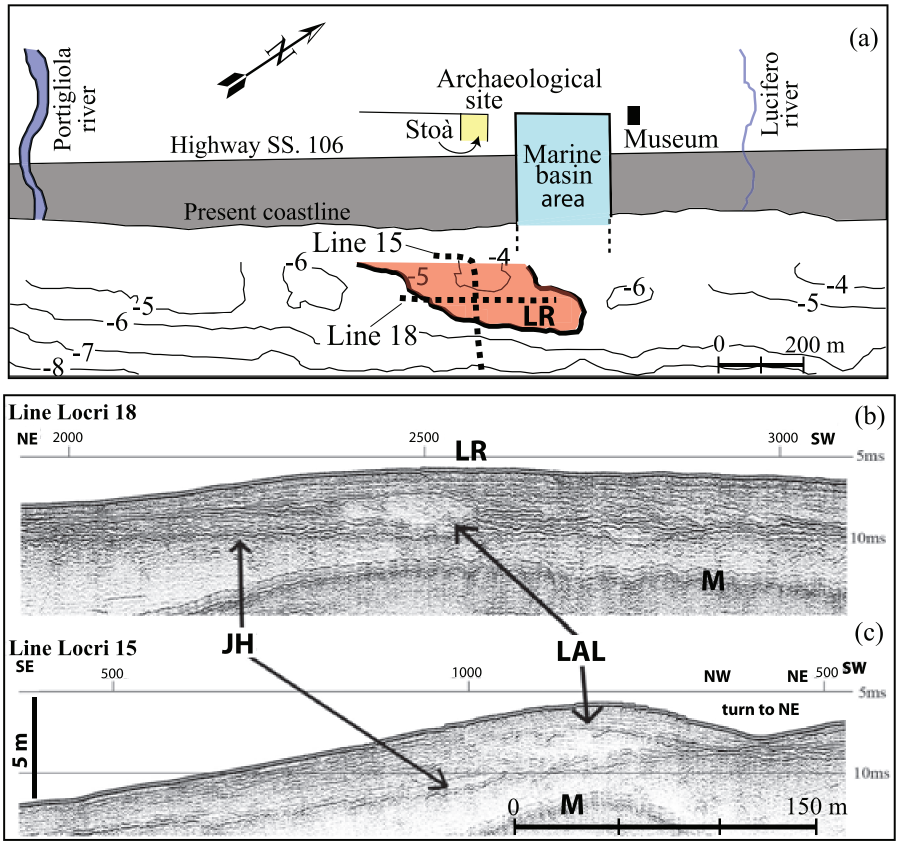

Figure 4 (a) Map of the Locri-Epizifiri study area on southern Calabria's Ionian margin indicates a coastal marine basin area adjacent to a hook-shaped low rise (LR) that extends at an angle offshore. (b, c) Two high-resolution subbottom seismic reflection profiles (lines Locri 18 and 15, shown in a) that cross the low-amplitude lens (LAL), are interpreted as a breakwater. Regionally important acoustic reflector J-horizon (JH) of Holocene age; water-bottom multiple (M). Modified from Bernasconi and Stanley (2011).

until the mid-20th century (Figure 1, site 1). Much of this area was buried for nearly two millennia beneath thick sequences (to >4 m) of fluvio-deltaic plain deposits of the Crati and Sybaris (now known as Coscile) rivers (Figure 2a). After many decades of search, major breakthroughs were made as to the geographic location and general configuration of the cities when major systematic exploratory efforts were undertaken in the 1960s (Rainey & Lerici, 1967; Guzzo, 1973, 1981). The perimeters of Sybaris and the two partially superposed, younger towns were at long-last determined primarily by using an extensive sediment drill coring program (>1500 cores collected), and then focusing on cores that recovered ceramic fragments.

A set of much longer drill cores (to >100 m depth) were subsequently collected in the Crati Delta plain for radiocarbon dating and interpretation of the Holocene stratigraphy and geotechnical properties of the sediment cover (Cherubini, Cotecchia, & Pagliarulo, 1994; Cotecchia, Cherubini, & Pagliarulo, 1994). As more core data accumulated, the Holocene history of the lower Crati Delta plain (core S18 and others in Figure 2a; Pagliarulo et al., 1995) and its contiguous coastal sector and offshore submarine fan in the Gulf of Taranto (Colella et al., 1984) became progressively better defined. From these and additional data sets, researchers (Cucci, 2005; Ferranti et al., 2011; and others) have indicated that the Sybaris archaeological park area landward of the coast has been subsiding at variable rates during the late Holocene. Their measurements suggest a lowering in the range from ~2.0 to 2.8 mm/yr until ~3500 yr B.P., and then a period of near stability and/or even slight uplift of the Crati Delta plain from ~3000 to 1300 yr B.P.

Subsequent information collected by us includes two 20 m long drill cores in the eastern portion of the Sybaris archaeological park at the seaward end of the Casa Bianca excavation (Figure 2b; Stanley & Bernasconi, 2009). It is in this area that coastal port facilities are believed to have

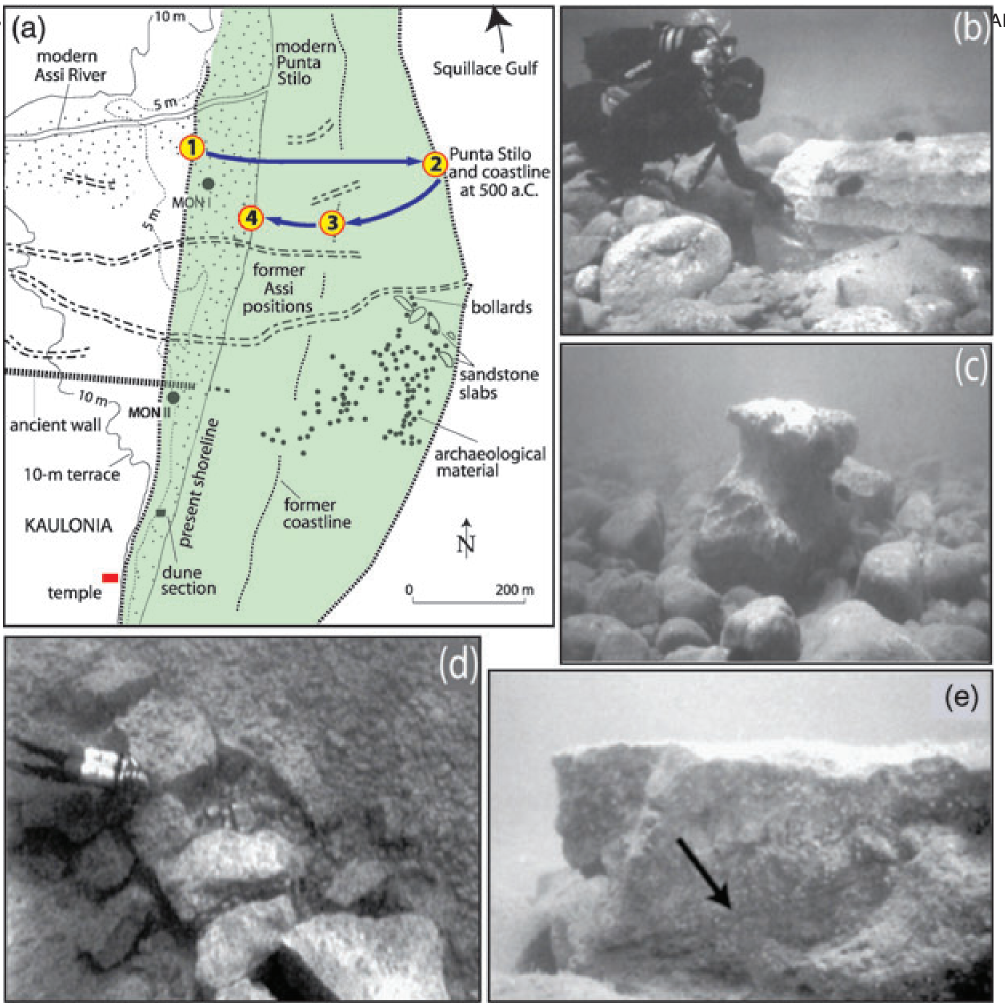

Figure 5 (a) Map of the Kaulonia study area on southern Calabria's Ionian margin showing archaeological material distributed offshore, cores on land and positions of former and present coastlines. Note former shoreline (1) displaced seaward to coastline position (2) and then, readvancing landward at (3) and (4). After Stanley et al. (2007). (b, c) Underwater photographs showing fluted Ionic column section and bollard. Modified after Iannelli (1997) and Iannelli, Lena, and Mariottini (1993). (d, e) Diver above seafloor, which is partially covered by large angular slabs of beachrock, and close-up of inclined sandstone stratification (arrow) beneath near-horizontal beachrock surface. Photos courtesy of S. Mariottini.

been emplaced (Zancani Montuoro, 1972–1973). The cores (CB1 and CB2, Figure 2b) were recovered in proximity to the ship-landing coastal locality (Figure 2b, P) in the excavation (Bernasconi, Stanley, & Caruso, 2010) in order to obtain more radiocarbon dates and further detail the litho- and biostratigraphy of the fluvio-deltaic sediment sections. Anthropogenic material in core CB1, consisting mostly of ceramic sherds and brick fragments, occur at three distinct stratigraphic elevations measured below msl (from base to top, at −4.5 m, −3.0 m, and at −2.0 m); these are attributed to coastal Sybaris, Thuri, and Copia, respectively (Figure 2c; in core CB1, levels S, T, and C). In core CB2, only 130 m to the east (Figure 2b), there are two artifact-rich layers positioned below msl (−3.5 and −2.5 m) and these are associated with Thuri and Copia, while the level with Sybaris material is absent (Stanley & Bernasconi, 2009).

Measured subsidence rate

With the data obtained and applying the method proposed earlier, recovered archaeological material suggests an average long-term subsidence rate of ~1.0 mm/yr for Sybaris in Archaic Greek time, and a decreased rate of no more than ~0.5 mm/yr for the younger, above-positioned Greek Thuri horizon.

Controlling factors

Coastal locality 1 is presently positioned inland, unlike three of the other sites discussed in the following sections (3–5; Figure 1). Its buried coastal structures are now positioned about 2.5 km west of the present marine Gulf of Taranto margin. The Greek landing zone at the Casa Bianca excavation (P in Figure 2b) was once positioned

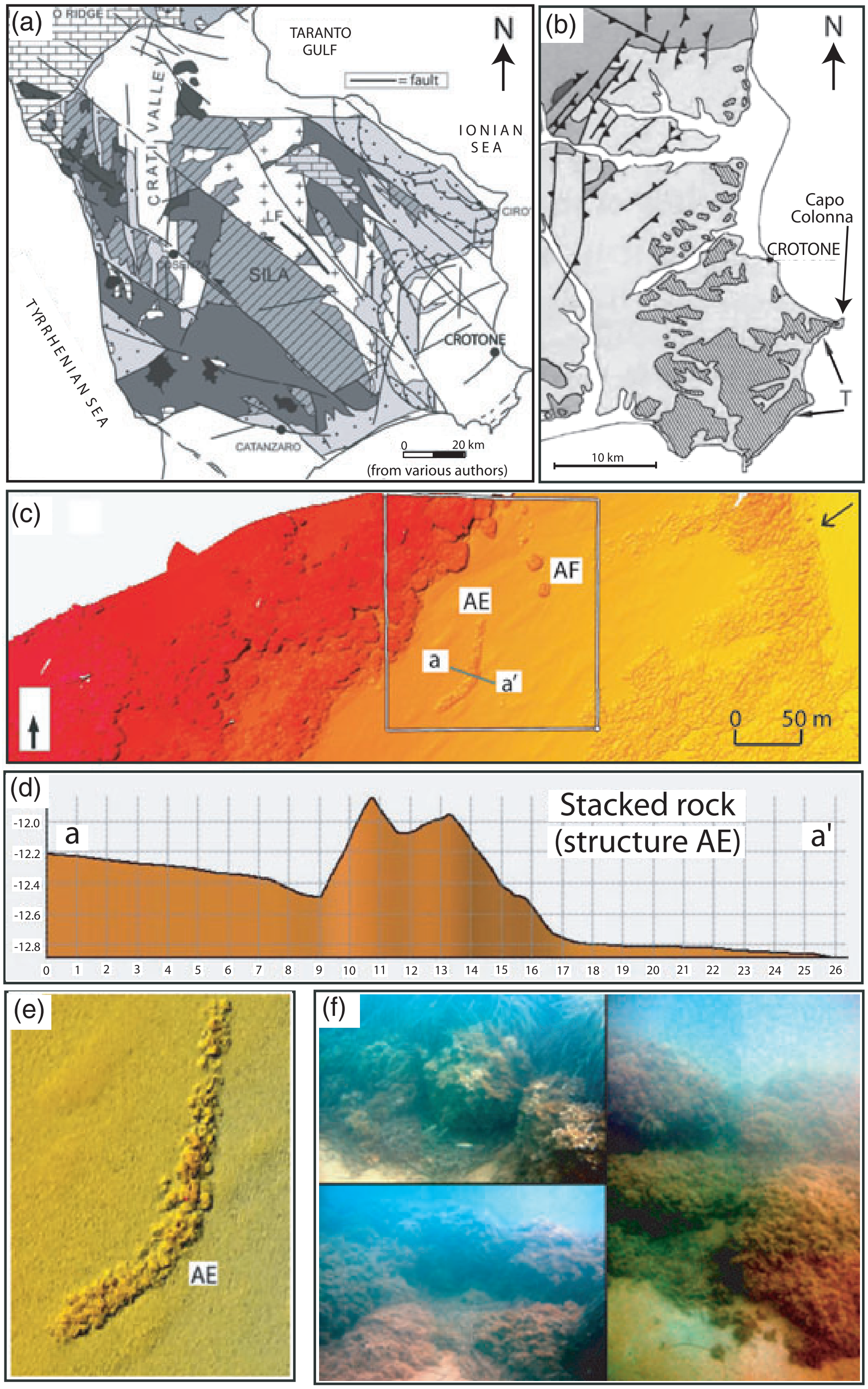

Figure 6 (a) Geological map showing Quaternary formations prevailing landward of the coast, and Tertiary to Paleozoic terrains inland (modified after Dijk et al., 2000; Spina et al., 2007; and other authors). Map emphasizes the complex of neotectonically active fault lines extending from northern to central and southern Calabria. (b) Map of Crotone peninsula south of the modern town of Crotone; hachured area depicts zone of uplifted Plio-Quaternary terraces (T) south of Capo Colonna (modified from Mauz & Hassler, 2000; Zecchin et al., 2003; Mellere, Zecchin, & Perale, 2005). (c) Archaeological structures AE/AF SW of Capo Colonna off the Crotone Peninsula viewed by multibeam sonar; arrow depicts contact between sand and rock slabs on the seafloor. (d) Multibeam sonar profile a to a′ across structure AE in (c); scales in meters. (e) Close-up plan view of structure AE shows continuous, curvilinear, stacked rock structure. (f) Diver photographs of stacked, uncemented, calcarenite rocks encrusted by vegetation.

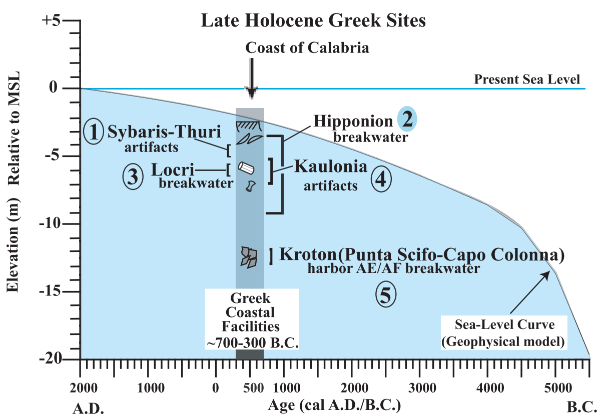

Figure 7 Synthesis of five submerged coastal facilities examined on the Calabrian margin, showing their present depths beneath the sea-level curve of Lambeck et al. (2004). Measured long-term average rates of subsidence, in approximate mm/yr: (1) 0.5–1.0; (2) 0.8–3.2; (3) 1.6; (4) 1.6–2.4, and (5) 4.0.

along the Crati Delta's coast (Figure 2d), and at the margin of a now-buried marine wetland system, perhaps a marsh-surrounded lagoon that could be reached by boat, either via canal and/or dredged fluvio-marine systems (Stanley & Bernasconi, 2009; Bernasconi, Stanley, & Caruso, 2010). As indicated by the available chrono-, bio-, and lithostratigraphy, the Crati Delta coastline has advanced seaward by about 2.5 km since the time of Sybaris in the 7th to 6th century B.C. Sybaris and the two younger and overlapping settlements became landlocked by a pattern of progressive, but irregular, sediment accretion seaward as affected by climatic fluctuations. The delta advanced (prograded) eastward at an average long-term rate of ~1 m per year. In addition to effects of world sea-level rise of about 2 m since the founding of Sybaris (Figure 7) and climatic controls (deposition, erosion), geotechnical studies provide evidence of considerable sediment compaction that induced lowering of the deltaic sequence at this site (Cherubini, Cotecchia, & Pagliarulo, 1994; Cotecchia, Cherubini, & Pagliarulo, 1994; Pagliarulo et al., 1995). Geological analysis of the Crati plain region also records the role of recent tectonic modification of this coastal margin by deformation and lowering of underlying deltaic, coastal, and offshore substrates (Cucci, 2005; Ferranti et al., 2009, 2011).

Hipponion-Vibo Valentia

Coastal facility

The Greek city of Hipponion (Figure 1, site 2) is located shoreward of the Tyrrhenian coast, on the northeastern margin of Calabria's Capo Vaticano peninsula (Figure 3a). This Greek center was founded toward the end of the 7th century B.C. by a population that emigrated from Locri-Epizifiri on the Ionian margin (Figure 1, site 3). Important vestiges of Greek and Roman settlements lie within, and close to, the modern town of Vibo Valentia that overlooks the sea and is positioned on a raised Pleistocene terrace (Dumas et al., 1991) about 500 m above msl. These remains are about 4 km south of the present shoreline, and southwest of the modern port of Vibo Marina. Hipponion's port (or ports) and associated coastal facilities are believed to be located along several nearshore sectors below the modern town, but remain poorly defined (Schmiedt, 1966; Lena, 1989; Jannelli, Lena, & Givigliano, 1992). These, for the most part, are now buried by base-of-slope alluvial sediments that cover the elongate coastal plain and also its contiguous offshore shelf (study in progress). It has been postulated that the probable sector of former nautical activity lies between Punta Safó and the mouth of the Sant'Anna River, an irregularly shaped coastline stretch ~4 km in length (Lena, 1989; Jannelli, Lena, & Givigliano, 1992).

Core drilling, geophysical surveys, and archaeological excavation in the coastal plain at Bivona, 3 km to the north of Vibo Valentia, have revealed buried structures, including a wharf and other features of probable Greek and possibly older age (Cucarzi, Iannelli, & Rivolta, 1995). Cores recovered in this plain area record some preexisting marshy wetland settings under a younger alluvial soil cover; these were separated from the open sea to the north by beach ridges and coastal dunes. South-to-north stratigraphic reconstructions based on cores collected at Bivona indicate that the coastline prograded seaward in the late Holocene (Cucarzi, Iannelli, & Rivolta, 1995).

It is probable that a harbor facility was also located near the mouth of the Trainiti River ~3–4 km north of Vibo Valentia. We have recently recovered artifacts in cores in the river's small delta formed of sand and sandy silt strata. This area lies just landward of two very large, well-defined and now fully submerged linear structures (Figure 3b, B). These, formed of stacked large rounded rock boulders and some angular blocks, are interpreted as probable breakwaters (Figure 3e, 3f; Lena, 1989; Jannelli, Lena, & Givigliano, 1992). Although no firm dates have as yet been determined, a review of historic documentation by archaeologists suggests a pre-Roman age for the uncemented rock structures (Figure 3e, 3f; cf. Lombardo, 1989; Cucarzi, Iannelli, & Rivolta, 1995). The longer of the two linear features extends seaward toward the northwest (N330°W) from the present coast for a distance of about 350 m (Figure 3d). The second, much shorter structure (~100 m long), extends from the coast toward the northeast. Immediately seaward of the present shoreline, the base of the longer breakwater is buried by sand and silt at a depth of ~4 m; its upper surface lies at a depth of −3 m (Figure 3c). The upper surface of this structure at its most distal (seaward) position, where it merges with the seafloor, rests at a depth of 9 m below present sea level.

It is likely that a coastal facility now lies buried beneath the alluvial soil cover landward (to the south) of the Trainiti Delta and in the vicinity of the two large wharf-like construction features. This is suggested, albeit indirectly, by the two massive breakwaters that form a semi-enclosed, harbor-like configuration near the present coastline and mouth of the Trainiti River (Figure 3b). This sector is presently under study by means of sediment core analysis, including petrologic examination, compositional analysis of clastic and biogenic content of sediment, and study of anthropogenic remains that have been recently recovered. From preliminary study of cores in the Trainiti Delta just landward of the coast (Figure 3b, locality C), this area appears to have once occupied a nearshore sector as indicated by a ~1 m thick stratum rich in marine vegetal (*Posidonia* sp.) matter (R. Cozza, personal communication, 2011). The vegetal-rich setting, indicating the presence of a sea-grass cover, was positioned close to the coast, probably after human occupation of a terrestrial zone in pre-Roman time.

Measured subsidence rate

The upper surface of the longer breakwater is used here as a gauge for measuring subsidence of the Hipponion inner shelf. Assuming the structure was originally constructed to an elevation of ~1.0 m above former sea level (estimated functional height), the long-term average rate of subsidence of the coastal structure has ranged from ~0.8 mm/yr near the present coastline, to as much as ~3.2 mm/yr at a distance of about 300 m seaward of the present Trainiti River shore. To this can be added findings of small (to 1.5 cm) fragments of ancient artifacts discovered at a depth from 9 to 10 m below msl in one of several cores collected in the Trainiti Delta a short distance landward (~30 m) from the coast (Figure 3b). The archaeological material, if released at the shore and *in situ*, indicates an approximate long-term average subsidence rate to ~2.6 to 2.8 mm/yr, that is, within the range of the breakwater's rate of submersion.

Controlling factors

The Capo Vaticano area is one of the most tectonically active sectors of the Calabrian arc, with tilting of cape terrains seaward toward the northeast (Tortorici et al., 2003). Geological studies, both on land and offshore, provide an ample record of Quaternary structural displacement, including vigorous uplift rates (to nearly 2 mm/yr; Bianca et al., 2011), ongoing fault motion (Tortorici et al., 2003), and powerful earthquake activity, some producing tsunamis affecting the study area coast (Piatanesi & Tinti, 2002; Anzidei et al., 2006; Cucci & Tertulliani, 2010). Examination of tectonic patterns indicates that terrains underlying the alluvial plain cover, between the base of raised terraces and adjacent offshore sector, were displaced by still-active uplift motion and effects of associated major normal faulting (Antonioli et al., 2009). These have led to distentional and some rift-type dislocation in Holocene time (Cucci & Tertulliani, 2010; Bianca et al., 2011). In addition to seismo-tectonic effects, the role of sediment compaction occurring beneath the large breakwaters, due to their mass, cannot be excluded.

Locri-Epizefiri and Kaulonia

Coastal facilities

Archaeological features at two Greek settlements located on Calabria's straight, northeast-southwest trending Ionian margin are considered here: Locri-Epizefiri and Kaulonia (Figure 1, sites 3 and 4). They are discussed together in this section since both are positioned within the Locride geological province. Recent archaeological studies of Locri-Epizefiri, settled in the late 8th or early 7th century B.C., include those by Costamagna and Sabbione (1990) and Barra Bagnasco (1999), the latter publishing numerous research articles that pertain to this site for more than a quarter of a century. The walled town is located along the coast between the Portigliola and Lucifero rivers, and about 3 km southwest of the modern town of Locri (Figure 4a); it is backed by hills that rise to 150 m within the boundary of the site. Kaulonia, founded at about 700 B.C., is positioned along the coast ~37 km northeast of Locri, and just to the north of the modern town of Monasterace Marina. Terrains within the town's walls rise from sea level to 70 m above msl; two major landmarks, the Assi River and Squillace Gulf, are located to the north of the site (Figure 5a). Archaeological vestiges on land at Kaulonia have been studied by Iannelli (1985, 1992, 2005) and Barello (1995), while abundant anthropogenic remains on the seafloor have been detailed by divers (Lena, 1997; Lena & Medaglia, 2002; Lena & Iannelli, 2003; S. Mariottini, personal communication, 2003). Geoarchaeological analysis of the studied coastal sectors has been made by means of high-resolution subbottom seismic profiles obtained seaward of the two sites, and by cores (Figure 5a) recovered just landward of the coast (Stanley et al., 2007; Bernasconi & Stanley, 2011).

The major anthropogenic feature recorded off the Locri site is a massive, elongate (~65 m long) buried structure detected on several high-resolution subbottom seismic profiles (Figure 4b, 4c). This feature is positioned ∼200 to 250 m off the present Locri shoreline and seaward of the Greek stoà and coastal marine basin now on land (Figure 4a). On seismic profiles, it appears as a near-transparent, poorly stratified lens with a thickness of at least 2 m (low-amplitude lens, in Figure 4b, 4c) and is interpreted as a breakwater (Tennent et al., 2009; Bernasconi & Stanley, 2011). This feature lies buried by >1.5 m of stratified sediment, mostly sand, that forms the core of what in plan-view appears as a large, angular, hook-shaped mass of sediment ∼450 m long with an average width of ∼200 m. The sediment mass forms a low rise on the seafloor surface and extends seaward, toward the NE, from the present coastline (Figure 4a). The top of the lens lies at a depth of about 5–6 m below msl, and the structure's upper surface is assumed to have been originally constructed at ∼1 m above msl (its functional height).

The inner shelf area off the coast of Kaulonia is covered by sand, coarse fluvial debris (cobbles and boulders; Figure 5b, 5c) derived from the Assi River, and massive slabs of beachrock strata (Figure 5d, 5e). These, in turn, are littered with abundant large and widely dispersed archaeological materials that cover an area of 200 by 300 m and are attributed a Greek age (Iannelli, 1997; Iannelli, Lena, & Mariottini, 1993; Parra, 2001; Medaglia, 2002). Archaeological debris includes numerous large sections of Greek Ionic columns, diverse construction blocks, a bollard, and other anthropogenic materials that lie at water depths ranging mostly from 5 to 7 m below msl (Figure 5b, 5c). These materials are dispersed to ∼300 m off the present coast on what has been interpreted as a broad arcuate headland that was subaerially exposed in the late Holocene (Stanley, 2007). The large debris field positioned over an extensive surface area, some of it formed by beachrock strata, has recently been interpreted as a now-submerged remnant of a Greek work area. This sector was once exposed landward of the shoreline and elevated to a functional height of at least 1 m, and possibly more, above msl (Stanley, 2007; Stanley et al., 2007).

Measured subsidence rates

Off Locri, a total minimal lowering of 6 m is calculated for the buried breakwater feature, and this is used to estimate a calculated long-term subsidence rate of ∼1.6 mm/yr. At Kaulonia, numerous archaeological features (columns, construction blocks, and other) resting on a work surface in the beach area were lowered by 6–8 m since Greek time, and this surface subsided at an average rate ranging from ∼1.6 to ∼2.4 mm/yr.

Controlling factors

Submergence offshore at sites (3) and (4), as in the case of previously discussed sites (1) and (2), is associated with combined late Holocene sea-level rise and tectonic displacement of adjacent terrains, including long-term average uplift to ∼1 mm/yr of terraces on land that back the shore. Landward of both the Locri and Kaulonia settlements are strata of Pliocene to Quaternary age that have been deformed and offset by faults (Gasparini et al., 1982; Sorriso Valvo, 1993; Dumas et al., 1995; Bordoni & Valensise, 1998; Ferranti et al., 2006). Seafloor lowering is likely associated with faulting and deformation of the substrate (Tennent et al., 2009). Geoarchaeological study indicates that, as a result of these controlling parameters that affected land and offshore terrains, both settlements experienced significant back-and-forth shifts of coastline and changes of sea-level positions during the mid- and late Holocene to the present (Stanley, 2007; Stanley et al., 2007; Bernasconi & Stanley, 2011).

Since the md-Holocene, shorelines at both sites advanced landward, and then moved back seaward before, once again, shifting landward. While in some ways similar, the back-and-forth coastline displacements were not synchronous at the two localities, and Locri and Kaulonia settlements were affected in a somewhat different manner. At Locri, the Greeks built their city and coastal facilities following a time of maximum shoreline advance landward, while at Kaulonia construction occurred along the coast, partially on a beachrock surface (Figure 5a, 5d, 5e), after the shoreline had already returned seaward by several hundred meters. The nonsynchronous timing of coastline migrations at Locri and Kaulonia likely resulted in part from different periods of accelerated Holocene uplift of the terrains that underlie the two settlements (Stanley, 2010: Figure 2.5). Support for this hypothesis is provided by the presence of several major faults that offset and separate the two study localities positioned along this coastline during the Holocene.

Offshore Capo Colonna and Crotone Peninsula

Coastal facility

A conspicuous feature seaward of Calabria's Crotone peninsula is positioned southwest of the Capo Colonna headland (Figure 1, site 5); it is the deepest of the five coastal facilities examined in this study. The structure is submerged ∼250 m from the Ionian coast, and its base lies in sand at a depth of −12.5 to −13 m; its upper surface rests at 11 m below present msl (structure AE in Figure 6c, 6d). This distinct, gently arcuate feature, with a marked relief of ∼1.5 m, was discovered in 2005 by means of a multibeam sonar survey and interpreted as a breakwater of Greek age (Royal, 2008). In proximity are two large square rock-cut features (4 by 4 m, and 5 by 5 m) lying about 30–35 m to the northeast of AE and interpreted as probable pier structures (AF in Figure 6c). Another hypothesis was subsequently formulated as to the elongate AE feature's origin, one emphasizing primarily its considerable depth, length (~42 m), and distance from the coast. Based on these attributes, a natural marine beachrock origin, and not one of anthropogenic origin, was proposed by Bartoli (2010). However, recent analysis of reprocessed multibeam sonar and direct visual diver and photographic data reaffirmed that the structure was built of stacked calcarenite rocks by human emplacement (Stanley et al., 2012). These rocks, piled without apparent use of a binder or cement (Figure 6e, 6f), present a triangular form in cross-section, with a near-consistent basal width of 6 m (Figure 6d). Examination and photographs of the seafloor, obtained by diving archaeologists, further confirm the original hypothesis that the structure is not a natural beachrock stratum but, rather, a breakwater (Stanley et al., 2012). It was originally constructed at a position nearshore by the Greeks as part of a harbor built along the coast, south of their major city of Crotone and southwest of Capo Colonna (Figure 6b) close to the sanctuary of Hera (Juno) Lakinia (Osanna, 1992; Cerchiai, Jannelli, & Longo, 2004).

Measured subsidence rate

A long-term minimal average subsidence rate of ~4.0 mm/yr is calculated on the basis of available data pertaining to the depth of the breakwater's upper surface of probable Greek age.

Controlling factors

Moderate to large blocks of calcarenite concentrated on the inner to mid-shelf surface of this area were derived from strata that once formed the cliffs of the Crotone peninsula coast. The cliffs were undercut by wave erosion resulting in large slabs toppling onto the adjacent beach and inner shelf. Some movement seaward of blocks of variable size was also triggered by gravity flows (cf. Middleton & Hampton, 1976), including slides and slumps (Lena et al., 2003). The continuous elongate and unbroken configuration of the submerged stacked rock feature examined here indicates that it has not been subject to substantial lateral displacement by a turbulent slump event. The possibility of some lateral gravitative shifts along a near-horizontal slide plane at depth, however, cannot be excluded. The detailed multibeam sonar survey of this feature and adjacent areas of the shelf-floor surface provides information as to how such harbor features may have reached their current depth. Distinctive natural structures include a tilted and broken floor offset by sharp linear scarps, terraces, ridges, and graben-like depressions. It is of note that these features have a fresh appearance and are delineated by distinct boundaries. Many are not masked by sand in spite of strong wave-driven bottom currents that, at these depths in this area, have the capacity to readily transport the sand cover and bury small seafloor relief features. To the contrary, the observed distinct seafloor structures record various stages of recent displacement of underlying consolidated strata as a result of tectonic deformation. Submergence of the coastal facilities off Capo Colonna is believed to have occurred by a number of modest tectonic pulses during the Holocene, perhaps some involving periodic lowering by extensional fault motion offshore.

It is recalled that this study area is located in one of Italy's most tectonically active regions, modified by powerful earthquake and seismic activity (Galli et al., 2006) and faulting (Zecchin et al., 2003), with rise, lowering, and/or some strike-slip motion of adjacent land terrains (Zecchin et al., 2010). Considerable attention has been paid to the seismic framework, stratigraphy, and complex neotectonic structure of the Crotone geological basin forming the adjacent landmass (Figure 6a; Van Dijk, 1991; Zecchin et al., 2003; Mellere, Zecchin, & Perale, 2005; Valenti, 2010). Displaced terrains on land, such as uplifted terraces (T in Figure 6b) and those of the substrate submerged offshore (Finetti & Morelli, 1973; Udias, 1985; Pirazzoli et al., 1997; Antonioli et al., 2009), record extensive regional, and local neotectonic responses to contact of the African against the southern European plate in this region.

SITE-TO-SITE SUBSIDENCE VARIABILITY

The observations summarized in the previous sections indicate that the positions of modern Calabrian shorelines at four of the examined localities (sites 1, 3–5) differ considerably from those that existed at the time of Greek and early Roman populations. Coastlines at sites 3–5 along the Ionian margin have advanced landward by 200 m or more, submerging what were once subaerially exposed and settled coastal terrains. Each of these three nearshore localities was affected by the world sea-level rise and seismo-tectonic lowering of former land surfaces in the late Holocene. Moreover, submergence at sites 2 and 5 occurred by particularly rapid rates of relative sea-level rise during and following human occupation.

Subsidence has been relatively minor at some localities (site 1), whereas submergence in others resulted from stronger and more numerous tectonic pulses (site 5). The sudden failure of sites in this region was also induced by climatic triggering that affected sedimentation locally, such as deposition by fluvial flooding and by wave erosion and storm surges (site 1), and/or by tectonic motion including earthquakes (among the strongest in Italy) and associated tsunamis (site 2). Each of the five localities has been modified by a different set of interactions that have involved two or more major controlling natural parameters. It is this diverse interplay of natural factors through time that has induced highly variable average long-term rates of coastal subsidence from site to site along the tectonically active Calabrian margin. As a result, we find that, excluding world (eustatic) sea-level rise, the role of subsidence during the past ∼3000 years in the late Holocene has ranged from a modest ∼0.5 mm/yr to a remarkably high ∼4 mm/yr.

Since the time of Greek occupation, coastal margins seaward of shorelines at the five sites have been modified in several ways. In all cases, glacio-hydro-isostatic factors and associated sea-level rise have had a role in submergence of coastal margins. However, it is the interaction of these factors with several other parameters that has induced the large variability of coastal submergence rates recorded among the Calabrian sites examined in the late Holocene. These other factors include (1) a high rate of sediment accumulation, (2) accelerated sediment erosion, (3) compaction of substrate sections, (4) role of mass gravity failure leading to slides and slumps and displacement seaward of sediment and rock to greater depths, and (5) substrate lowering resulting from seismo-tectonic readjustments and shifts of sediment sequences at variable (shallow to considerable) depths of the surface and subsurface underlying former coastal facilities. In contrast, geological studies conducted in this region during the past century recognized that much of the Calabrian land mass shoreward of the coast has been subject to uplift, especially from the mid-Pleistocene to the Holocene. Thus, seismo-tectonic activity has induced both land uplift and submergence of offshore margins by extensional fracturing and increased vertical steepening of seafloor surfaces (Gamberi, Rovere, & Marani, 2011)

As a result of the various interactions, archaeological materials at Sybaris-Thuri are now landlocked and buried at about 2.5 km landward of the present Gulf of Taranto shore, while those at Hipponion appear to have been actively lowered in proximity to the Tyrrhenian coast. Moreover, as a function of shorelines that have markedly shifted landward, coastal facilities at the three Ionian margin sites (Locri-Epizefiri, Kaulonia, and off Capo Colonna) are now submerged ∼200 to ∼300 m from the present shoreline. The seafloor on which anthropogenic structures and artifacts are positioned is usually associated with recent tectonic deformation, including folds and faults. It is also noted that some submerged coastal facilities (Locri-Epizefiri, Kaulonia, Capo Colonna) lie seaward of, but not distant from, uplifted terraces on land that have risen at long-term rates to ∼1.0 mm/yr. Terraces at Hipponion-Vibo Valentia have been uplifted locally at a somewhat higher rate that has, at times, reached ∼2.0 mm/yr.

It is apparent that neither eustatic sea level rise nor climatic influences (such as thermal expansion of the water column) alone can account for the remarkably different rates of submergence and/or burial of Greek coastal facilities along Calabria's margin in late Holocene time. Rather, the variable displacement patterns of coastal facilities on both the Ionian and Tyrrhenian margins are to a large extent a response to their position on one of the Mediterranean's most tectonically active sectors, the Calabrian arc, at the junction of the mobile North African and European plates.

CONCLUSIONS

This investigation records long-term average subsidence rates of coastal archaeological facilities at five Calabrian sites that range from as low as ∼0.5 mm/yr to as high as ∼4.0 mm/yr during the late Holocene (Figure 7). These values exclude the role of sea-level rise during this period. These observations lead us to expect that other submerged coastal harbor and landing sites, including those of Greek and perhaps earlier age, are yet to be discovered offshore of southern Italy. As has been noted along different Mediterranean margins, measurements of moderate to rapid submergence are not limited to highly tectonically active coasts. For example, in the Western Mediterranean where numerous coastal sites are documented (cf. Flemming, 1969), many are submerged offshore in areas of low to moderate tectonic activity. Also of special interest in respect to rapid lowering are submerged coastal sites that have subsided at rates from ∼0.9 to ∼4.3 mm/yr on the relatively tectonically stable Nile Delta margin (Stanley & Toscano, 2009). The range of land lowering rates off the Egyptian coast, while surprisingly comparable to that of Calabrian margins, is largely a function of the interaction of factors other than those that dominate off southern Italy. In addition to hydro-glacio-isotatic parameters, these include the impact of climate and generally high depositional rates, extensive sediment compaction of water saturated fluvio-deltaic substrate sequences of Holocene age, and remobilization and displacement of older strata at shallow to great depths beneath the modern Nile Delta surface.

Increased geoarchaeological databases pertaining to Magna Graecia coastal facilities are deemed essential for updating the study of early settlements where the past populations were involved with nautical activities, especially regional and long-distance trade. Extensive changes in relative sea level that we have identified here would almost certainly have impacted such coastal activities during and following Greek time. To obtain more precise measurements with which to calculate subsidence rates and relative sea-level rise and better evaluate their impacts, there is a continuing need to (1) more precisely date ancient archaeological structures and materials discovered beneath and seaward of coasts and (2) to use updated sea-level curves for the region as they become available. For example, it may eventually be determined that sea level ~2500 years ago was −1 m and not −2 m lower than present msl, and/or that the archaeological materials considered are actually younger than presently indicated. The recalculated average annual rates of subsidence using such revised databases will prove to be considerably higher than those estimated in this study. In turn, such revised values will likely suggest even greater rates of shoreline shifts and submergence of coastal facilities during this relatively short (<3000 years) time period.

In addition to fulfilling archaeological needs, measurement of reliable subsidence rates has direct practical implications for assisting present human populations living in rapidly evolving coastal settings such as those in Calabria. Archaeological vestiges that provide information on land motion in times past will increasingly serve as valuable gauges to more accurately predict future changes in relative sea level. It is thus anticipated that increasingly accurate measurements of land motion based on dated past human activity can provide coastal engineers and managers with needed supplemental databases. It will be useful to apply these gauges to assist in the planning, devising, and implementing of protection measures for those Calabrian shoreline sectors particularly susceptible to coastal submergence and rapid relative sea-level rise.

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