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Coast of Ancient Kaulonia (Calabria, Italy): Its Submergence, Lateral Shifts, and Use as a Major Source of Construction Material

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ABSTRACT

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Divers in the 1980s discovered a large concentration of archaeological material on the seafloor off Kaulonia, a Greek colony on the Ionian coast of southern Italy. It has been proposed that a small hook-shaped cape, now submerged, was present off the site during settlement from about 700 to 389 BC. Since 1992, however, most of Kaulonia's seafloor sector has been buried by a thick (to 4 m) sand cover. This investigation resumes study of Kaulonia's margin by high-resolution seismic survey, analysis of sediment in cores and excavated sections buried along the coast, and petrologic examination of rock used for construction of a temple, the site's major structure. The sector, located in the tectonically active Calabrian arc, has been subject to considerable elevation rise of land onshore, and an equivalent rate of seafloor subsidence (~1 mm/yr). A distinct Holocene sequence, composed of beachrock-type sandstone and fluvial-marine-transported conglomerate, in sediment sections landward of the beach can be traced seaward to depths of ~7 m about 300 m from the present shoreline. Correlation of the sequence helps define changes of coastline position from before Greek settlement to the present. Rather than a generally progressive migration landward of the shoreline in response to relative sea-level rise, the coast has experienced more complex shifts (sea-to-land, land-to-sea, and return to land) due to up-and-down motion in the sector between the alluvial plain behind the beach and innermost shelf. By the mid-Holocene, the shoreline had advanced seaward, resulting in coastal emergence, and it did not return landward (resubmerging the margin) until after the site's abandonment; submergence was complete by late Roman time. We now recognize a broad arcuate headland, rather than a small hooked cape, seaward of the site ~2500 years ago. Without a lagoon, sufficiently deep lake, or man-made port available for protected anchorage, vessels sailing to Kaulonia for trade were either beached or anchored close to shore and, perhaps seasonally, within the mouth of the Assi River. Composition of beachrock-type sandstone in Holocene sections on land is comparable to that offshore and also to sandstone used for temple base construction. Extensive sandstone exposures along this coast may have been one reason why Greeks selected the site for settlement.

ADDITIONAL INDEX WORDS: *Archaeological material, beach processes, beachrock, building material, coastline shift, cores, faulting, land uplift, late Holocene, seismic survey, submerged cape, subsidence, temple, wave erosion.*

INTRODUCTION

Ancient Kaulonia is positioned immediately north of the modern town of Monasterace Marina on the Ionian Sea coast of Calabria in southern Italy (Figure 1). This small Magna Graecia colony was founded at about 700 BC by Achaean people from the Peloponnesus, and possibly by settlers from Kroton (Crotone), another Greek site farther to the NNE on the Ionian coast. In 389 BC, Dionysius first conquered Kaulonia and deported the population to Locri (COLDSTREAM, 1977; IANNELLI, 1985, 2005; ORSI, 1916; RANDALL-MACIVER, 1931; SCHMIEDT, 1975; TREZINY, 1989). The settlement was rebuilt, and a necropolis on a hill behind the coast is attributed to the Brettii (a nomadic, war-like Indo-European tribe) in the third century BC. In 205 BC, the town was once again conquered, this time by the Romans.

Major initial excavations at the site were conducted in the early part of the twentieth century (ORSI, 1916), and subsequent archaeological investigations have continued actively to the present (IANNELLI, 1992, 1997; IANNELLI *et al.*, 1993; MEDAGLIA, 2002a, 2002b; PARRA, 2001). The major structure at Kaulonia is a Doric temple, dated to 430–420 BC and located in the eastern part of the settlement about 100 m from

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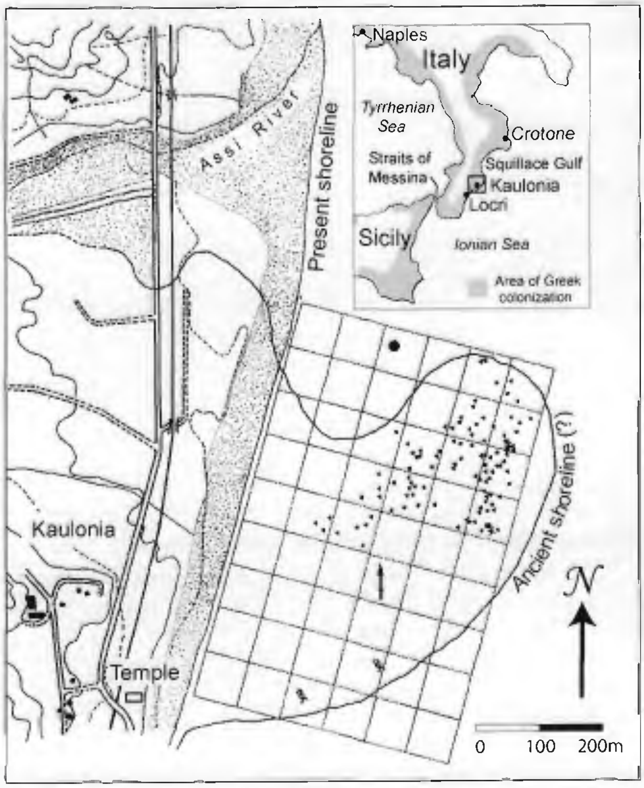

Figure 1. Map showing Kaulonia (about 1 km north of the town of Monasterace Marina) on the Ionian coast of southern Calabria, Italy (inset). Small dots east of the present shoreline show distribution of archaeological material discovered offshore by diver surveys. Line delineating submerged material has previously been believed to indicate a small, now-submerged, hook-shaped cape at time of the Greeks, as proposed in previous archaeological studies (after Iannelli, 1997; Iannelli *et al.*, 1993; Lena and Medaglia, 2002).

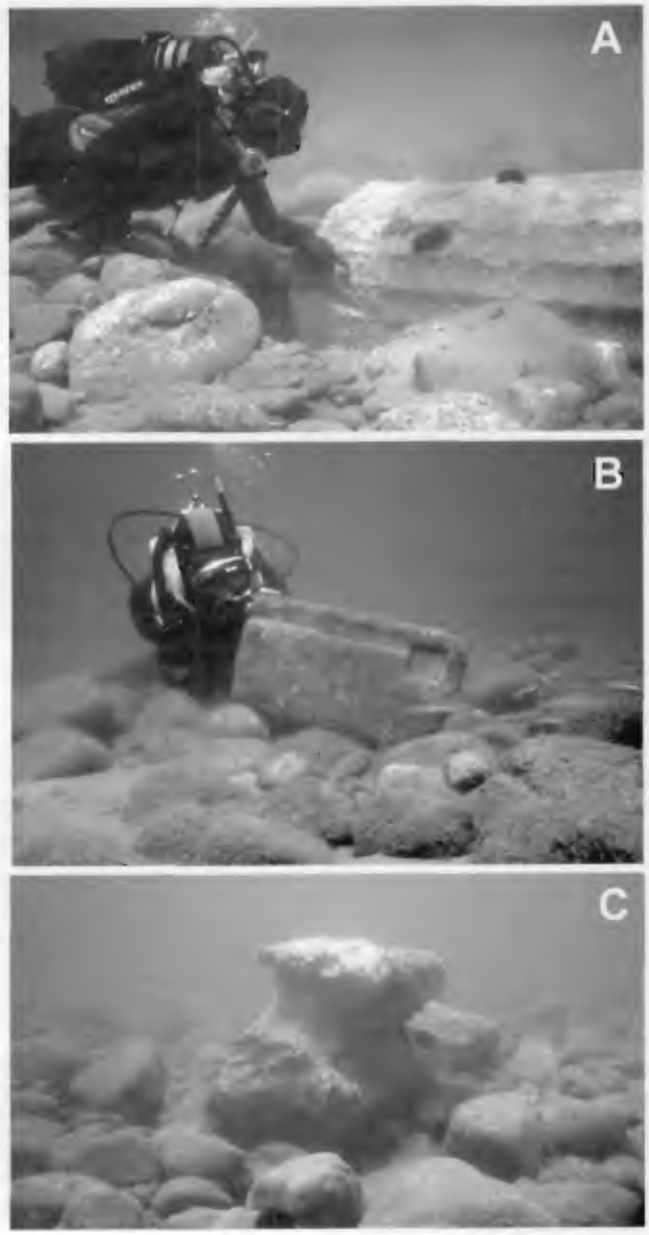

Figure 2. Underwater photographs taken in the 1980s show examples of archaeological material off Kaulonia, including (A) fluted Ionic column section, (B) construction block, and (C) bollard (after IANNELLI, 1997; IANNELLI *et al.*, 1993). Large, rounded boulders (some to >50 cm diameter) of igneous and metamorphic material of Assi River derivation (Figures 8D–E) are widely distributed in this offshore sector (photos by S. Mariottini).

the shoreline (Figure 1). Only the base of the temple, formed of weathered cut stone, remains in place; ongoing excavations are still recovering other parts of this structure. The temple is positioned on a narrow, terrace-like alluvial plain (to ~120 m wide) that parallels the coast and gently slopes seaward. The lower plain lies at an elevation of about 10 m above mean sea level (m.s.l.), between the base of low hills to the west and coastal dunes to the east. The temple and other excavations have been described in ORSI (1916) and in subsequent archaeological reports (summarized in BARELLO, 1995; MERTENS, 1976; PARRA, 2001). Subsurface studies of the soil cover and underlying sediment sequences at this locality have previously been made by means of short (1–4 m) borings (FONDAZIONE ING. G.C.M. LERICI, 1982) and shallow-penetration (<3 m) georadar profiles (LERICI PROSPEZIONI ARCHEOLOGICHE, 2002).

Among more recent exploratory surveys at Kaulonia are those that focus on archaeological finds discovered offshore by diver surveys. These have described numerous ancient column sections, construction blocks, and other materials (Figure 2) that are positioned offshore, mostly from about 100 to 300 m seaward of the present shoreline and at water depths of ~5 to 7 m. Investigations to date have suggested that the objects had once been placed on a small cape-like headland (Figure 1) called Punta Stilo (or cape of columns), which presumably subsided in the late Holocene and is now entirely submerged (IANNELLI, 1997; IANNELLI *et al.*, 1993; LENA and IANNELLI, 1996; LENA and MEDAGLIA, 2002; MEDAGLIA, 2002a, 2002b).

In this investigation, several still-undefined aspects are considered with respect to Kaulonia's coast, including: (1) how abundant anthropogenic material and underlying substrate were submerged to their present considerable depth seaward of the site; (2) to what extent such materials and substrate were related to a previously postulated and now-submerged cape; (3) in what manner this coast evolved before, during, and following time of Greek settlement; and (4) the extent to which natural materials, once positioned along the coast and now under the waves, were used by the inhabitants for construction at the site. New findings for this geoarchaeological study were obtained by means of a high-resolution subbottom seismic survey conducted offshore and by lithofacies analyses of sediment recovered in cores and excavations on the landward margin of the coast. A petrologic examination was also made of some cut sedimentary rock used at the archaeological site to determine if perhaps such material may have been derived from once-exposed nearshore sectors that are now submerged offshore.

GEOGRAPHIC SETTING AND HISTORICAL BACKGROUND

The walled land area once occupied by the colony of Kaulonia was roughly pentangular in shape (SCHMIEDT, 1975). The western sector of the site, which includes the area of the recently discovered ancient necropolis (IANNELLI, 2005), rises to an elevation of ~70 m above mean sea level (m.s.l.); these hills are formed of marine and terrestrial sediment strata of Pliocene and Quaternary age. To the east, the site's coastal margin is ~1 km long, straight, and trends SSW to NNE (Figure 1). The main complex of archaeological structures is positioned on a narrow, soil-covered alluvial plain that slopes seaward from ~20 to 8 m above m.s.l. This plain is bounded on its seaward margin by sand dunes (some of them fossil), which form what is referred to here as a 10 m terrace. Below the plain is the much lower, coarse-textured (sand, granule, and pebble) beach. The linear shoreline north of the site extends to the Assi River mouth and gently arcuate Punta Stilo headland, both mentioned by PLINY THE ELDER (1887) in his *The Natural History* almost 2000 years ago. Shortly beyond the Assi and Punta Stilo, the shoreline direction shifts northward and forms the western coastal margin of Squillace Gulf (Figure 1).

At some earlier time in the Holocene, the mouth of the Assi River was located much farther offshore, perhaps by as much as 500 to 600 m southeast of the present fluvial course. The lower channel was thus positioned much closer to what has been identified as the emerged and submerged parts of the site (IANNELLI and RIZZI, 1985). This is denoted by a remarkable concentration offshore of pebbles, cobbles, and boulders, some to >50 cm or more in diameter, derived from the Assi (IANNELLI *et al.*, 1993). The very coarse material, now found offshore to at least 0.5 km SE of the modern river mouth, lies at depths to >5 m (Figure 2).

Divers mapping the seafloor east of the site from 1984 to 1991 indicated that beach-to-offshore profiles were inclined from the coast to a depth of ~6 m below sea level, then leveled or rose to 3.5 m below m.s.l., before again deepening progressively to depths of 20 m and beyond on to the open Calabrian Ionian shelf. Preliminary studies interpreted the nearshore seafloor rise as a drowned coastal berm or dune system, perhaps associated with a lower stand of sea level (IANNELLI *et al.*, 1993). Potsherds and fragments of terra cotta, bronze, lead, and copper were discovered on the seafloor, along with numerous items including large column sections (length to 113 cm, diameter to 80 cm), column bases, rectangular blocks, bollards and anchors, and considerable amounts of smaller rock construction debris. The columns are Ionic and date to about 480–470 BC, by stylistic comparison with similar archaeological materials discovered at the site of Lokroi Epizephrioi (Locri), located on the Ionian coast ~37 km southwest of Kaulonia (inset in Figure 1). The submerged assemblage is concentrated in an area about 250 m × 500 m NE of the Doric temple, suggesting that Kaulonia was probably a manufacturing center as well as one of exchange and trade. THUCYDIDES (1976) in the *History of the Peloponnesian War* also noted the importance of wood at this locale in the fifth century BC.

Previous archaeological studies have considered possible origins of archaeological debris and artifacts positioned at considerable distance (to 300 m) from the present shore. Two initially proposed hypotheses have now been rejected (LENA and MEDAGLIA, 2002): one, that large features such as columns and construction blocks accumulated in this area as a result of shipwrecks; and the other, that these materials had been artificially placed along the shore about 2500 years ago as part of an embankment built for coastal protection of the site. The wide distribution of the materials, along with manufacture debris, over such a large area of seafloor does not favor a predominant release-by-shipwreck postulate. Moreover, lead, a valuable metal commonly found associated with the submerged construction blocks, almost certainly would have been removed prior to placement of such materials as part of a coastal barrier built along the Kaulonia shore. A third hypothesis remains under consideration, *i.e.*, that columns and construction blocks may have been transported to the site or manufactured or modified nearshore for building of a temple or other important structure to be assembled at Kaulonia or perhaps at a nearby site. This project apparently was not realized (IANNELLI *et al.*, 1993; MEDAGLIA, 2002b).

Offshore exploration has shown that much anthropogenic material is positioned on, or in proximity to, large cemented sandstone strata that appear detached from each other and are generally little more than 50 cm thick (Figures 3C–E). Some sandstone beds show horizontal and low-angle stratification (Figures 3D and 3E). Breakage of sandstone slabs was a response to weakening, likely by removal of the once-underlying sand and pebbly sand support. Removal of the sandy substrate from beneath sandstone slabs resulted from strong swash and bottom current activity, especially in winter, when wave surge and associated erosional activity are intensified along this coast. It is of note that these strata are generally underlain and/or surrounded by large cobbles and boulders (Figures 2 and 3C–E).

Wide distribution of archaeological debris on the sandstone-conglomerate substrate suggests that this offshore area was once a work and anchorage zone. This was likely located

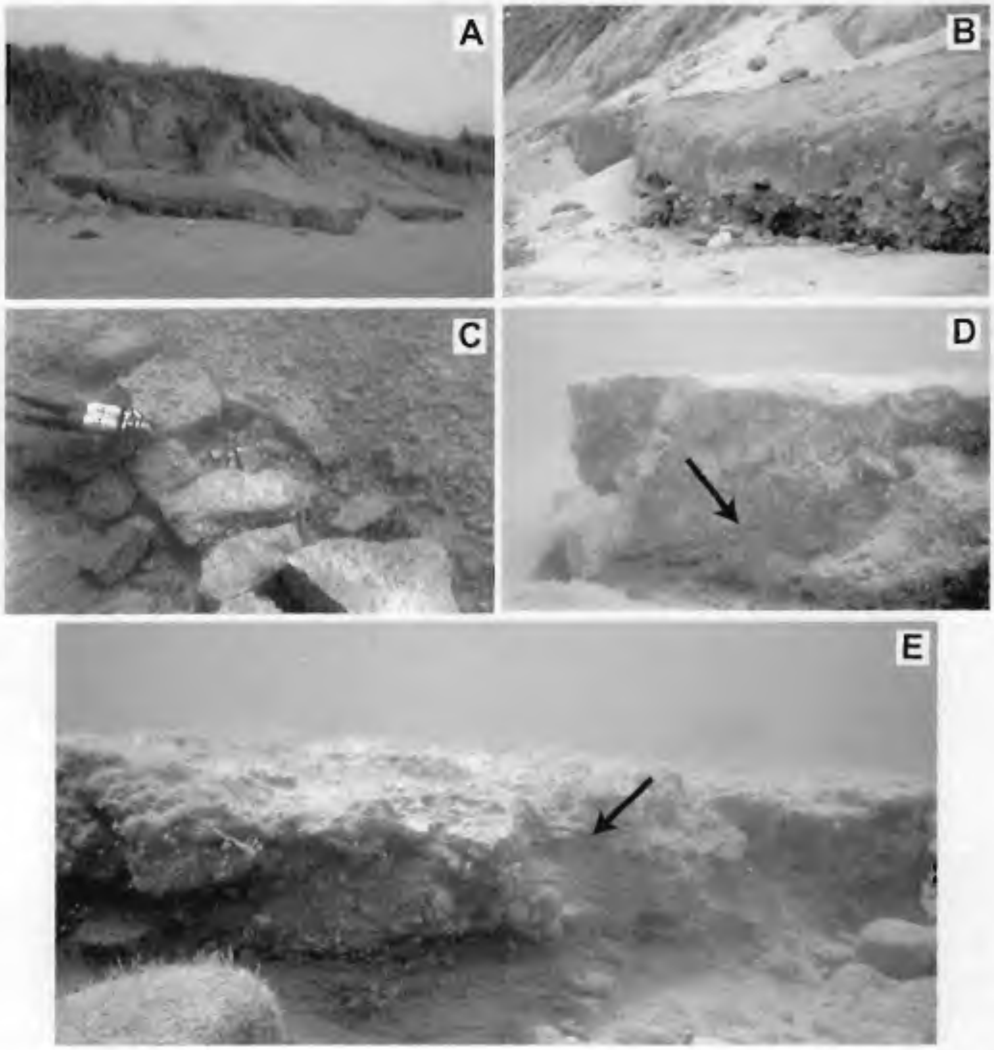

Figure 3. (A) and (B) Photographs (1998) at dune base show ~1-m-thick exposure of a partially consolidated coarse sand unit above a conglomerate, formed mostly of rounded pebbles and cobbles (primarily igneous and metamorphic lithologies). (C) Diver above seafloor surface partially covered by large angular slabs and debris of sandstone and rounded cobbles and boulders. (D) and (E) Close-up of inclined stratification (arrows) in calcareous-cemented sandstone welded to underlying conglomerate comprising pebbles and cobbles in a sand matrix. Photos C–E were taken in late 1980s by S. Mariottini.

at, or proximal to, a sector where columns were loaded and/or discharged from vessels and perhaps also worked upon. It is envisioned that a powerful natural event, or sequence of events, caused anthropogenic materials to be rapidly shifted from what had once been an emerged nearshore sector to one below the waves. The prevailing hypothesis emphasizes that the work area during time of Greek settlement was a small promontory that extended seaward in a NE direction (IANNELLI, 1997; IANNELLI *et al.*, 1993; LENA and MEDAGLIA, 2002). The hook-shaped headland was positioned just seaward of Kaulonia, extending NE of the temple and SW of the present Assi River (Figures 1 and 4).

Archaeological finds used to define the configuration of the cape margin include rectangular blocks (Figure 2B), some shaped for construction of steps, bollards (Figure 2C), and anchors. The step-like blocks may have been used to help load and discharge material from ships anchored close, or attached, to the small emerged cape platform (LENA and MEDAGLIA, 2002). Another argument used to favor the cape hypothesis emphasizes measurements of size, mass, and quality of preservation of submerged column sections and distribution patterns of other debris on the seafloor (IANNELLI *et al.*, 1993). These measurements indicate that larger, better preserved manufactured pieces are positioned farther offshore to the E and NE, presumably at the more distal cape margin located close to deeper water. In contrast, smaller archaeological materials are distributed in shallower water closer to the present shoreline and consequently are less well preserved due to erosion and wear. Major anchorage areas were likely located south and north of the small cape promontory. Archaeologists have not yet specified when the land surface began to subside nor when submergence was complete. How-

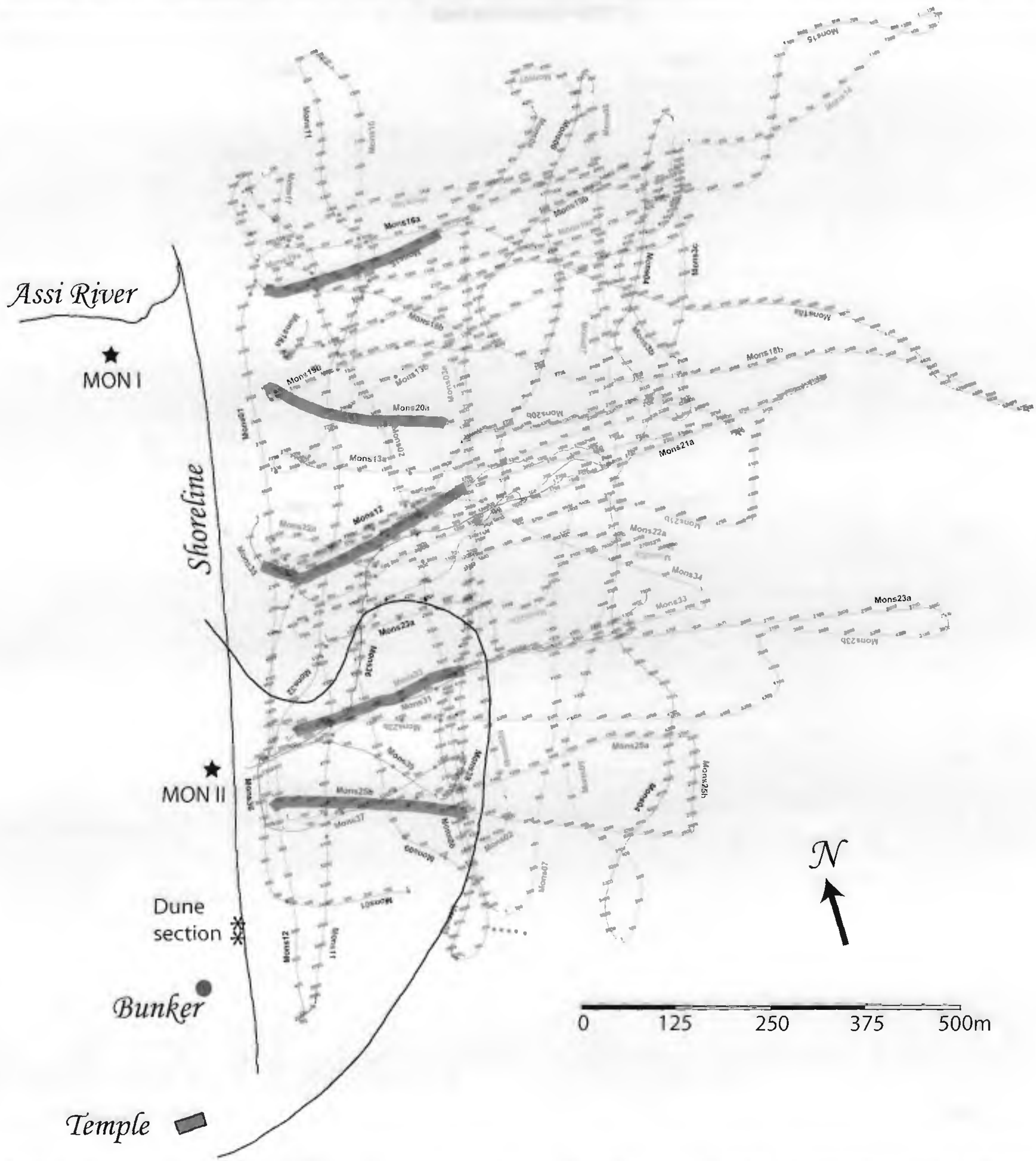

Figure 4. Geophysical survey coverage off Kaulonia. Dark wide lines indicate positions of five coast-perpendicular seismic segments shown in Figure 6. Configuration of postulated small submerged hook-shaped cape is shown, as in Figure 1. Core sites MON I and MON II, dune excavation sites, Doric temple, World War II bunker, and present Assi River channel are also indicated.

ever, it follows that if the cape-like feature was of low elevation above m.s.l., submergence would have occurred shortly (within several centuries) after the columns were positioned on this coastal sector in the fifth century BC. It is possible that the locality had not completely subsided until Roman time, inasmuch as PLINY THE ELDER (1887) refers to the headland as Punta Stilo, or cape of pillars.

By 1992, before additional exploration could detail the origin of this offshore sector, two events caused rapid and almost complete burial of archaeological finds and their substrate by a depositional cover of variable thickness (IANNELLI *et al.*, 1993). At that time, major construction and modification of the port at Roccella 20 km to the south is believed to have altered sedimentation patterns along the coast as far northward as Kaulonia. In addition, intense winter storms subsequently resulted in a landward shift of sand-rich deposits. Rapid burial by the new sediment cover has consequently hampered exploration efforts at the site's offshore sector during the past 15 years.

METHODS

A seismic survey was made over a large sector immediately seaward of Kaulonia in order to once-again pursue research efforts on the former coastal work area and the vessel beaching and anchorage facilities, now submerged. Geophysical data, including a series of closely spaced, high-resolution subbottom profiles, are complemented by petrologic and lithofacies analyses of sediment in the archaeological area. Sections include those in borings of moderate length recovered at two sites just landward of the dunes, and those at excavations in the dunes proper. Moreover, an investigation involving petrologic, petrographic, and age-dating analyses was undertaken to determine the origin of cut sedimentary rock used to construct the temple base and some other structures at the site.

Seismic Survey

The geophysical survey made in July 2004 covered an area of ~1 km², extending from the shallow near-shoreline sector (water depths of −2 to −3 m) to depths seaward of nearly 40 m (Figure 4). A total length of ~37 km of high-resolution seismic profile line was collected, composed of 48 transects (average length of 0.8 km/line). The survey area was crisscrossed by a series of coast-parallel (averaging ~1.3 km in length) and coast-perpendicular (averaging ~0.5 km) lines. Spacing between geophysical profiles ranged from <50 m to 200 m. The seismic survey methodology is detailed in the Appendix.

Core Drilling and Dune Excavation

Two continuous drill cores were obtained approximately 575 m apart on the terrace-like lower alluvial plain located just landward of the dune system (Figure 4). These were recovered using a track-wheeled mounted Clivio 600 rotary drill rig, with a core diameter of 101 mm. Core MON I, at a ground elevation of +3.0 m, was positioned about 170 m south of the main Assi River channel. Core MON II, at a ground elevation of 4.5 m, was collected ~420 m north of the temple (Figure 4). Boring lengths were 20 m (MON I) and 16.8 m (MON II). Core samples are retained at the University of Calabria, Cosenza, for additional petrologic, faunal, floral, and age-dating analyses. Petrologic and dating investigations were also made of sediment in trench excavations at the basal seaward margin of dunes, ~220 m south of core MON II and 210 m north of the temple (Figure 4).

Temple Base Material

The base of the Doric temple, largest structure at the site, is about 42 m in length by 20 m in width and is formed by numerous rectangular blocks of cut rock stacked upon each other. A cursory examination might suggest that this base is formed of tan to gray, poorly cemented limestone, but petrographic analyses show that the now extensively weathered material is primarily a detrital sandstone. It is made up of mostly noncarbonate sand-sized particles bound by dolomite, high Mg-calcite, and weathered argillaceous material, which in thin-section appears as a matrix paste between framework grains. A set of 14 samples of temple base material was texturally and petrographically analyzed, with a focus on identification of composition of clastic grain components, some minor associated faunal assemblages, and cement and matrix. Radiocarbon (accelerator mass spectrometry [AMS]) dates were also obtained for three temple base sandstone samples.

OBSERVATIONS

Seismic Profiles

Geophysical profiles provide information on the configuration of subbottom strata to depths of about 7 to 8 m (~10 ms) beneath the sediment-water interface. Most profiles record a distinct, subbottom reflector that can be traced from nearshore to the inner shelf (Figure 6). Coast-perpendicular lines show a former incised seafloor form that begins about 75 m to 120 m from shore; the incision is positioned somewhat closer to the coast in the north. This feature is buried by the recently emplaced (post-1991) unconsolidated sediment cover of variable (to ~4 m, or ~5 ms) thickness (rc = recent cover, in Figure 6). The cover is thinner (~2 m) to the south. Diver observations indicated that by 1992 this deposit had covered most of the archaeological remains, and it consisted mostly of sand of medium to coarse size and granules. The sand layer is mobile and can be displaced by bottom current activity, and thus its thickness is seasonally variable.

A number of seismic profiles were obtained specifically across the margins of the postulated submerged small hooked cape shown on Figures 1 and 4. However, none of these lines reveals the presence of well-defined fault offsets and scarps as would be expected at the edges of a large coastal feature that has recently subsided (Figure 6, geophysical lines Mons 25 and 33; Figure 5, lines 09 and 06). Rather, all seismic lines obtained perpendicular to the coast, from N to S across and beyond the postulated cape, show the hard reflector dipping seaward in similar incised manner to a depth of about 7–8 m below m.s.l. (~10 ms). This surface then becomes near-hori-

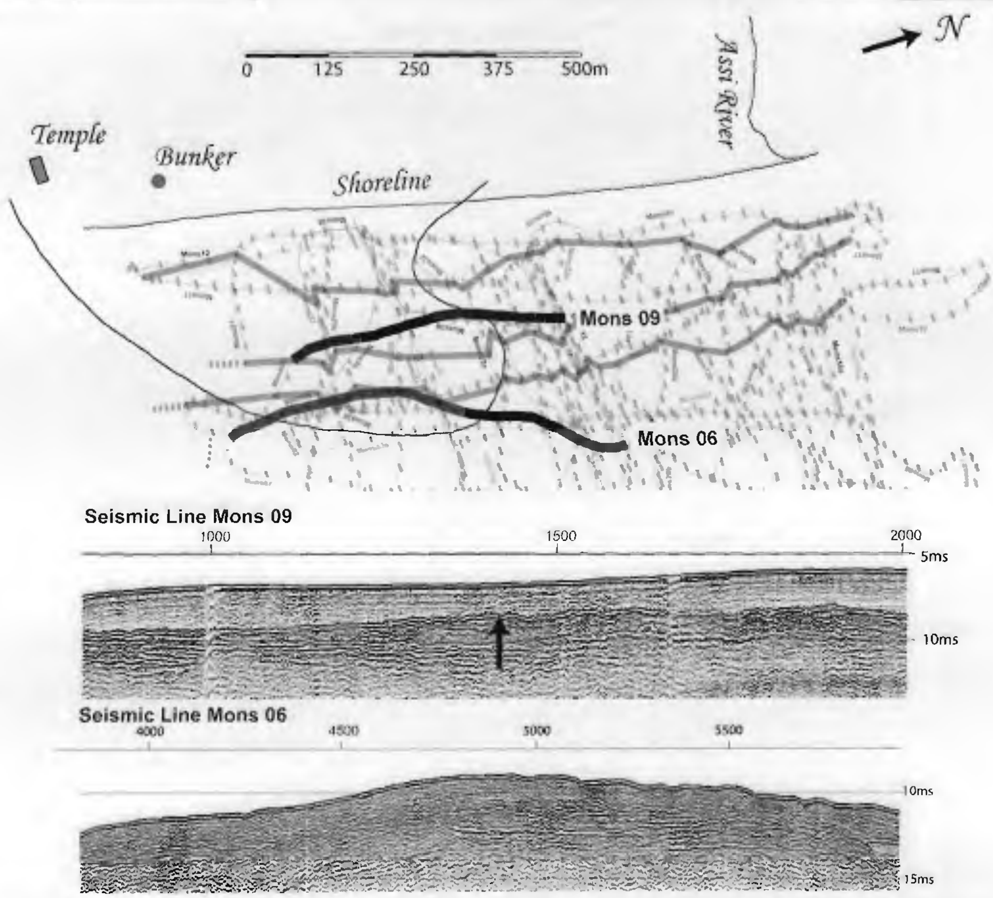

Figure 5. Two coast-parallel seismic lines (Mons 09, Mons 06) that extend across a postulated submerged small cape. Subbottom records do not record fault traces or scarps as expected at margins of such a recently subsided cape.

zontal, or locally rises back up by one to several meters in a gentle offshore bar-like fashion, before again deepening progressively seaward. The distinctive step-like shape defined by the hard reflectors is similar in form and depth on all cross-section profiles, varying only in horizontal width, from 125 to 200 m (Figure 6). It is significant that this buried step-like feature is apparent on all profiles in the study area, both within the sector of the presumed recently submerged cape, as well as sectors north and south of where this small headland was supposedly positioned (Figure 6).

The present seafloor in the study area now appears as a smooth, almost featureless, gently seaward-sloping surface as a result of burial by recent sediment. The deepest part of the depression in the underlying, once-exposed step-like feature is oriented parallel to the entire coastline throughout the Kaulonia area surveyed. The configuration and depth recorded by the hard acoustic reflectors in the subsurface closely approximate those formed by the cemented sandstone slabs and associated layers of pebbles, cobbles, and boulders examined prior to their rapid burial by sand in the early 1990s (Figures 2 and 3C–E). Up to that time, most archaeological materials and construction debris had been identified and carefully located on maps but had not been recovered. Thus, they are still positioned directly upon these distinct strata, but now lie beneath the recently deposited sediment cover.

Sediment Sections at Kaulonia

Substrate sediment on land at the site was previously examined in more than 100 short (1–4 m) cores collected primarily for archaeological exploration. These are formed primarily of unconsolidated sand, granule, pebbly sand, and sandy pebble strata under a thin soil cover (Fondazione Ing. G.C.M. Lerici, 1982; Lerici Prospezioni Archeologiche, 2002). The base of these small borings only reached elevations of one or more meters above m.s.l., and they did not recover cemented sandstone and coarse cobble units of the type observed offshore. Petrologically, the gray sands and pebbly sands are similar to the upper 1 to 4 m sections in the two much longer cores collected on land, at sites MON I and MON II (Figure 7).

A distinct ~40-cm-thick coarse-grained (pebble to cobble) horizon was collected in boring MON II at a depth of 5.0–5.4 m beneath ground surface elevation; conglomeratic material was as large as could be retrieved by the drill core with a 10 cm diameter. In addition, a poorly cemented coarser sand lay-

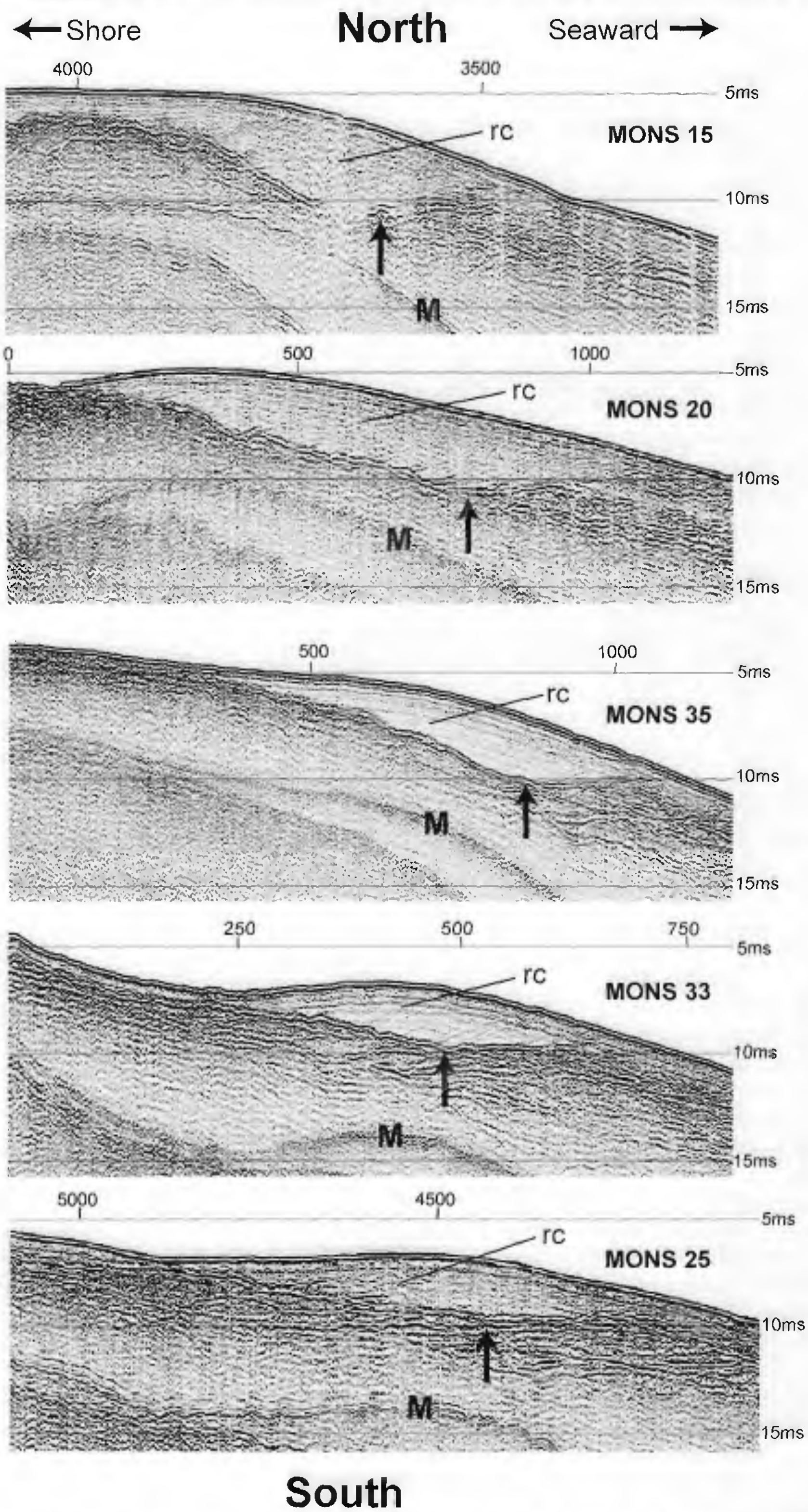

Figure 6. Five short segments of seismic lines perpendicular to the coast show incised configuration of seafloor on which archaeological material is positioned (locations in Figure 4). Distinct hard reflectors (arrows) record incised wave-cut features of identical depths and similar widths (~125–175 m). Note recently deposited (post-1991) sand cover (rc). M = multiple. Depth scale in milliseconds (ms); 1 ms penetration in subbottom sediment is about 0.7 to 0.8 m.

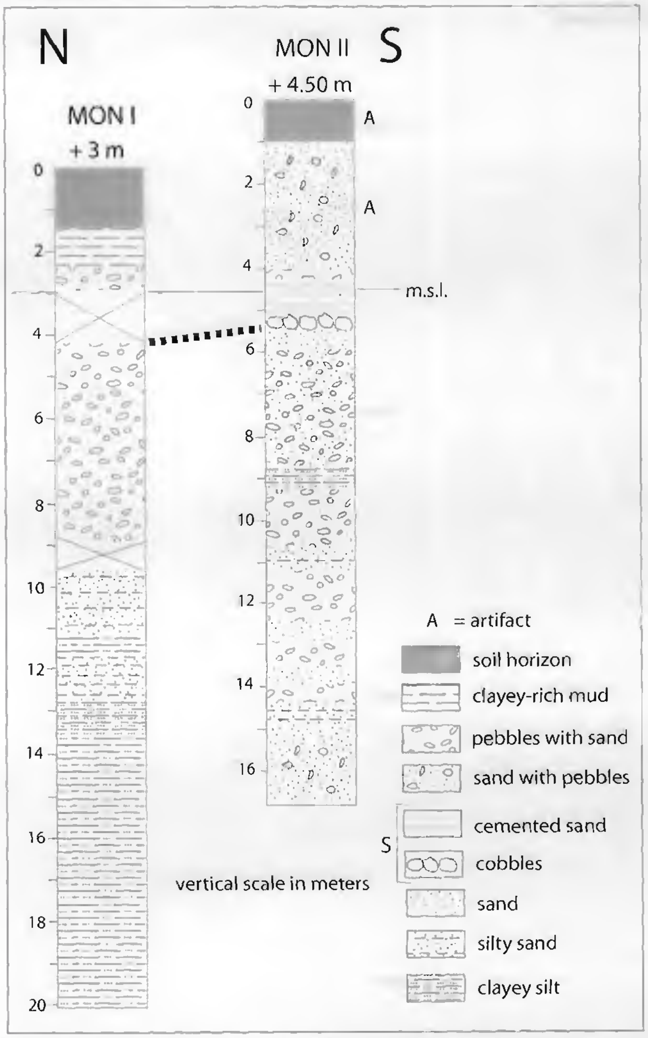

Figure 7. Lithologic logs of two drill cores (MON I, MON II) recovered at Kaulonia (sites shown in Figure 4). Partially consolidated sand-coarse conglomerate sequence (s) in MON II is at ~4.5 to 5.5 m from core top. (A) Potsherds of Greek origin. Dates for the sand-conglomerate sequence (s) were obtained on a prorated basis (depth of sand beneath Greek artifacts; assumes continuous sedimentation and no hiatus), and by radiocarbon (AMS) dating analysis of the sand's carbonate cement and matrix. See discussion in text.

er, ~50 cm thick, was recovered immediately above the conglomerate. This partially consolidated sandstone-conglomerate sequence is positioned at about present m.s.l., that is, at an elevation much higher (by nearly 5 m) than that of this sequence offshore. In core MON I, a difficult-to-penetrate stratum, almost 1 m thick, was encountered between 3 and 4 m below the core top (also positioned at an elevation of about −1 m beneath m.s.l.). The core barrel at this site did not recover sediment, likely a result of very coarse material encountered at that depth.

The sand to pebble and coarser fractions in both cores consist of mainly igneous (granitic) and metamorphic (mica schist) lithologies representative of exposures eroded by headwaters of the Assi River in the Serre Mountains (IBBEKEN and SCHLEYER, 1991). These materials are closely comparable to the bed load of the lower fluvial channel of the modern Assi River, which, during heavy rainfall (October to April), still transports sand and coarser sediment to the coast (Figures 8D–E). The lower 6 m of core MON I, positioned at an elevation of ~9 m below present m.s.l., is a grayish-green (5GY 6/1), finer-grained silt to clayey silt unit without fauna. It is of probable nonmarine origin, and likely of Pleistocene (unspecified) age, largely on the basis of lithological similarity with some exposures at higher elevations in the exposed western part of the Kaulonia site. The Pleistocene-Holocene contact occurs in the sand and pebble layers above this lower fine-grained unit and beneath the coarse cobble unit in core MON I. Several Greek potsherds were found in the upper 2.5 m of a section of core MON II (Figure 7). A basal Holocene date (conventional radiocarbon age of 10,160 ± 40 y BP; Beta-Analytic identification number 216827) was determined by radiocarbon (AMS) analysis of the dolomite and carbonate cement (high Mg-calcite) and associated matrix in the partially consolidated sandy deposits that lie directly above the conglomerate in MON II. A younger (mid-Holocene) age of 4500 y BP was also estimated separately for this same sandstone unit in MON II, using a prorated method: this date takes into account the core depth of ~2.5 m of the 500 BC Greek artifacts, and depth at 4.5 m of the cemented sandstone unit that lies 2 m beneath the archaeological material; the assumption (not confirmed) is that there is no erosional hiatus and/or missing stratigraphic section in this part of the core.

A sandstone-conglomerate sequence was also observed in 1998 along the seaward-facing base of dunes, ~220 m to the south of MON II (Figures 3A–B). The sequence here includes a 50-cm-thick stratum of seaward-tilted, weathered, brown, poorly to noncemented sand, positioned at an elevation of ~1.0 to 2.0 m above sea level (Figures 3A–B). This stratum, observed NNE of the temple, lies directly above and appears "welded" to an approximately 50-cm-thick sequence of rounded pebbles, cobbles, and boulders of Assi River derivation. Moreover, renewed examination of this horizon in excavations at the base of dunes in this sector in March 2006 also revealed a weathered brown to reddish-brown sand directly above the conglomerate. Here, the rounded igneous and metamorphic cobbles and boulders, some to >50 cm diameter, are at an elevation at and just beneath present m.s.l. (Figures 8A–B). As in core MON II, archaeological material of Greek origin (tiles, potsherds) was recovered above the sequence in the dunes (Figure 8C).

Remarkably, almost no carbonate shell of either microfossil or molluscan origin, either whole or fragment, is observed in sand, sandstone, and pebbly sand sections above the conglomerate layer in the two cores and dune excavations.

Sedimentary Rock at Temple Base

Field observations show that cut blocks of rock used to construct the base of the Doric temple (Figure 9A) are formed primarily of current-swept, shallow-marine detrital sediment. Some display well-defined, low-angle stratification

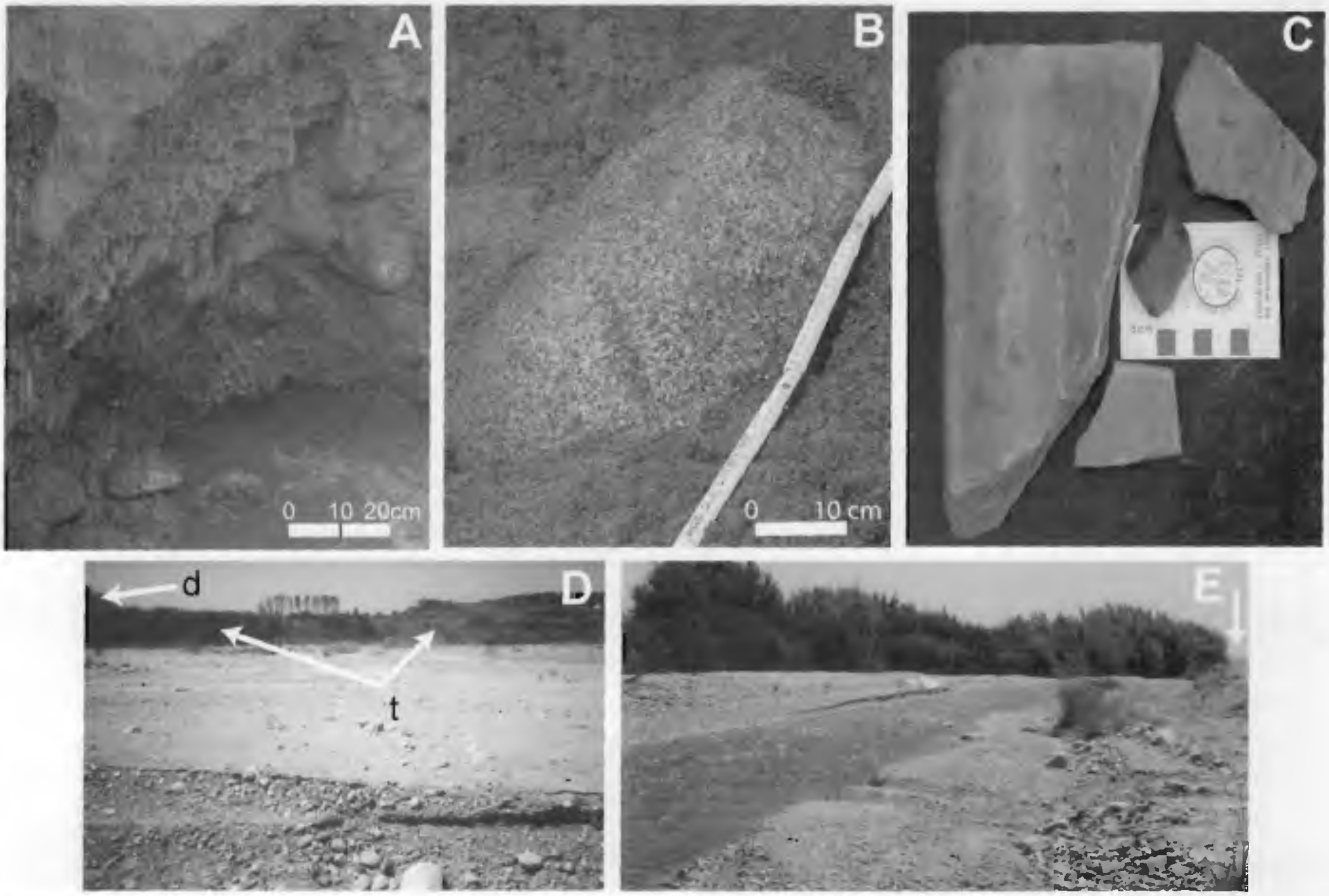

Figure 8. (A–C) Photographs (March 2006) of excavated sediment and artifacts at base of coastal dunes (seaward margin, location in Figure 4). These show (A) the sand-conglomerate sequence (s) of coarse stratified sand positioned directly above mostly rounded pebbles, cobbles, and boulders (in B, to 50 cm diameter; each segment of ruler scale is 20 cm long). Water seeping near base of conglomerate (in A) is at about sea-level elevation. (C) Greek tile and potsherds from above the sand-conglomerate sequence in A. (D) and (E) Low Assi River flow stage during summer (photos in late June 2004); coarse bed load includes rounded elongate boulders (to nearly 50 cm diameter) of mostly igneous and metamorphic lithologies transported to the coast. (D) View to south, toward site of core MON I on flat floodplain west of coastal dunes (arrow d); 10 m terrace appears in distance (arrow t). (E) Arrow denotes Assi River channel mouth discharge point at the Ionian coast.

(Figures 9B–C). Texture varies from relatively well-sorted medium and coarse sand to poorly sorted, coarse granule-rich sand and pebbly sand. Petrographic analysis shows that most sand-sized and coarser framework grains are angular to subrounded particles of clastic origin, primarily quartz, orthoclase and plagioclase feldspars, lithic (igneous and metamorphic) particles, and biotite, along with lower amounts of muscovite, heavy minerals, and minor illite. Faunal remains in a few samples include shells of small marine mollusks, such as Naticidae, and benthic foraminiferal tests (including miliolids, rotalids, and others). These and other forms, mixed with detrital sand-sized material in current-stratified deposits, indicate a gently to moderately reworked, shallow inner-shelf seafloor environment. Framework grains and faunal remains appear to "float" in the calcareous and/or dolomitic (sometimes iron-rich) mass and weathered argillaceous and fine-quartz matrix paste, some of postdepositional origin, that fills interstices and supports the detrital grains.

Grain-count identification shows that proportions of sand-size clastic mineral components of the cut sandstone of the temple base closely resemble those of sand samples collected in the bed of the Assi River and on the modern beach. In both cases, the sands are derived primarily from disaggregated igneous and metamorphic rock material of the type brought to this Ionian sector coast by the Assi River and other adjacent small and seasonally still-active rivers. Some marine shells and stratification in the cut rock of the temple (Figures 9B–C) indicate an origin involving active lateral displacement of particles in a current-agitated marine setting. Petrographic analyses show that beach sands and temple base sandstones include the presence of biotite mica. The considerably smaller amounts of biotite and faunal shell in modern beach samples indicate more effective selective removal by winnowing and abrasion processes by present-day higher-energy longshore transport. Radiocarbon (AMS) analysis of three sandstone temple-based samples provided inconclusive data, *i.e.*, ages

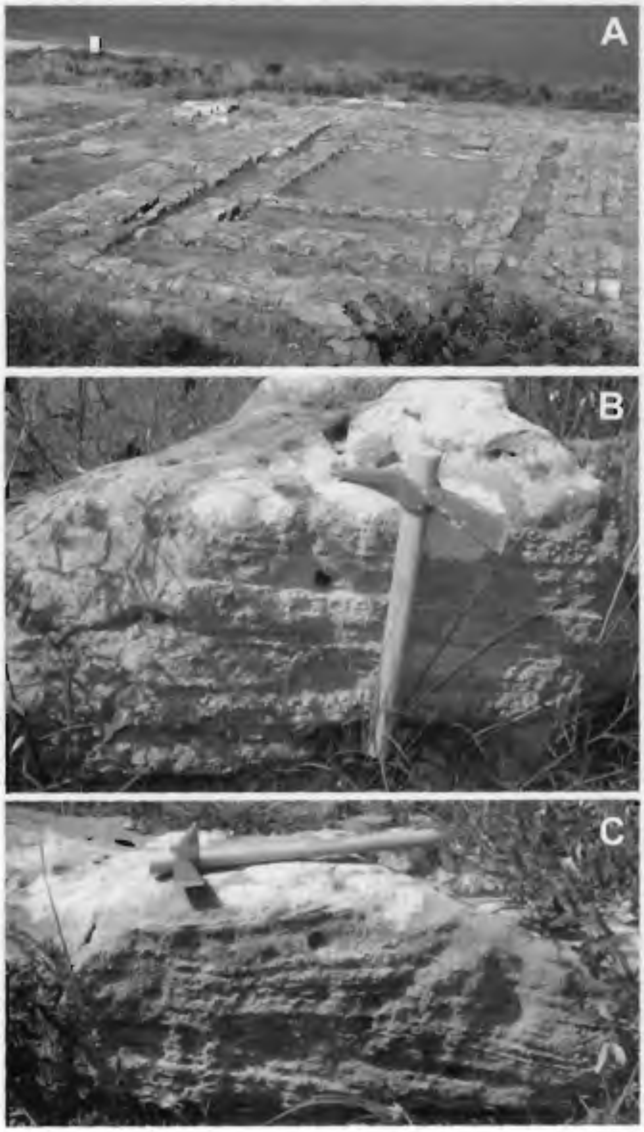

Figure 9. Photographs of Doric temple base at Kaulonia. (A) View toward east shows temple configuration. (B) Cut block of poorly cemented detrital sandy sediment, with typical low-angle stratification. (C) Cut sandstone block, showing low-angle cross-laminations. Hammer handle length = 35 cm. See Figures 3D and 3E for similar sandstone lithofacies now submerged offshore.

ranging from as young as 100 y to 44,000 y BP (Beta-Analytic identification numbers 218089, 218090, 218091). These dates appear anomalous and likely record the presence of reworked, much-older carbonate (perhaps introduced by much older continental water) and also recent material (postdepositional age) incorporated in the sandstone matrix.

SUBMERGENCE OF THE KAULONIA COAST

The large amount of archaeological material present offshore indicates that Kaulonia's shoreline was located east of its present position during Greek colonization and that it subsequently migrated considerably to the north and west, to its present position (LENA and IANNELLI, 1996; LENA and MEDAGLIA, 2002). Moreover, the Assi River channel has shifted northward since 500 BC. This landward-directed coastal shift is similar to that observed along many stretches of Mediterranean sectors during the Holocene, primarily as a response to *relative* sea-level rise. This latter is generally induced by world (eustatic) sea-level rise and local land motion, commonly subsidence. However, the cause, amount, and rate of shoreline displacement since occupation of Kaulonia and following its abandonment in the late Holocene warrant further attention here. Especially important for these considerations are the amount and nature of offshore lowering to greater than shoreface depths of the abundant, once-emergent archaeological material associated with the solid substrate of sandstone and Assi River cobbles and boulders.

Submergence in the study area could be the result of several factors. The simplest, most straightforward condition would be one where only world sea level has risen progressively during the past 2500 y, while the land mass near and seaward of the coast has been stable, *i.e.,* has not substantially risen or subsided. In this case, however, the Kaulonia shoreline at *ca.* 500 BC would have been positioned seaward of the present one by little more than 100 m. Yet, a considerable amount of archaeological material of this age is found up to 300 m from shore. At 500 BC, sea level was only about 2 m or less below present m.s.l., according to some presently used world curves (*cf.* FAIRBANKS, 1989; PIRAZZOLI *et al.*, 1997). However, intense shoreface erosion by strong winter wave activity at the time, such as the one prevailing at present, would have accounted for additional lowering of the shoreface seaward of the coastline by 1 to 2 m. This eustatic rise plus seafloor erosional downcutting phenomenon would thus account for total lowering of shoreface elevation to about 3 to 4 m below present m.s.l. at the time of Greek settlement. It is noted, however, that archaeological materials presently rest on the substrate sandstone-boulder sequence at depths of 5 to 7 m below sea level, or deeper by 2 to 3 m than can be readily accounted for by the above two factors alone. An additional component, seafloor subsidence, is needed to account for the additional lowering of 2.5 m beneath m.s.l. during the past 2500 y. Averaged over the long term, the calculated mean annual subsidence rate is ~1 mm/y.

Interpretation of controlling factors thus requires lowering of the seafloor at some geographic position between the coast and inner shelf offshore, a process that occurred concomitantly with world rise in sea level and local high-energy shoreface erosion. Subsidence would have induced an increased seaward inclination of the seafloor, resulting in a slower rate of landward advance of the shoreline. It is also important to consider possibilities of variable and substantial land motion that may have occurred near and landward of the coast during this period. This latter phenomenon, in turn, would have altered both rate and direction of coastline migration. Several possible scenarios are envisioned during the mid- to late Holocene, depending on the amount and rate of vertical up or down displacement of land taking place periodically landward and/or seaward of the coast that would result in: retreat of the shoreline to a point more inland than

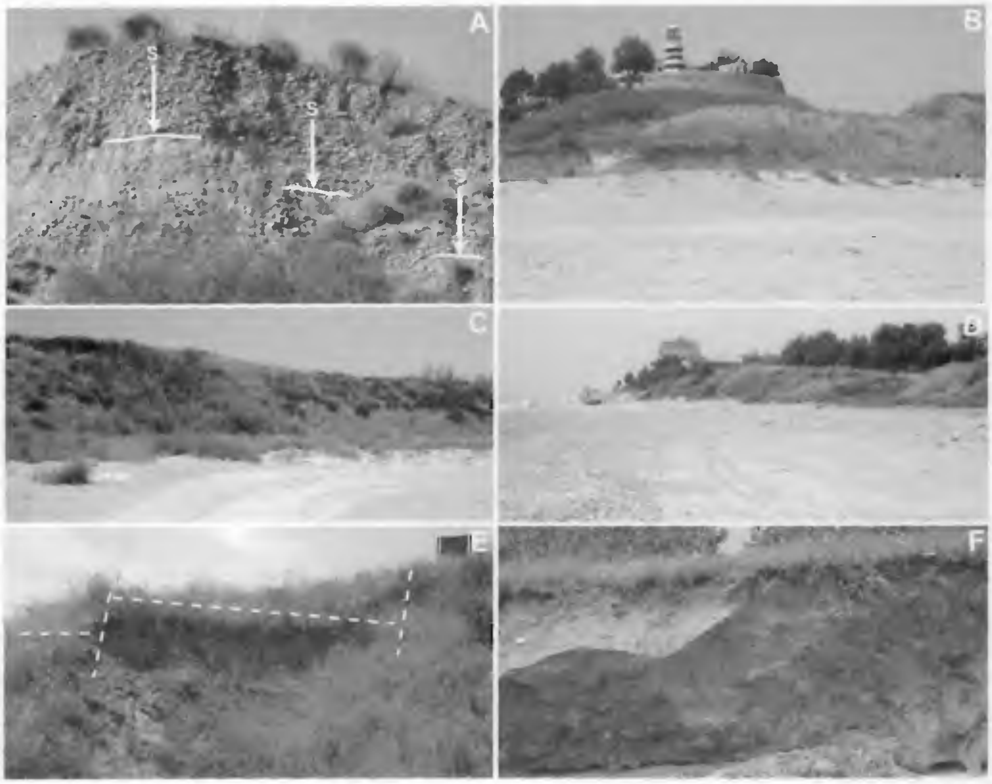

Figure 10. Photographs (May 2006) illustrating structural displacement of strata near coastal margin. (A) Pleistocene terrestrial deposits in hill backing Kaulonia show fault offset, as highlighted by displaced thin fine-grained (s) layer. (B) Displaced Pliocene and Quaternary sequences on and seaward of steep hill forming base of lighthouse, and in young alluvial deposits on which Kaulonia was built. (C) and (D) Tilted blocks of the 10 m terrace near Doric temple site. (E) and (F) Offsets in alluvium and dune sand sections beneath and seaward of Doric temple.

at present; or relative stabilization of the shoreline position through time; or even a reversed (seaward) advance of the coastline that would have drowned previously emerged sectors.

Geological study of this tectonically active Calabrian arc sector provides evidence of recent land displacement, such as recorded by rise landward of the shoreline (AMATO and MONTONE, 1997; CARTA GEOLOGICA DELLA CALABRIA, 1968; DUMAS and RAFFY, 1994; DUMAS *et al.*, 1995; FERRANTI *et al.*, 2006; GUERRICCHIO, 1988; WESTAWAY, 1993). The margin has been active during much of the Quaternary, with shallow, intermediate, and deep earthquakes that presently displace this mobile arc setting (GASPARINI *et al.*, 1982). Moreover, it has been suggested that the study area is also affected by a regional seaward tectonic shift of several millimeters per year toward the ESE (GUERRICCHIO, 1988). Still other phenomena, such as isostatic depression and/or compaction of underlying sediment substrate, may have induced additional lowering of offshore sectors.

Pliocene and Pleistocene sections exposed in the low hills that back Kaulonia provide ample examples of geologically recent displacement (Figure 10A). Evidence of such stratal offsets and topographic changes is also recorded on land within 100 m of the coast, such as in the alluvial plain sector on which a large part of the site was built, and which is distinctly separated from the much lower beach below (Figure 10B). Of note is the distinct, terrace-like alluvial plain–dune contact sector along the coast between the Assi River and site south of the temple. Here it ranges in elevation from 7 to 12 m and resembles a series of tilted structural blocks (Figures 10C–D). The terrace forms the marked step-like dune-beach boundary near the temple, and farther to the north, this block is then defined by an E-W–trending topographic demarcation (Figure 8D, arrow t). Some step-like relief offsets at the alluvial plain–dune contact just landward of the beach also record neotectonically displaced surfaces (Figures 10E–F).

Studies indicate that the land margin of this coast has been subject to long-term uplift rates averaging 0.89 mm/y (AMATO and MONTONE, 1997; DUMAS and RAFFY, 1994; DUMAS *et al.*, 1995; FERRANTI *et al.*, 2006; WESTAWAY, 1993). In sum, it appears that our finding of the average long-term annual rate of seafloor subsidence (~1.0 mm/y) off Kaulonia approximates that of land surface rise during the late Holocene.

LATERAL SHIFTS OF THE COAST

To what extent has land rise in the Kaulonia coastal plain-dune-beach area and lowering of the margin seaward of the shoreface affected coastline migration since time of Greek colonization? Correlation of Holocene sediment units on land with equivalent ones offshore helps to identify the pattern of lateral shoreline displacement on this margin through time. A particularly useful marker is the sandstone-conglomerate sequence recorded to the west (on land) and east (offshore) of the present shoreline. Core MON II (Figure 7) on the alluvial plain behind the coastal dune recovered a gray, poorly consolidated coarse detrital sandstone that lies directly above a conglomerate. The sandstone consists of detrital particles of sand- and granule-size bound by a dolomitic, calcareous, and weathered argillaceous matrix. Proportions of angular to subrounded framework grains (quartz, feldspars, lithic fragments, mica) are comparable in composition to those of particles in samples of the modern Assi River bed and the present Kaulonia beach. This shallow-marine unit of modest thickness (~50 cm), interbedded in an otherwise unconsolidated sediment section, resembles a weathered sandstone of possible beachrock origin. As indicated in an earlier section, radiocarbon (AMS) analysis of the carbonate cement in this sandstone layer indicates a basal Holocene date, while a prorated age based on the sandstone depth of 2 m beneath Greek artifacts (*ca.* 2500 y BP) suggests a possibly younger (mid-Holocene) age of *ca.* 4500 y BP.

The distinct sandstone-conglomerate sequence predates the founding of Kaulonia by at least two millennia, and perhaps more. The large size of the conglomerate beneath the sandstone in the distinct Holocene sequence, such as the one found buried landward of the beach, could only have been displaced in a water medium, *i.e.*, transported during flood by the Assi River to seaward of the former shoreline and then moved along the coast by powerful wave-current activity. The conglomerate positioned at about m.s.l. is covered by a beachrock-like sandstone stratum in MON II. A similar coarse layer was also drilled at about the same depth in core MON I (Figure 7). Coarse material in both borings includes rounded pebbles and cobbles of Assi River derivation.

The presence of a beachrock-type sandstone is somewhat surprising since the Ionian coast does not occupy a tropical setting of the type usually associated with such carbonate rock formation. Such a facies of dated Holocene age nevertheless has been identified on many Mediterranean margins between Spain and the Levant (ALEXANDERSSON, 1972; DALONGEVILLE, 1984), including Calabria's Ionian coast (PIRAZZOLI *et al.*, 1997). Mediterranean beachrock and carbonate-cemented sandstone of shallow-marine origin likely formed at times of altered climatic fluctuations, such as some that occurred during the Holocene (*cf.* BERNIER and DALONGEVILLE, 1996; DRYSDALE *et al.*, 2006; HEARTY and DAI PRA, 1992; MASTRONUZZI and SANSO, 2002; MAYEWSKI *et al.*, 2004; STANLEY and KROM, 2003; STANLEY and MALDONADO, 1977; WEISS *et al.*, 1993). Such fluctuations may have in some instances modified critical parameters, such as temperature, salinity, and evaporation/precipitation ratios, that influence beachrock formation.

The sandstone-conglomerate sequences in cores MON I and II are confidently correlated with similar sequences observed at the base of the dunes. The facies are of comparable thickness, texture, composition, and are generally positioned at similar elevations near present sea level. Observed differences include absence, locally, of carbonate cementation, a more weathered aspect, and reddish oxidized coloration in some dunes sections. The position of the sequence landward of, and in, the coastal dunes (Figures 7 and 8) records migration inland of a former Holocene coastline by 100 m to the west of its present position prior to the time of Greek colonization. The conglomerate unit along some dune sectors at an elevation to +1 m above m.s.l. also indicates that uplift locally exceeded 1 to 2 m since time of its deposition seaward of a former coastline.

The above-described lithofacies sequence on land positioned in and behind the dunes is separated by at least 200 m from the sandstone-boulder sequence offshore, where it is also about 1 m thick (Figures 2 and 3C–E). As on land, the coarse, rounded debris forming the conglomerate offshore is of Assi River derivation and was displaced in a high-energy, shallow-marine setting seaward of a mid-Holocene paleoshore. The Holocene sediment facies sequence on land and its extension offshore, as indicated by diver observation and recorded by seismic reflectors, allow it to serve as a stratigraphic marker to measure the extent of lateral shoreline shifts.

The depth and position of the step-like features, first observed by divers and then buried by sand, can now be viewed by seismic lines obtained between ~100 and 300 m seaward of the present coast (Figure 6). The incised configuration is similar to wave-formed shoreface profiles observed on some modern, high-energy, microtidal coasts (SHORT, 1999; WOODROFFE, 2002). Such features resemble cut-and-incised forms that, in present coastal settings, record short-term erosional and depositional effects resulting from intense wave activity in the breaker zone.

Stratification features and erosional depressions formed at and near the shoreface, however, are usually eroded and backfilled as wave conditions change. The configuration of modern seafloor settings nearshore changes almost continuously as a result of reworking and displacement of mobile surficial sediment layers along the shoreline. Consequently, concave-up seafloor depressed features tend to be rapidly smoothed, modified, and ultimately obliterated by renewed strong nearshore wave, swash-zone, and coastal current activity. Over a longer period, landward advance of the coastline tends to erase such earlier-formed nearshore configurations, and they are not commonly preserved in older unconsolidated sand-rich coastal sequences. In other words, it is unexpected that a former erosional coastal sedimentary configuration was preserved on Kaulonia's margin, since this sector has long been affected by tectonic activity and strong wave pulses, especially in winter. Preservation of nearshore features at this locality is thus most likely the result of the stratal consistency of the sandstone-conglomerate sequence, which apparently resisted bedform erosion during the back-and-forth migration of the shoreline in the mid- to late Holocene.

In sum, marked structural up-and-down land motion, eustasy, and seaward-directed sediment displacement in the coastal margin during the Holocene have induced pronounced lateral shifts of the Kaulonia shoreline and submergence. Moreover, evidence of accelerated erosion and powerful coastal processes, which also led to shaping of the coastal sector documented on the southern Italian peninsula, should not be

Figure 11. (A) Photograph taken in February 2006 showing normally strong winter waves breaking onshore and eroding the shoreface along Kaulonia's coastline. (B) Walkway (promenade) built in 2003 in Monasterace Marina, just south of Kaulonia, heavily damaged by storm wave surge effects in winter 2003–2004. In distance, note normally calm summer sea state at coast (photo: June 2004).

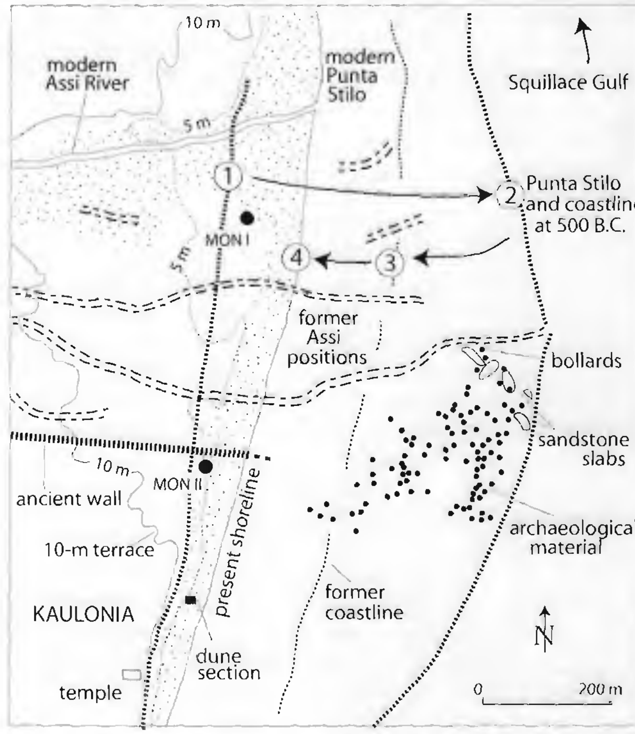

Figure 12. Paleogeographic scheme highlights Kaulonia margin evolution and lateral shifts of broad arcuate coast in mid- and late Holocene: shoreline to inland of the present dunes (1, pre-Greek time; before 2500 BC); then advancing seaward (2, Greek time; *ca.* 500 BC); and then migrating back landward (3, post-Roman) to present shoreline (4). At time of Greek settlement, the Assi River channel had migrated southward, and Punta Stilo extended considerably farther seaward to the SE. It is proposed that rock material similar to large sandstone slabs along this once-emerged coastal margin (Figure 3C) was used for Doric temple base (Figure 9) and other construction at the site. See discussion in text.

overlooked. Significant among the latter are strong winter wave activity and episodic tsunamis, some originating in more distal tectonically active Mediterranean settings, such at those to the SE (*cf.* GUIDOBONI *et al.*, 1994; MASTRONUZZI and SANSO, 2000; STIROS, 2001). As occasionally occurs at present, these events produced powerful surges of water that were driven onto the emergent coast; the surges were sometimes associated with earthquake tremors and tsunamis but probably most often were associated with strong winter storms. Such physical processes modified the beaching areas and anchorage facilities for vessels during Greek occupation, and they continue to affect this coastal area at present (Figure 11). Backwash from unusually large surges could have dislodged structures and materials in nearshore settings. It is also conceivable that such phenomena at times may have displaced seaward features such as massive column sections by rolling them down the shoreface to depths from which they could not readily be salvaged.

PALEOGEOGRAPHY AND COASTAL SETTLEMENT

Paleogeographic interpretations for periods before, during, and following Greek settlement can be updated and revised by integrating new findings presented in this study with earlier information pertaining to the Kaulonia coastline. Significant information includes seismic survey data that show the presence of an incised wave-cut incision to almost the exact same depth (~7–8 m) at about the same distance from the present shoreline along the entire Kaulonia coastal margin. A seismic survey of this sector does not reveal distinct faults and fault scarps offshore between the Assi River to the north and the temple to the south. The entire margin seaward of the site appears to have been submerged by vertical lowering and/or tilting of the seafloor by about the same amount during the late Holocene. Preservation of the incised, wave-cut step-like configuration observed by divers and recorded on geophysical profiles was made possible by relatively resistant strata, primarily sandstone and coarse fluvial conglomerates, rather than by unconsolidated mobile deposits. Instead of a small hooked-shaped cape, seismic observations indicate the former presence offshore of a broad, gently arcuate headland as shown in Figure 12.

Here, we evaluate the age and origin of the large angular sandstone slabs observed off Kaulonia. These were assigned a Würmian (Pleistocene) age in some previous studies (IANNELLI *et al.*, 1993; LENA and MEDAGLIA, 2002), but unfortunately this dating was not confirmed prior to their recent burial. Two possibilities are considered here. The sandstone offshore is either: (1) an older (Pleistocene) coastal deposit, perhaps Würmian in age as indicated by LENA and MEDAGLIA (2002), and thus it is analogous to some Quaternary terrace-forming strata now uplifted along the Ionian coast of Calabria (*cf.* DUMAS and RAFFY, 1994; DUMAS *et al.*, 1995); or (2) possibly of much younger (Holocene) age and carbonate-cemented beachrock origin, typically formed at or near the intertidal and sea-spray zone, or it is a cemented shallow-marine sandstone (*cf.* MILLIMAN, 1974). With respect to the first hypothesis, there are some Quaternary coastal series, including units of Tyrrhenian and much older age, exposed in highlands west and northwest of the coast (DUMAS and RAFFY, 1994; DUMAS *et al.*, 1995; FERRANTI *et al.*, 2006; WESTAWAY, 1993). With regards to the second postulate, beachrock as young as late Holocene age (*ca.* 3000 y BP) has been identified on the Ionian coastal margin at Bova Marina, 94 km SW of Kaulonia, and at Soverato, 27 km N of the site (PIRAZZOLI *et al.*, 1997). To our knowledge, there is no beachrock-type sandstone of such young age (Holocene) exposed in the hills and quarries (modern and ancient) behind Kaulonia.

On the basis of petrological and dating analyses in this study, we propose that (1) the age of the carbonate-cemented detrital sandstones observed in both land close to the coast and offshore in seafloor sections is young, *i.e.*, more likely Holocene than Pleistocene, (2) the sandstone formed in the vicinity of a shoreline in this sector at a time prior to settlement by the Greeks, and (3) blocks were cut near the site and used by the settlers at Kaulonia for construction purposes at their site, including the base of the Doric temple (Figure 9). In addition, (4) it may follow from the above that the presence of extensive sandstone exposures along the shore may have been one of the reasons this locality was selected for settlement between the more important coastal colonies at Crotone and Locri (Figure 1). It is probable that the sandstone-conglomerate sequence was a distinct coastline feature visible to those sailing along this Ionian margin in late Holocene time when the coastline was positioned 300 m to the east of its present location (Figure 12). Petrologic (composition, sedimentary structures, thickness) analyses indicate a close similarity between sandstone facies on land (in core MON II and dune excavations) and those used for construction at the site.

We postulate that a considerable amount of beachrock-type sandstone was extracted at the former Punta Stilo shoreline for building at the site prior to the exile of settlers in the fourth century BC. The temple base covers an area of 840 m^2, and about 80% of the area is lined and filled with cut rock. To determine the dimensions of large blocks used for the project, 12 were measured and found to have an average length of 115 cm, width of 53 cm, and thickness of 39 cm; each block of this size covers a surface area of 0.61 m^2. Excavation by ORSI (1916) showed that the base of the structure, built on a slope, was made horizontal by superposing rock slabs: as many as six blocks were stacked along the lower 6 m stretch; four were stacked along the middle 10 m stretch; and two were superposed along the upper 10 m stretch. Thus, to level the base, rock sections at its lower elevation would have been raised to a height of about 2 m. Based on the detailed field excavation drawings and descriptions by ORSI (1916) and our measurement of cut rock dimensions, it is conservatively estimated that as many as 2500 blocks were needed for the temple base construction alone, material that would have been recovered from a surface area of at least 1250 m^2. This, for example, would be equivalent to an elongate sector about 100 m in length by 12.5 m in width along the former coastline. The quarried surface area was even larger, since this sandstone was also used in some other structures excavated at Kaulonia. Rock material may have been collected from the emerged coast positioned east of the temple, perhaps in the area where sandstone slabs offshore were observed *in situ* (Figures 3C–E and 12) and presently lie beneath the modern sand cover.

A simplified paleogeographic scheme highlights the back-and-forth shoreline migration over a distance of at least 400 m in the mid- to late Holocene, with ultimate submergence taking place at some time after departure of the Greeks (Figure 12). The reconstruction indicates that Kaulonia was settled when both Punta Stilo and the Assi River channel were positioned farther to the SE than at present. Petrological examination of the late Holocene core and excavated dune sections primarily records an accumulation of fluvial and coastal deposits; no lithofacies or faunal assemblages clearly indicative of a lagoonal or lacustrine setting were observed. A thin (~1 m), light olive gray (5Y 5/2) sequence of finer-grained (clayey silt, silty sand, and sandy silt) section near the top of core MON I (Figure 7) is interpreted as Assi River overbank deposits. This sediment, rich in pollen, likely accumulated during seasonal (fall to spring) floods that released fine-grained material on a low broad plain south of the river bank (Figure 8D).

No natural wetland (lagoon, marsh, lacustrine) settings and artificial port structures that could have provided sufficiently protected anchorage sites for vessels have been identified at, or in close proximity to, Kaulonia. It is possible, however, that some loading and discharge of boats took place at, or just within, the river mouth during nonflood periods (primarily summer), as suggested by positions of some anchors and bollards identified on the seafloor (Figure 12). This, however, assumes that the river mouth was considerably deeper than it is at present Assi. Based on archaeological and geological findings to date, it is more probable that vessels sailing to Kaulonia for trade were, for the most part, either beached at or anchored close to the former Punta Stilo shore.

CONCLUSIONS

The present investigation of Kaulonia's coastal margin focuses on newly collected geophysical, sedimentological, and petrological data and integrates these with earlier gathered geographical and archaeological information. Together, these data indicate that the coastline at this site, located in the tectonically active Calabrian arc, experienced a relatively complex pattern of back-and-forth shoreline migrations over a distance of at least 400 m during the mid-Holocene to present. A sea-to-land migration was followed by a land-to-sea advance, and then by a return landward shift of the coastline to its present position. This shoreline displacement resulted primarily from geologically recent up-and-down land motion in the coastal sector positioned between the low hills and alluvial plain behind the beach and the inner Ionian shelf. We measured subsidence offshore during the past 2500 y at a mean annual rate of 1 mm/y, or at a rate almost identical to that of land rise in the highlands that back the site. At that rate, submergence of the once-emerged Greek coastline likely occurred by the end of Roman time.

The Holocene paleogeographic scheme presented here for the Kaulonia margin incorporates information obtained from stratigraphic correlation of a sequence that consists of beachrock-type sandstone and fluvial-marine transported conglomerate. The sequence, widely distributed in the study area, can be correlated between sections examined in and behind dunes on land and the seafloor to ~300 m from the present shoreline. Earlier studies had proposed the presence of a small hook-shaped cape positioned at the coastal margin during the time of the Greeks. The present analysis, however, indicates a broader and more gently arcuate headland about 2700 to 2400 y ago, across which the lower channel and mouth of the Assi River dispersed sediment east of the site. Moreover, study of sediment sequences does not reveal the presence of a lagoon, perennial lake, or artificial port available for protected anchorage of ships during this period. It appears that vessels sailing to the site were beached or anchored close to shore off the broad headland and perhaps also within the mouth of the Assi River during nonflood periods.

The composition of the Holocene beachrock-type sandstone recovered in the sediment sections behind and at the base of dunes on land is similar to that of numerous cut rock blocks used to construct the base of the Doric temple at Kaulonia. This leads us to suggest that availability of extensive sandstone exposures along the once-wider emerged coast may well have been one reason why the Greeks selected the site for settlement.

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APPENDIX: GEOPHYSICAL SURVEY METHODS, EQUIPMENT, AND PROCEDURES

Equipment

An IKB-Seismic™ single-channel high-resolution seismic profiler (SIMPKIN and DAVIS, 1993) was used for this study. The profiler consists of a boomer source (EDGERTON and HAYWARD, 1964) and a cone-on-line receiver group placed on the same catamaran float. The advantage is a fixed and very small offset useful for work in shallow aqueous environments, such as Kaulonia's coastal marine region. The focusing cone built around the vertically positioned group of seven hydrophone elements also provides several advantages, including a fixed and constant geometry with respect to the water surface; circular symmetrical directional properties with strong downward directivity and almost complete reduction of side reflections; and low noise while the hydrophone elements are in still water.

SIMPKIN and DAVIS (1993) indicated a possible 16 dB signal-to-noise (S/N) ratio improvement resulting from the application of the line-in-cone receiver configuration. Another important aspect for shallow-water surveys is that interference of the direct arrival at the first water bottom reflection is eliminated as well, due to the small (0.7 m) fixed offset and effective shielding of the focusing cone.

The sharp signal of the boomer source ensures decimeter-scale resolution and provides enough energy to penetrate several tens of meters of water and sediment column. The reflected energy is sensed by the hydrophone group and, following analogue preconditioning, is digitized using a PreSEIS system running on a portable PC. The following are the main parameters of the integrated seismic profiling and recording system:

Seismic source:	HWIKB B3 Boomer operated at 150 J and 3.1 kV
Receiver:	Cone-in-line group of 7 hydrophone elements
Source-Receiver offset:	0.7 m fixed
Shot rate:	Varying between 6 and 8 shots/sec depending on water depth
Analogue signal processor:	SPA-3

Analogue low-cut filter:	400 Hz
Analogue high-cut filter:	10 kHz
Sampling frequency:	100 kHz
Recording format:	SEG-Y 2 byte integer UTM DGPS coordinates recorded in the trace header

The seismic profiler was towed behind the survey vessel at >10 m distance from the stern of the boat. The tow point was at the end of a pole attached to the side of the survey vessel to avoid the unwanted effect of propeller wash.

Positioning

Accurate positioning was critical for this close-grid high-resolution seismic survey. Global positioning system (GPS) receivers with real-time differential correction provided a reliable and simple approach, as good satellite visibility was available. A Trimble ProXRS system with Omnistar differential correction was used throughout the survey area, thus providing submeter accurate position data at a 1 s update rate. The GPS antenna was mounted on the geometrical center of the seismic profiler to avoid any position error due to an offset between the GPS antenna and seismic system.

The differentially corrected GPS data (DGPS) and the GPS time were logged in the header of each seismic trace recorded and used at the same time for navigational purposes. Predefined survey lines in two perpendicular directions were displayed on the navigation screen of a laptop computer along with the actual position of the seismic profiler. These provided the necessary navigational information needed by the captain of the survey vessel.

Data Processing

Processing of the seismic data set consisted of the following steps:

- Position data recorded in the trace headers were reviewed and edited as necessary. The coordinates were linearly interpolated for each shot since the shooting rate (6–8 shots/s) significantly exceeded the GPS update rate (1 s).
- Recording time delay changes were compensated for the significant water depth variation in the surveyed area.
- Band-pass filtering was applied to further improve the signal-to-noise ratio of the recorded data with 1 kHz low-pass and 10 kHz high-pass frequencies.
- Amplitude correction was applied to compensate for spherical divergence and attenuation effects.
- Sea-surface waves were estimated from the recorded data, and appropriate compensation was made. This was a critical adjustment needed prior to interpretation of seismic data, since the seismic profiler was towed on the sea surface, and wave action could exceed the resolution of the seismic data set. To make the estimation, a proprietary algorithm was used based on correlation of the seismic traces.
- For depth conversion of the seismic data, a velocity of 1450 m/s was used in the water column, while a value of 1600 m/s was used in the recent (Holocene) unconsolidated sediments below the water-sediment interface.