Multibeam Sonar Technology and Geology to Interpret Ancient Harbor Subsidence off Crotone Peninsula, Italy

Approche géologique et géophysique croisée pour l'étude des ports antiques Le cas de la subsidence de la péninsule de Crotone, Italie

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Multibeam sonar (MBS) technology was developed to examine in great detail large stretches of the seafloor surface, providing accurately positioned and excellent 2-D and 3-D images of features as small as a few centimeters or covering areas as large as hundreds of square meters. In the present study, such high quality images obtained in plan and oblique views are used primarily for archaeological purposes as related to geological (sedimentological and tectonic) parameters. Presented here as example is an area on Calabria's Ionian coastal margin, the Capo Colonna-Punta Scifo shelf platform located off the Crotone peninsula. We show how multibeam sonar can help solve geoarchaeological problems with respect to identification, origin, and subsidence of seafloor structures that were once positioned near a former coastline but now rest at a considerable depth of 12.5-13 m below sea level. MBS images, coupled with diver observations, indicate the structures are of human construction, not of natural origin, and were once part of a now-submerged Greek harbor facility. These structures are positioned on a seafloor that subsided by ~10 m since late or post-Greek time; submergence occurred not by mass gravity flow processes, but by a number of tectonic pulses over time that most probably involved lowering by extensional faulting and possible strike-slip events. Linear structural features observed on the seafloor show axial trends similar to those mapped on land, indicating that both subaerial and submerged areas of this Calabrian Arc sector were modified tectonically to the present time. Multibeam data show that this Crotone shelf platform has been subject to considerable structural offset and subsidence on Calabria's Ionian margin since ancient Greek time.

Keywords: archaeology, breakwater, Calabria, Crotone peninsula, Greek harbor, multibeam sonar, shelf platform, sedimentation, shelf structures, subsidence, tectonics

La technologie du sonar multifaisceaux a été développée pour examiner en détail les fonds marins. Cette méthode offre une précision excellente de quelques centimètres et couvre des surfaces de plusieurs centaines mètres carrés. Dans notre étude, ces images sont utilisées à des fins géoarchéologiques en relation avec le contexte géologique. L'exemple présenté correspond à la marge ionienne de la Calabre, la zone de Capo Colonna-Punta Scifo située au large de la péninsule de Crotone. Nous montrons comment le sonar multifaisceaux peut aider à résoudre des problèmes d'identification et d'affaissement du fond marin jusqu'à une profondeur de 13 m au-dessous du niveau actuel de la mer. Ces images, couplées avec les observations des plongeurs, indiquent des structures d'origine humaine qui peuvent correspondre à une installation portuaire grecque maintenant submergée. Ces structures sont positionnées sur un fond marin qui s'est affaissé d'environ 10 m depuis la fin de l'antiquité. Cette immersion traduit un certain nombre de pulsations tectoniques en relation avec l'arc de Calabre.

Mot clefs : archéologie, brise-lames, Calabre, Crotone, port grec, sonar, plateforme littorale, sedimentation, subsidence, tectonique

During the past half century, there has been an increased number of projects conducted in offshore coastal and shelf settings in different world regions and this has fostered closer research collaboration between marine geologists and archaeologists. The hammer, camera, compass and tape measure commonly used by diving geologist are often supplemented by equipment to recover subsurface sediment, including drills and vibracores. In addition to these are high-resolution subbottom seismic and side-scan systems, ROVs and submersibles that are also included in the earth scientist's tool kit, especially when working in deeper settings. To the above, one should add multibeam sonar, a widely available technology that details the seafloor surface, a zone usually poorly defined by subbottom geophysical profiles due to the indistinct seismic signal usually obtained at and just beneath the water-bottom interface. To date, this technology remains underutilized by marine scientists attempting to resolve seafloor surface and geoarchaeological

Fig. 1 - Map showing ancient Greek centers in southern Italy, including Kroton (modern Crotone) and other geographic locales mentioned in the text near the Capo Colonna-Punta Scifo study area (*modified after* CERCHIAI et al., *2004*)

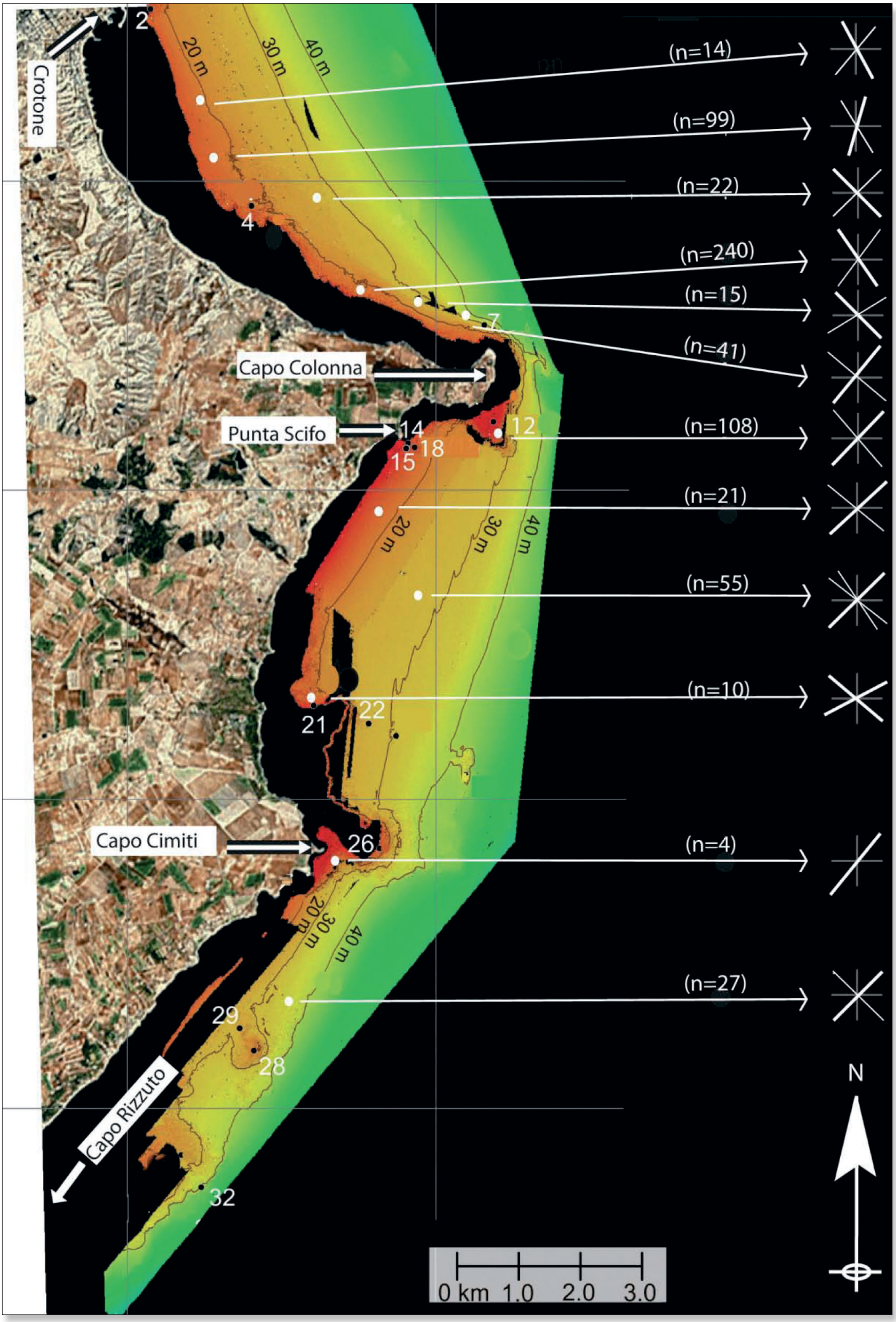

Fig. 2 - Map compiled using the 2005 MBS survey data showing the Capo Colonna-Punta Scifo area and general configuration of the shelf. Numbers in white refer to site localities depicted in figures 5 to 9. The NW-SE and NE-SW trends show averaged axis trends of seafloor structures of tectonic origin in 12 areas; thicker white lines indicate predominant axes. Measurements (total of 656) were made for this compilation. Depth in meters

problems in marine environments. The present study provides an example of the use of the MBS system applied specifically to a problem of archaeological site identification in what can be defined as a zone of extensive subsidence off Calabria's Crotone peninsula, southern Italy (fig. 1).

I - Purpose of Study

MBS technology was developed after World War II as an acoustical observational method for naval research projects that required considerably more precise and realistic images of the ocean floor than had previously been available by single beam systems. Rendering of three-dimensional visualization of bottom surface features obtained rapidly over broad areas is a particularly attractive aspect of the technology, and for this reason it is now widely used for systematic seafloor mapping and varied offshore hydrographic purposes (Hughes Clarke *et al*., 1996; Lurton, 2002). This acoustic system, one that records a broad swath of seafloor data, has been commonly employed since the 1970s by the offshore oil and gas industry. It is also increasingly applied to harbor management studies, marine civil engineering projects, fishery surveys and other purposes where it is essential to depict seafloor features in detail and accurately record their position and depth. Examples of the now diverse and practical applications of MBS are provided on search engines.

MBS, sometimes in conjunction with side-scan sonar, has been increasingly used during the past 3 decades for offshore archaeological exploration on shallow continental shelves, in deeper marine environments, and also in estuaries, lagoons and lakes. These swath acoustic systems have been particularly valuable for examination of recent shipwrecks and other anthropogenic debris such as airplanes, military armament and construction materials (Mayer *et al*., 2007; Dean *et al*., 2007), as well as ancient shipwrecks now resting or partially buried on the seafloor (Foley *et al*., 2009). Most recently, MBS has proven helpful in the investigation of once subaerially-emerged coastlines and discovery of associated archaeological sites and materials that are now submerged, sometimes to considerable depths, in aqueous environments (Royal, 2008; Nickerson *et al*., 2010).

A case study is presented here in which MBS is applied to a geoarchaeological problem on the Ionian continental shelf off the coast of Calabria, southern Italy. Attention is paid primarily to a sector positioned seaward of Capo Colonna and Punta Scifo (fig. 1), where features of questioned origin lie in a geologically complex and recently modified tectonic sector off the Crotone peninsula (fig. 2). Databases used are those collected in 2005 by RPM Nautical Foundation (Royal, 2008). The investigated seafloor relief features, including anthropogenic targets of interest, were originally discovered by means of MBS analysis in an area southwest of the Capo Colonna headland and about 250 m south of Punta Scifo (Royal, 2008, his seafloor target coded AE/AF in his figs. 2 and 9). This AE/AF site on the inner continental margin (site 14 in fig. 2) was also visually examined in 2005 by divers and interpreted by Royal as part of a now-submerged harbor facility of probable Greek Archaic age. This was based on construction style and comparisons with associated features and settings as illustrated and discussed at length later in this article. It comprises target AE, a long narrow structure attributed by him to be a breakwater**.** Northeast of the breakwater structure, there are also two large square and flat-surfaced blocks (target AF) interpreted by Royal as piers. These AE/AF structures now rest on the seafloor at a depth of about 12.5 to 13 m below present mean sea level (m.s.l.). Royal proposed that AE and AF were once part of a harbor facility that functioned from *ca*. 700 to 300 B.C., and then were submerged, perhaps during, or following, late Greek to Roman time.

It is of note that these same features were subsequently reinterpreted by another archaeologist, D. Bartoli (2010), not as anthropogenic in origin but as naturally deposited rock strata, with Royal's (2008) proposed breakwater attributed to a possible beachrock origin. Bartoli based his conclusions in part on the long narrow shape of the rock structure and absence of ceramic sherds and other human artifacts associated with it; he also calls attention to the considerable seafloor depth on which the associated AE/AF features occur. One of his main arguments is that it would have been unlikely that the AE/AF targets identified by Royal (2008), and attributed to quarried stone, could have been submerged to a much greater depth than that of the quarry which supposedly supplied the calcarenite blocks used to build it. Bartoli contends that if the blocks had indeed been obtained from such a quarry, it would have been necessary to transport them from a source locality well to the north of where the AE/AF structures now lie*, i.e.* one likely positioned much closer to the present shoreline. By this reasoning, he proposes that the source quarry, which he locates in the now-submerged Bay of Punta Scifo (Bartoli, 2010, his p. 405 and fig. 6), was of roughly equivalent age (Archaic to Hellenistic Greek). However, this proposed quarry at ~6 m below m.s.l. is at a much shallower depth than the AE/AF structures. Bartoli (2010, his p. 406) thus remains "skeptical that an Archaic breakwater could be located 13 m deep."

Several pertinent questions as to the origin of the AE/AF targets thus need to be addressed. Were these structures positioned south of Punta Scifo actually of human construction, *i.e.* once part of a harbor installation built along a former coastline during the Greek Archaic period, perhaps as early as 2800-2700 years ago? Were they still above sea level as recently as the 4th century BC as suggested on the basis of what is known of ancient Greek Kroton and its associated sanctuary of Hera (Juno) Lakinia, of which vestiges remain on the Capo Colonna headland (Cerchiai *et al*., 2004)? Or, are the structures, especially the AE target, formed of beachrock and therefore of natural origin? In either case, beachrock or breakwater, it becomes necessary herein to explain how such features normally associated with coastal to shallow marine settings could have been lowered to their present considerable seafloor depth (13-12.5 m) in a time-span as brief as ~2300 years.

Our investigation pursues these matters of origin and submergence using a multi-pronged geoarchaeological approach. It takes into consideration (1) direct observational records on the seafloor obtained by divers, including photographs and direct measurements of the AE/AF structures of interest in the study area. This is needed primarily to address the question of whether the AE/AF targets are of human construction or natural origin. If this question can be resolved, then (2) the direct diver records of the ocean floor are to be integrated with images derived from the 2005 MBS datasets that have been reprocessed specifically for this present study by applying up-dated state-of-the-art electronic software systems. It would also be useful (3), to identify and interpret the numerous small (few cm) to large (more than 100 m long) physical (sedimentary, tectonic), non-archaeological features on the seafloor of the study area; these had not received attention during the first analysis of MBS records by ROYAL (2008), or in the subsequent studies by BARTOLI (2008, 2010). For this exercise, (4) an attempt is made to compare some of the physical features recorded by MBS on the submerged shelf margin with physical features identified on land in the proximal Crotone peninsula. This approach may perhaps provide some new insight on seafloor subsidence, or absence of such movement, in this area.

2 - Setting of the Study Area

The Crotone peninsula, inland from the cliffs at the Capo Colonna-Punta Scifo coastline, is characterized by an irregular, dissected topographic terrain that rises toward the northwest to Calabria's Sila mountains (fig. 1). Two small

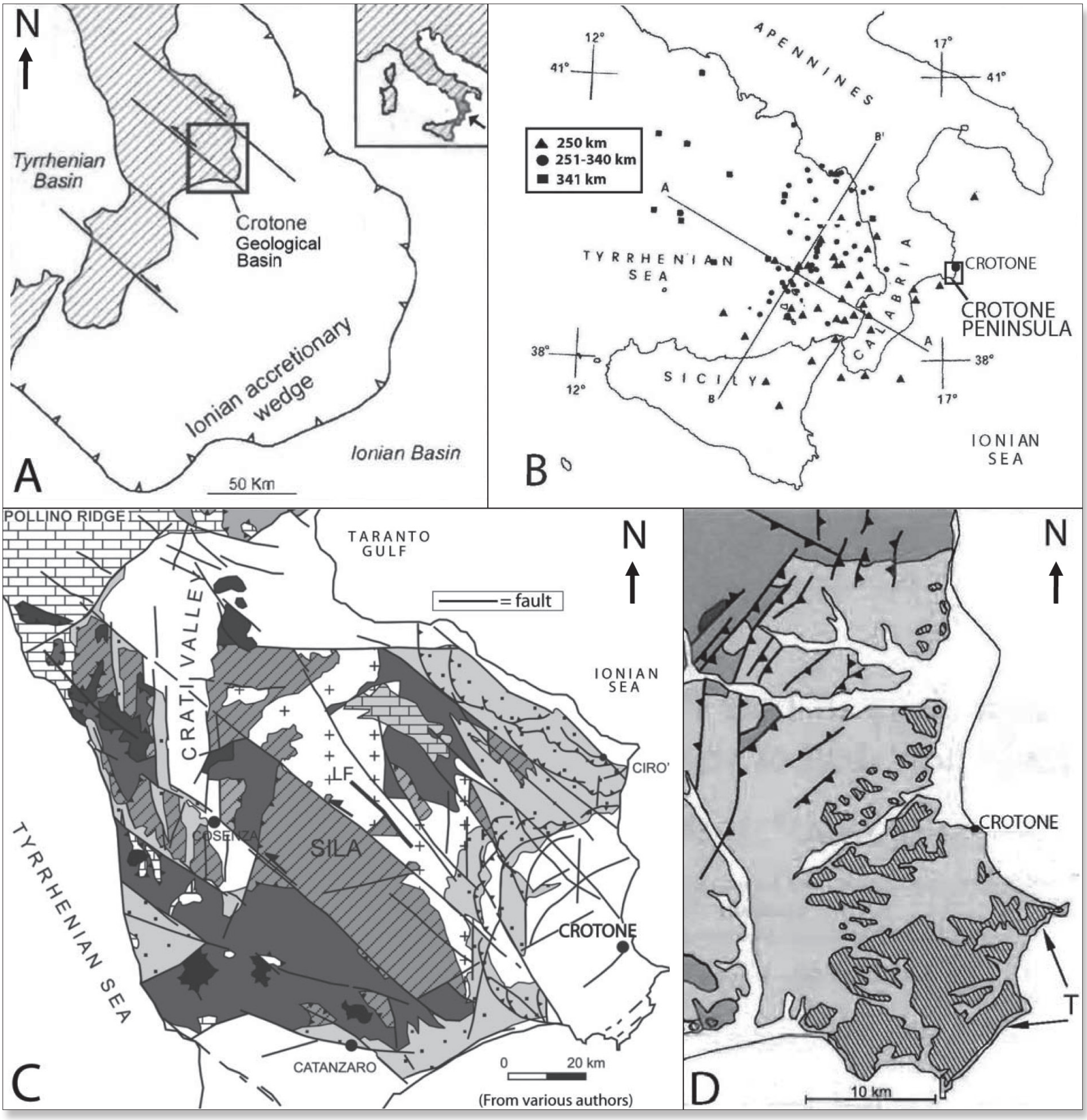

Fig. 3 – Geological setting of the Crotone study area. A – Crotone geological basin in the Calabrian Arc study area positioned in the Ionian accretionary wedge (Mellere et al., 2005). B - seismicity map showing earthquake epicenters in the Calabrian region (Gasparini et al., 1982). C - major fault trends in the Crotone Basin (Spina et al., 2007). D - area comprising marine terraces on land in the Crotone peninsula, shown by diagonally hachured pattern (T, arrows; after Mauz and Hassler, 2000). Modern town of Crotone in C and D is located on the northern Crotone peninsula

rivers flow across parts of the peninsula to the sea: to the north, the Esauro extends to the coast where the ancient Greek coastal city of Kroton (CERCHIAI *et al*., 2004), now modern Crotone, was once positioned; and at the southern end of the peninsula, near Le Castella, is a more modest stream, the Vorga. Seasonally important rain water runoff in the study area is also channelized seaward in topographic lows that are otherwise dry during much of the year. These include several broad U-shaped depressions and smaller dissected badland type gullies that incise cliffs at the coast.

The peninsula's geologic record, one that provides a record of long-term tectonic mobility, is positioned in one of the Mediterranean basin's more active structural settings (UDIAS, 1985). Tectonic processes over time have intensely deformed, offset and displaced the diverse geological terrains (fig. 3C) of this region during the Tertiary to the present, and especially in the Pliocene and Pleistocene (Carta Geologica della Calabria, 1967). The peninsula's geology has been described in numerous articles with, amazingly, more than one hundred published during the past quarter century. These studies detail the seismic framework (fig. 3B), stratigraphy, and structure (fig. 3C, D) of the Crotone basin, of which the present study area is an integral part (fig. 3A). For a background search, the reader is directed to several recent geological and geophysical summaries (VAN DIJK, 1991; ZECCHIN *et al*., 2003; MELLERE *et al*., 2005; VALENTI, 2010) as well as the numerous citations of earlier studies which are listed therein. The attraction to this region is due in part to its geologically recent (post-Miocene) active structural evolution and displacement of land associated with the area's position within the Ionian accretionary wedge of the Calabrian Arc (fig. 3A). The marked offset and dislocation of terrains on land are in large measure responses to contact of the African against the European plate in this Mediterranean sector (FINETTI and MORELLI, 1973; UDIAS, 1985; PIRAZZOLI *et al.,* 1997; ANTONIOLI *et al.,* 2009).

The seafloor examined here lies in the Crotone province's protected marine zone (Area Marina Protetta "Capo Rizzuto"), where restrictions on navigation, fishing and other activities apply (LENA *et al*., 2003; BARTOLI, 2008). The present irregular coastline is backed by steep to near-vertical cliffs that rise to 15-20 m above m.s.l., and seaward-facing slopes that are largely covered by rock slabs (fig. 4). It is on the near-horizontal platform behind the cliffs at Capo Colonna that the Greek sanctuary of Hera (Juno) Lakinia was erected; presently only one of its columns remains standing (OSANNA, 1992; CERCHIAI *et al*., 2004). The Ionian shelf platform that surrounds the Crotone peninsula is very narrow, mostly <3 km in width and a decrease to <1 km east of Capo Colonna.

The present configuration of the coastline is clearly an actively evolving one, being shaped by ongoing interactions of several processes: failure of thick jointed and offset rock strata exposed at steep to near-vertical coastal cliffs (fig. 4A) that leads to toppling of large angular rock blocks and their gravitative slide seaward to shallow water depths (fig. 4D-F), followed by erosion of these slabs once they reach the shoreline and shallow shorefront depths. Powerful wind-driven waves are then able to further undercut the newly exposed base of cliffs (fig. 4C), and this leads to renewed downslope failure of large slabs of reddish brown, fossiliferous calcarenite strata of Pleistocene age (Carta Geologica della Calabria, 1967). The calcarenites on land and offshore lie upon the Pliocene Cutro Shale (fig. 4B), a blue-gray clayey silt and silty clay mudstone unit, that reaches a thickness of ~400 m in this area (LENA *et al*., 2003). Ground water flowing along the contact between the two formations, one that in the study area is positioned near sea-level elevation, is also believed to play a role in fostering the disintegration, disassembly, and erosion of the exposed jointed calcarenite strata as discussed by LENA *et al*. (2003) and BLOIS (2008). Moreover, seasonally very strong nearshore wave energy and coastal currents transport sand and fine pebbles that serve as abrasives that, over time, progressively erode the large slabs. It is also conceivable that blocks reaching the inner shelf may be subject to some displacement at shallow depths, perhaps to 5-6 m, by the effect of powerful wave motion (fig. 4B, C) transmitted onto the seafloor (data available from the Crotone Buoy Ondametrica Nazionale). In addition to the above processes, sudden mass gravity flows (slides and rotational slumps) triggered along cliffs can displace material of variable size and even shift large slabs seaward for hundreds of meters on the gently inclined surface of the inner shelf (LENA *et al*., 2003; BLOIS, 2008).

There is some available subsurface geological and geophysical information for the offshore sector positioned seaward of the AE/AF study area, mostly for the outer continental margin and more distal basin. This has been obtained by deep penetration seismic surveys (FINETTI and

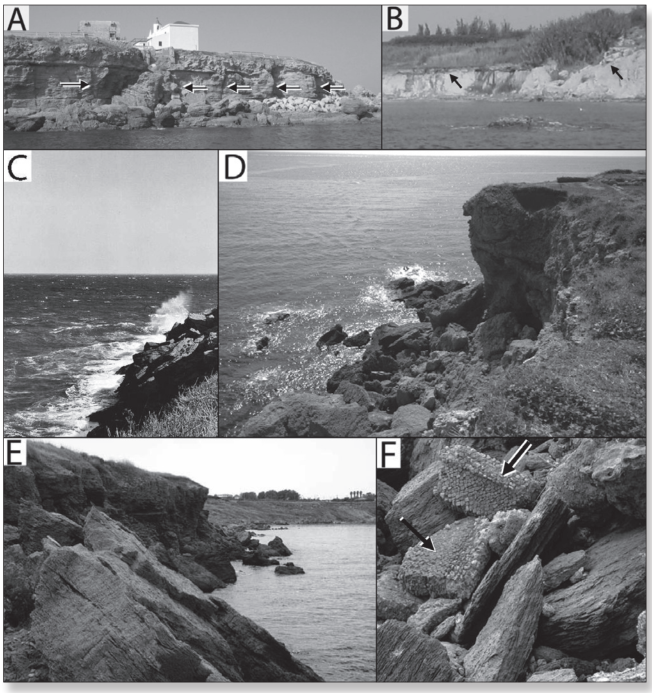

Fig. 4 – Photos along the Capo Colonna headland and coastal margin of study area. A - jointed and offset Pleistocene calcarenites (arrows). B - contact (see arrows) between the Pliocene Cutro Shale and overlying Pleistocene calcarenites. C - wind-driven waves breaking against calcarenite cliffs. D - near-vertical and over-hanging coastal cliffs produced by coastal erosion. E - massive slab (foreground) toppled from the cliff face. F - large angular debris, including parts of the Roman wall (two arrows), accumulating at base of eroded cliff

Morelli, 1973) and petroleum exploration drilling on the shelf off the peninsula (Lena *et al*. 2003). Such subsurface data, especially deep geophysical exploration surveys and seismicity records, have been used to help interpret major regional tectonic patterns and their effects on the stratigraphy and configuration of geological terrains (mostly farther offshore) in the Calabrian Arc (Finetti, 1985). Unfortunately, most information does not detail the subbottom configuration of the late Holocene seafloor of most interest here, as these strata usually lie within the discordant seismic signal recorded at the water column-subbottom horizon on geophysical profiles.

In marked contrast to land on the Crotone peninsula and deeper Ionian sectors discussed above, the Capo Colonna-Punta Scifo shelf study area between the cliff coast and the mid- to outer shelf has received relatively little systematic geological scrutiny. No high-resolution seismic survey lines or cores detailing the late Pleistocene to Holocene record for this 0-50 m deep sector are known to us. Without these, the available MBS and seafloor diver records become all the more important as data sets for the present geoarchaeological investigation.

3 - Methods

The 2005 MBS survey discussed here extends from off the modern town of Crotone in the Gulf of Taranto, southward to and around Capo Colonna, the major topographic feature along the Crotone peninsula, and then to the SW ~10 km south of Capo Cimiti and east of Capo Rizzuto (fig. 2). Lines were run parallel to shore, from a depth of <5m to 80 m, along sailing profiles of ~35 km in length; the survey encompasses an area of 69 km^2. Two vessels were used, the 36-m R/V *Hercules* and the 9-m R/V *Juno,* each with a MBS echo sounder: the system on the R/V *Hercules* is rated by manufacturer to a depth of 250 m but was effective for our survey to a depth of 100 m, while the system on the *Juno* has a manufacturer rating of 120 m depth but for our purposes was effective to a depth of 45 m. Accordingly, the R/V *Juno* covered areas from about 5 m depth off the coastline to the 45-m contour, and the R/V *Hercules* the area between the 40- and 100-m contours. The designed overlap between each vessel's coverage ensured minimum gaps when merging the two data-sets.

The system used on the R/V *Juno* featured a pole mounted Reson Seabat 8125 MBS echo sounder. This single-head unit emits 240 beams at a maximum ping-rate (number of times a depth measurement is made at each beam) of 40 per second, operates on a frequency of 455 kHz, and has a swath coverage of 120°. The data has a horizontal resolution of a few centimeters at depths to 45 m. Remote sensing with the R/V *Hercules* was conducted with a hull-mounted MBS echo sounder, model type EM3002D from Kongsberg Maritime division. This employs two transducer heads fixed to the underside of the research vessel, emitting a total of 508 beams at a maximum rate of 40 pings per second. Its multiple frequencies (293, 300, and 307 kHz), and ability to control angular coverage dynamically out a maximum of 200°, result in a practical depth resolution of 1 cm and horizontal resolution of 10 cm at survey depths. After MBS data were collected and processed, they were reviewed as shaded 2-dimensional images. Likely seafloor anomalies were examined in this manner and assessed for either association with physical sedimentary structures and geological features, or characteristics consistent with anthropogenic sites such as shipwrecks and submerged coastal facilities (Royal, 2008, his fig. 2). Those meeting the anthropogenic criteria had their positions logged as targets and used to navigate both the research vessel and a ROV equipped with a transponder to each anomaly.

During the verification of the seafloor process, the forward-scanning sonar fixed onto ROV facilitated locating anomalies and also examined random objects in the area surrounding an anomaly or anthropogenic site. After locating an anomaly, a visual investigation was made using the video camera mounted on a ROV and still photography obtained by divers as all archaeological sites discovered in the Capo Colonna-Punta Scifo area were within safe diving depths. Video and still photography then allowed the drafting of preliminary site-plans. Furthermore, the visual documentation permitted identification of individual objects, once thin layers of sediment covering the objects were hand-fanned away. Shallow archaeological sites in the study area not covered by MBS were also explored by divers who employed metal-detectors and recorded each site by taking photographs and sample measurements. Measurements were obtained in the models derived from four MBS surveyed area sites (AB, AD, AE/AF; *in* Royal, 2008, his fig. 2). Several include features that some studies identify as shipwrecks (Bartoli, 2008, 2010).

To help resolve the question of how non-shipwreck anthropogenic structures became submerged to considerable depth requires rigorous analyses. In the present study, for example, it is proposed that in shallow water depths, the use of the Reson system could better detect small and large bedforms produced by sediment transport processes on the seafloor and distinguish these from tectonically formed features and archaeological materials. Additionally, modern methods used for processing, visualizing and storing MBS data have become more efficient and involve a processing flow adopted from collaboration between academic researchers and hydrographic agencies (*cf.* Hare *et al*., 2004). The original 2005 data collection and processing did not utilize the powerful tools now available such as area-based editing and, until recently, data processing and product generation was time, resource and effort consuming. The shift in hydrographic data cleaning strategy, based on work by Calder (2003), resulted in many of the stochastic product surface creation and cleaning tools now being used. While this approach is mainly designed for data reduction and plotting on nautical charts, the marine science community has also benefited from the new generation of filters, data structures and surface editing tools. The sum of these improvements are such that data can be processed more quickly, inspected using better visualization tools and then archived in a much more efficient manner. Computing technology has advanced to a point where processing of some older survey data can now be reasonably achieved with desktop computing resources and commercial mapping solutions.

The original 2005 MBS data was reprocessed using the above improved methodology, namely CARIS and Fledermaus software with support for the PDS2000 acquisition system and data format. The data acquisition and processing flow was completely overhauled to include the use of these specialized marine mapping tools (Nickerson *et al.*, 2010). The recent inclusion of the PDS file format support (originally collected by the PDS2000 acquisition system) allows complete reprocessing of the data that incorporates the PDS2000 hardware setup into the CARIS vessel file. This allows for the correct horizontal positioning of ray traced sounding depths. A discussion of Reson PDS2000 and the technical details of the PDS file format are available from Reson (2008). The direct import of the PDS files as raw data allowed for quick and easy data filtering of spurious data and outliers using CARIS HIPS tools and the conversion of the original format into the CARIS proprietary but well known HDCS (Hydrographic Data Cleaning System) project format. Hoggarth (2009) provides a good summary of CARIS processing software and its functionality. The cleaned dataset was then converted into a PFM file and imported into Fledermaus. Fledermaus is a powerful tool that augmented the visual inspection of data and furnished additional interpretation of the final cleaned dataset by providing tools to view and measure data features in 3 dimensions, either as traditional surfaces or as point clouds. The merits of the Fledermaus software tool and a good discussion regarding the benefits of visualization to seafloor mapping can be found in Paton *et al.* (2003).

The ability to produce the two different data types was necessary because the depth range of the survey area extended from the shallow inner shelf to the operational limits of the MBS systems; this made gridding data at a single optimum resolution impossible without overgeneralization or large gaps of empty grid cells between cells populated by data. Therefore, a series of grids were created; small scale maps were gridded between 60 and 90 cm, and large scale maps were generated between 10 and 20 cm, approaching the limits of resolution of the relative systems. Using the excellent 3-D visualization tools provided in Fledermaus, fine details were investigated and images created. A thorough discussion of sound propagation theory and refraction is presented in Medwin and Clay (1998) which explains factors that control resolution related to depth below transducer as well as many other aspects of marine acoustics.

4 - Origin of AE/AF Targets

The 2005 survey was organized specifically to explore for and assess submerged archaeological structures and artifacts in the study area (Royal, 2008), a sector where some sites were already known to be present along this inner shelf margin since the early 20th century (Orsi, 1921; De Francisis and Roghi, 1961; Pensabene, 1978). Most are within about 200 m of the Punta Scifo coast in water less than 7 m deep. A more recent examination of this area was made largely by dive surveys and summarized by Bartoli (2008, 2010) who attributed a shipwreck origin to several of these sites. Also of note are studies of ancient quarries in the Capo Colonna-Punta Scifo area, some on land and others now resting offshore (Marino, 1996).

The present study focuses primarily on two targets, AF and AE, that Royal (2008) discovered ca. 250 m offshore by means of MBS and which had not been recorded prior to the 2005 expedition. As described by Royal, AE is a 42 m-long, curvilinear to gentle chevron-shaped feature with a concave form facing northwest (fig. 5A). MBS images show that it is formed by a linear pile of rocks up to 6 m-wide at the base and that rises to 1.0-1.5 m above the sandy shelf floor (fig. 5B-D); the structure is oriented in a direction roughly parallel to the coast (fig. 2, site 14). Diver examination supplements the MBS data, and reveals that the entire structure is formed of separate large individual rocks and blocks of variable size that are stacked upon each other and not cemented together (fig. 5E). The structure comprises a fairly even pile of large boulders that are not dressed and about 1 m in diameter. The mound is wider at the base than at the top (fig. 5B), and rock surfaces are almost entirely encrusted by flora, including *Posidonia* (fig 5E). The dives also reveal that the stack of rock extends into the sand floor, such that the actual depth and width of the very base of the structure is not visible. The AE structure is thus at least 1.5 m in height above its base. The linear rock pile is separated from a massive accumulation of rock slabs that vary in size, some to 10 m in diameter, and that lie about 30 m to the

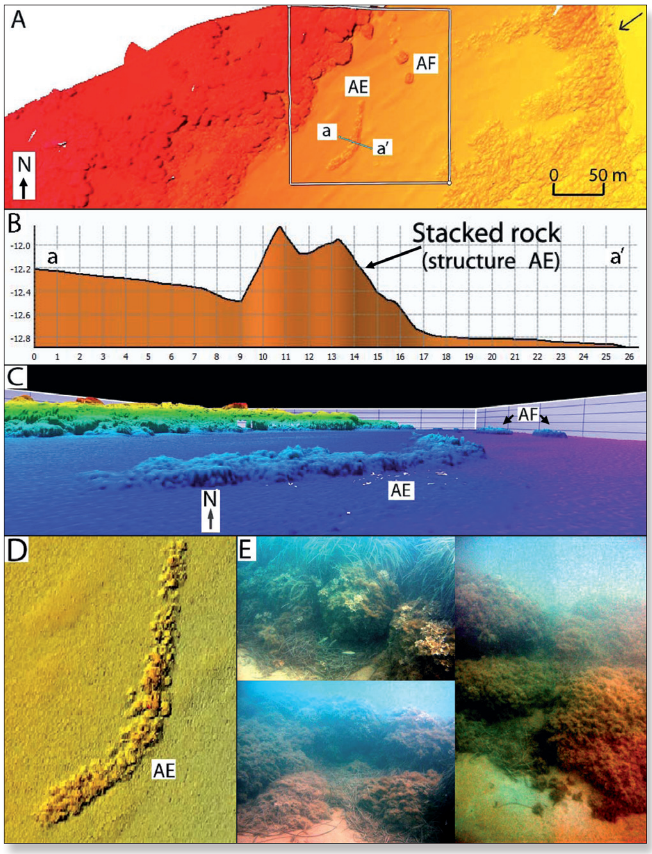

Fig. 5 - MBS images of AE/AF targets (Sites 14, 15 in fig.2). A, B - plan view and horizontal profile of structures (small arrow in A shows sand-rock debris contact). C - oblique image of the structures. D - close-up plan view of AE showing stacked rock. E - diver photographs of AE, showing vegetation encrusted calcarinite blocks that are not dressed or cemented together. Note: vertical and horizontal scales in B and also those in profiles of figs. 6-9 are in meters

northwest; the near-flat seafloor separating AE from the debris field is formed by a near-flat, current-swept sandy floor. In addition to AE, there are two large square-shaped and flat-surfaced blocks (target AF) positioned about 30 m and 35 m to the east-northeast of feature AE (fig. 5A, C). One is 4 by 4 m and the larger is 5 by 5 m in form, and these rise to ~2 m above the sandy floor. Their flat faces are at right angles to each other and their bases, buried by sand as at AE, are not visible. Not surprisingly, artifacts were not recovered in the long rock pile as these are completely covered by flora (fig. 5E). Bartoli (2010) does not add to the above description except to suggest that if AE were a pile of quarried stone, these rocks would be of calcarenitic lithology and, in this, he is correct.

The above observations indicate that, regardless of depth, the origin of both AE and AF are not of natural formation and can be confidently attributed to human construction. Taking into account their overall shape, size, manner in which the large rocks are stacked upon each other and their relative position, the two structures were clearly placed with a specific purpose in mind, almost certainly part of a harbor facility as originally indicated by Royal (2008): AE as a breakwater, and AF as part of probable pier structures. Together, MBS and diver records indicate the rocks stacked at AE preclude the beachrock origin suggested by Bartoli (2010). This conclusion is also based on comparison with attributes of beachrock examined along the Crotone peninsula (Pirazzoli *et al.*, 1997), the Ionian coast (Stanley *et al.*, 2007), areas elsewhere in the Mediterranean, and around the world where that facies has been examined petrologically and petrographically (Dalongeville, 1984). Beachrock commonly indicates a coastline to shallow marine origin, with an elongate stratal form and orientation parallel to the shoreline. However, the similarity ends here: beachrock, unlike the AE structure, presents a much different set of attributes. It is formed of well-defined, cemented horizontal layers, with distinct superposed flat strata each of which are usually <50 cm thick (*cf.* Pirazzoli *et al.*, 1997, his fig. 5). When beachrock strata break apart, pieces separate as angular fragments of variable size (Stanley *et al.*, 2007, their fig. 12), not as a high vertical pile of large subangular to subrounded rock blocks and boulders of calcarenite as observed forming the AE structure.

The lack of human artifacts recovered to date from the AE/AF site precludes formal dating of the structures. A pre-Roman harbor origin is favored in view of the absence of concrete features forming a more structured facility. By comparing findings off Punta Scifo to other similar ancient stacked stone structures dated in the Mediterranean, Royal (2008) indicates that the AE/AF site was most likely part of a Greek harbor. This facility would have been established along a protected section of natural coast in proximity to the sanctuary of Hera Lakinia. That coastal margin is now submerged and covered by the coarse debris fields of large slabs positioned northwest of a flat sand field and the AE/AF targets (fig. 5A). We propose that linear stacked rock structure AE was emplaced at, or seaward, of the surf zone with its shape likely taking into account the strong wind-driven wave energy directed from southern and eastern quadrants. It is expected that future removal of the vegetal cover and systematic excavation of the rock pile will recover datable archaeological materials so as to more firmly establish the age of the AE/AF construction.

5 - MBS Images of Sedimentary Structures

The above-described coastal facility (fig. 5B-D) must have been submerged to depths exceeding 12 m as a result of physical processes that modify the seafloor. Some bottom structures are produced by sedimentation *per se*, including gravitative mass flows and bottom currents, while others result from sediment compaction and tectonic displacement that have modified the seafloor surface and its subsurface. Numerous and diverse physical structures recorded by MBS in the immediate study area and farther seaward on the shelf platform off the Crotone peninsula were examined in order to determine which ones, if any, could have played a role in the possible submergence-of-site scenarios. The focus of this section is on identifying some common bedforms viewed on MBS images that resulted primarily from sediment transport and depositional mechanisms on the shelf.

The most prominent sedimentary deposits are those that comprise very coarse clasts that cover large areas of the seafloor in an almost continuous and generally coast-parallel distribution pattern. The deposits comprise large angular slabs and subrounded boulders, some to 10 m or more in diameter (Figs. 5A, 6A, 7A), that appear concentrated on the inner shelf between the present coastline and depths to about 20 m. For the most part, blocks and slabs lie in a disorganized, non-oriented manner. These are identified as products of former cliff materials that were undercut and failed during the landward incision of earlier (Pleistocene-Holocene) coastline margins, partially due to the rise in sea level. Some coarse materials mapped at depths greater than 5-10 m serve as now-submerged markers of relict late Pleistocene and Holocene shoreline positions.

The debris fields observed by means of MBS are interpreted as the surface exposures that in all probability bury parts of older deposits, some comprising clasts that are just as coarse. It is likely that such debris are also present seaward of the inner shelf, but in these more distal positions are now masked by a surficial sand- and sandy silt-rich sediment cover. Most of the large materials were introduced by powerful coastal processes of the type that are still active along the modern cliffs, and result from seismicity (fig. 3B) and undercutting by wave action (fig. 4C). Failure of large rock deposits is facilitated by the fact that the strata are jointed, faulted and have otherwise been dislocated by tectonic deformation on land (fig. 4A). Processes involve toppling of large portions of the rocky cliffs, and sliding of these blocks to the base of slope and into shallow water along the coastal margin (fig. 4D-F). Some coarse units recorded by MBS may have also been displaced by mass gravity flows where large volumes of material of fine to very coarse size are derived from land backing the cliffs. These sediments suddenly fail and are shifted seaward, in some cases for hundreds of meters, by debris flow, slump and slide mechanisms (Middleton and Hampton, 1976).

To confirm this, high-resolution seismic profiles are needed to supplement MBS images.

Recent examples of such sudden events described in this area (Lena *et al.* 2003; Blois, 2008) have formed lobes and rises at the leading edge of some mass gravity flow deposits**.** On the inner shelf, at some distance from shore, the width of coarse debris fields is irregular and does not always parallel the configuration of the present coastline. Rather than forming a band of equal breadth and thickness, some of these deposits display fan-shaped cones (fig. 6B1) or irregular configurations (fig. 6B2). The seaward margin of coarse deposits is often quite sharp, usually the result of masking by recent sedimentation processes (fig. 5A, arrow). Mass gravity-emplaced debris, especially those of pre-modern (late Holocene) age, in time become covered by current- and suspension emplaced sandy and silty sediment beyond a critical depth where currents of lower energy prevail. A sediment cover accumulates beyond this depth and increases in thickness toward deeper shelf environments.

There are only few seafloor sectors of the inner to mid-shelf we examined where surficial sandy deposits do not display well-defined sedimentary structures. Bedforms of sand in these sectors most commonly record evidence of ongoing sediment transport and deposition produced by moderate to powerful bottom currents. Included are various types which, in plan view, present linear to somewhat undulating forms; their usual asymmetric shapes record prevailing current directions. By form and size, most are mega-ripples (Reineck and Singh, 1980), with some that have wave lengths (crest-to-crest distance) to 10 m and heights (from trough to crest) to 40-50 cm (fig. 6D, F). Such large mega-rippled forms are usually covered by smaller ripples with lengths of <60 cm. However, most common on the seafloor are ripples with lengths of <2m and heights to 10-20 cm. Crests of individual ripples can sometimes be traced laterally for distances to 100 m (fig. 6E, G), and rippled areas can cover >1000^2 m.

Another bedform type associated with strong bottom currents is the scour depression, a feature sometimes recorded along the contact of coarse debris flow deposits and surficial sand. An example illustrated here is a sandy depression ~40 m wide, eroded to a depth of ~30 cm, and partially filled by a rippled floor; the sharp linear trace of this scoured sector can be followed laterally for at least 120 m (fig. 7A, C). A less common sedimentation type occurs as a long, straight depression oriented NW to SE that crosses the shelf perpendicular to the coast (fig. 7B); the linear channel is parallel-sided, about 40-50 m wide, and approximately 1-2 m deep. Sediment in this channel-like feature is transported to the outermost shelf: material is dispersed at its mouth, and accumulates near the shelf-to-slope break at a depth of ~50 m. This cross-shelf transported sediment has formed a cone-shaped deposit ~100 m wide and nearly 1.5 m thick (fig. 7D). We do not exclude the possibility that these large features affected by sedimentary processes are positioned along structures such as recently active faults.

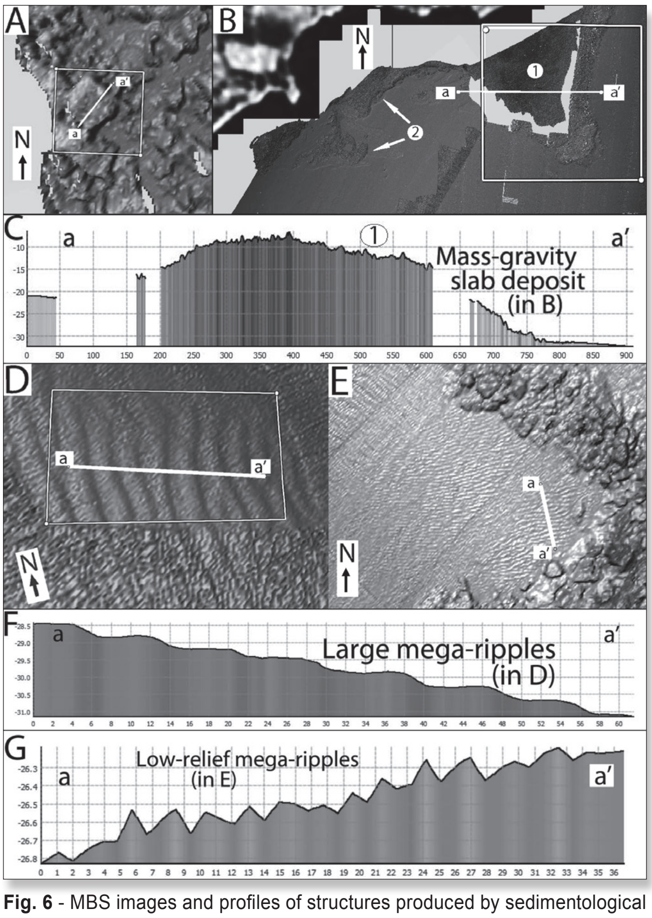

Fig. 6 - MBS images and profiles of structures produced by sedimentological processes. A - very large slab (length ~12 m; Site 2 in fig.2), part of a mass gravity flow deposit. B,C - plan view and profile of extensive coalescing mass gravity deposits: fan-shaped (1) and irregular (2) units extending seaward from the coast (Site 12). D, F - large mega-ripples (Site 7). E, G - more common low-relief mega-ripples (Site 29)

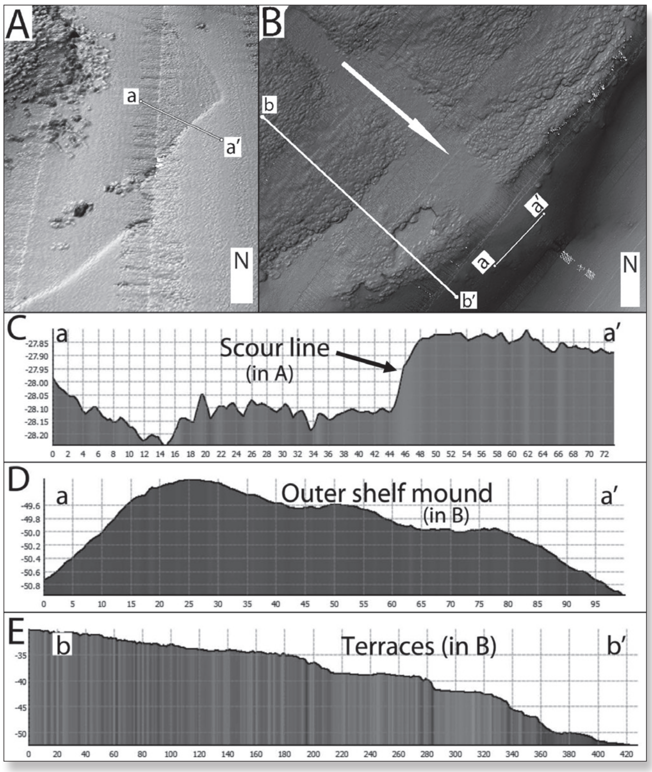

Fig. 7 - MBS images and profiles recording effects of several processes. A, C- scoured seafloor bound by a distinct low amplitude (fault?) scarp (Site 22 in fig.2). B, D – straight cross-shelf linear channel, perhaps of tectonic origin, in which sediment is transported (arrow) to the shelf-upper slope break; note a large mound-shaped deposit accumulating at the outer shelf (Site 32). E, profile parallel to channel in B showing series of terrace-like features on the outer shelf

This brief review of sediment structures viewed by MBS records sediment processes that highlight two salient points pertinent to interpreting the AE/AF structures. The first (1) considers the possible seaward displacement of coastal margin sediment and associated anthropogenic material by gravitative mass flows. These mechanisms can carry a mix of sand to very coarse material to deeper, more distal sectors of the shelf. However, such transport mechanisms are precluded here as an explanation for the presence of the AE/AF structures of originally shallow water origin to depths ~12.5-13 m. It is recalled that the long narrow curvilinear AE structure is formed of stacked but uncemented individual blocks of fairly uniform size that can be traced laterally for a considerable distance without any major breaks, offsets and marked changes in elevation above the seafloor (fig. 5A, C, D). These attributes would not be preserved if the AE feature had suddenly shifted and slid laterally to greater depth by mass flow processes. The second point (2) is that there are distinct linear bottom structures of variable lengths, ranging from a few centimeters to tens or more meters, widely preserved on the seafloor. However, bottom currents that form ripple and scour bedforms could not have induced any significant lateral displacement of the AE/AF structures that weigh hundreds of tons. In our review, it is thus necessary to seek and identify seafloor features other than those associated with either gravity flows and/or bottom current transport to explain the presence of the distinctly shaped AE/AF targets now positioned at least 250 m from the present shoreline at water depths to 13 m.

6 - MBS Images, Neotectonics and Subsidence

It is of special note that many linear bedforms, with relief of <1 m, have maintained sharp distinct morphologies. Under most seafloor conditions affected by bottom currents that are strong enough to transport sandy sediment, as is clearly the case of the shelf study area, shallow depressions tend to be rapidly filled by sediment entrapment. Seafloor irregularities, including steep low-relief scarps, would be rapidly smoothed over and attenuated or become indistinct by effects of bottom current transport and settling of finer material from suspension. This clearly is not the case here and explanations other than sedimentological ones are necessary to interpret the numerous sharply defined structures on the present shelf surface.

In this respect, we recall that the Crotone geological basin is one of the most tectonically modified regions of Italy. It has been affected by relatively frequent and powerful earthquake and seismic activity (fig. 3B; *cf.* Gasparini *et al.*, 1982; Galli *et al.*, 2006; Spina *et al.*, 2007; Stewart and Morhange, 2009), faulting (fig. 3C; *cf.* Zecchin *et al.*, 2003), rise or lowering of land, and strike-slip motion (*cf.* Valenti, 2010; Zecchin *et al.*, 2010). For example, step-like marine terraces on the peninsula in the vicinity of the coastal margin (fig. 3D, T arrows) provide evidence of geologically recent uplift (Pirazzoli *et al.,* 1997; Mauz and Hassler, 2000; Zecchin *et al.*, 2006; Mellere *et al.*, 2005; Nalin *et al.*, 2007; Santoro *et al.*, 2009). In contrast, responses to Quaternary and ongoing displacement of the adjacent shelf have remained much less well documented in the literature.

Evaluated here are those features of probable tectonic origin detected on the shelf surface, including those off Capo Colonna and Punta Scifo, by MBS data analysis that can shed new light on submergence off the peninsula. During the course of the present study, a total of 656 such structures, many quite long (to >100 m), were examined and their axis orientation measured at twelve different inner to mid-shelf areas distributed between Crotone and Capo Rizzuto. Axes of linear structures measured at each of the twelve areas were averaged and plotted (fig. 2). Two directional trends were recorded in most areas, and the heavier white lines on the twelve directional compass graphs indicate the predominant axes. The NW-SE and NE-SW orientations, quite constant throughout the MBS survey area, are similar to the two major structural trends mapped on land (fig. 3C). This could indicate that late Holocene tectonic motion affected both the emerged and submerged terrains in a comparable fashion.

The predominant features are mostly linear, for the most part >10 m long, and could have resulted from extensional tectonics, down-stepping, subsiding motion and/or strike-slip displacement as on land (*cf.* Zecchin *et al.,* 2010). The sharp morphology of so many structures indicates that seafloor deformation has not been masked by surficial sedimentation and is thus most likely of geologically recent origin, with some displacement that may be continuing. The majority of features on the shelf platform viewed as tectonically influenced are grouped into four general categories as summarized below:

Tilted seafloor

Seafloor surfaces in areas where tectonic displacement is moderate to minimal and sedimentation is active tend to be near-horizontal and flat with muted relief features. In the studied region, however, this is not necessarily the case. An example is shown of a sector that is >400 m wide and where all flat seafloor surfaces between areas of relief are tilted and preferentially lowered toward land, indicating a broad regional offset of this shelf sector (fig. 8A, B).

Linear scarps and terraces

The most commonly encountered linear features are scarps (steep-sided ledges) and step-like terraces, each with a relief of 50 cm or more, that can be traced laterally for distances of 50 m or more (fig. 7B, E; 8D, F). Both types are best observed on the mid-shelf to the shelfbreak and uppermost slope and, in many instances, the linear axes of scarps and step-like structures are oriented roughly parallel to the coastline, with their steep drop-off slope facing seaward.

Ridge and graben-like depressions

MBS images and their horizontal profiles record ridges (fig. 9A, C) and graben-like depressions (fig. 9B, D), both widely distributed on the shelf. Ridges may rise to 4 m or more above the surrounding seafloor, while depressions are usually less than 2 m below the adjacent shelf topography.

In plan view some ridges display an angular or zig-zag shape as if formed, or at least partially controlled, by a criss-cross set of faults oriented at different angles (fig. 9A).

Submerged islands

Probably most remarkable in terms of size and depth on MBS images are large features mapped in the survey area that are of oval shape in plan view. Two of these SSW of Capo Cimiti (fig. 2) most likely indicate submerged island platforms. One illustrated here as example is >800 m long by 400 m wide, and rises above the surrounding seafloor by as much as 10 m (fig. 9E, F, G); its upper surface lies at a depth of 19 m below present sea level. With a tail-like extension that trends landward, this feature probably originated as part of a former coastline, perhaps a headland. As a result of continued erosion and perhaps submergence, it then became partially detached and eventually fully separated from the retreating coast as a stack (*cf.* Sunamura, 1992). Subsequently, this former land mass was further eroded and, in its final island phase, reduced in size before its deep submergence beneath the waves.

Evidence of what may be viewed as extreme subsidence is indicated by MBS mapping of the two above-cited relict island-like forms now observed resting at depth off Capo Cimiti (fig. 9E-G). It is possible that these two are part of a group of five islands that were once positioned off the Crotone peninsula and originally described by Pliny in the 1st century AD; several of these were subsequently recorded off Capo Cimiti on nautical charts such as those prepared by the geographer Piri Reis in 1521-1525 AD and other cartographers until the early 1700s (Mercator, 1595; Mallet, 1683; Goeree and Goeree, 1710). Most charts published after this time do not show the islands, indicating they had disappeared by the 18th century (Bartoli, 2008,). Considering the present depths at which the top of the two islands we observed now lie, this vertical lowering in little more than three centuries records averaged subsidence rate of ~6 m per hundred years. Although it has been documented that this region is the most tectonically active along the Ionian margin of Calabria, most coastal geologists would still view a shelf lowering rate such as this as a natural catastrophic event. Displacement beneath and up to the shelf surface (fig. 2) has apparently involved recent subsidence, uplift, and lateral strike-slip motion, much as mapped on the emerged Crotone peninsula (Fenoglio-Marc *et al.*, 2004; Del Río Vera *et al.*, 2009). Causes of subsidence are the result of several factors as yet specifically undetermined, including compaction (likely involving the thick sequences of the Cutro Shale formation that lie beneath the seafloor surface), and readjustment of strata at depth affected by frequent and powerful seismicity and plate motion.

To calculate the submergence rate of the AE/AF targets that are presently at depths of 13-12.5 m, it is necessary to take into account the sea-level stand during the late Holocene about 2700-2300 years ago. Regional (eustatic) sea level at

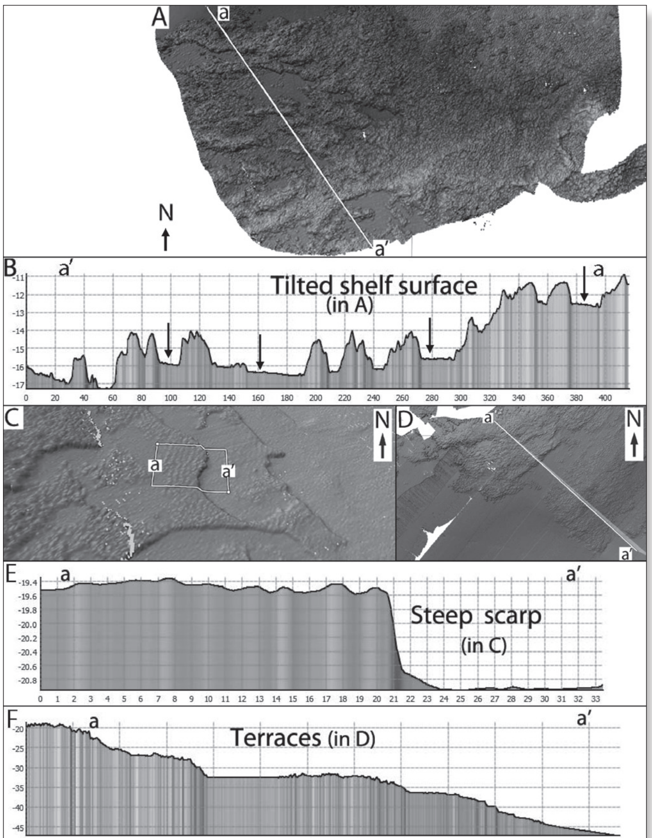

Fig. 8 - MBS images and profiles recording effects of tectonically deformed shelf surface. A, B – highly irregular terraces on inner and mid-shelf show flat surfaces between higher relief features preferentially tilted northward (arrows) (Site 21 in fig. 2). C,E - detail of steep, seaward facing scarp; note mega-rippled upper surface (Site 1). D, F – terrace-like features with axes parallel to coast (Site 26)

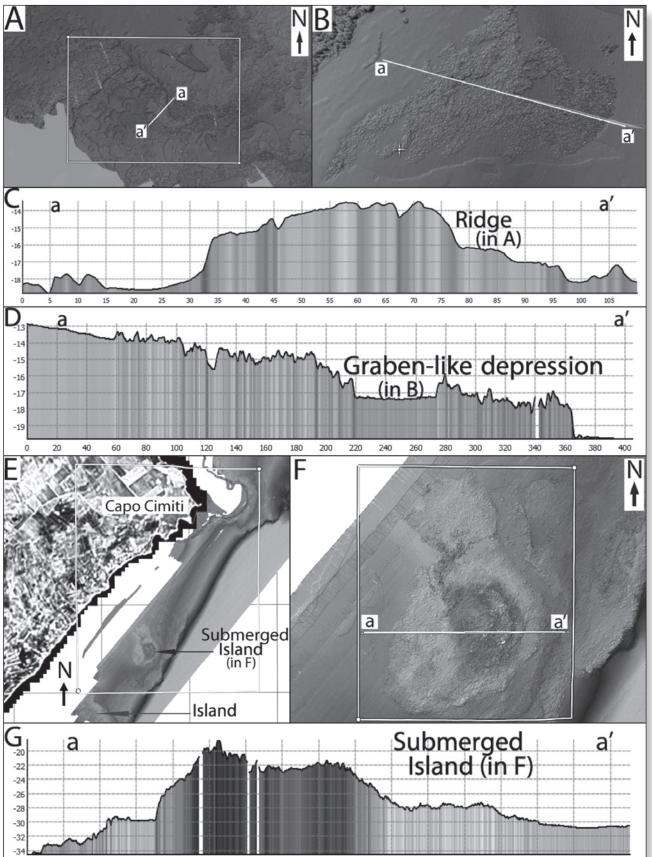

Fig. 9 - MBS images and profiles of large tectonically formed features. A, C - high relief ridge that, in plan view, presents an angular zig-zag trend, probably related to intersecting fault lines (Site 4 in fig.2). B, D - graben-like depression on the mid-shelf (Site 18). E - two submerged islands SSW of Capo Cimiti: in F and G - center of northern island, about 1.8 km from shore, with upper surface depth of -19 m (Sites 28, 30)

the time of Greek occupation is estimated on the basis of sea-level curves (*cf.* LAMBECK *et al.*, 2004). At *ca.* 2500 years ago, this level was nearly 2 m lower than at present (fig. 10).

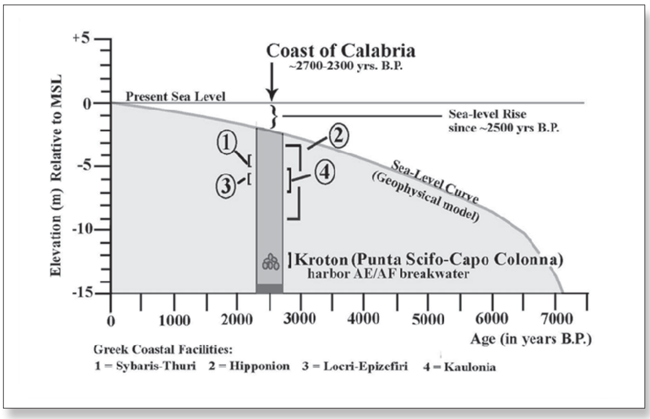

Fig. 10 - Diagram comparing submergence of AE/AF structures with four other offshore Greek archaeological targets examined by authors off Calabria; note sea-level stand at about 2500 years ago (sea-level curve after Lambeck *et al.*, 2004). Subsidence of site AE/AF off Capo Colonna- Punta Scifo study area (in fig. 5) is considerably greater than at the other Greek sites shown

It is also assumed that the top of the AE structure, emplaced as a breakwater close to shore for harbor protection, may have extended ~0.5-1 m above sea level at time of construction. Taking into account these two estimated values, one derives a minimal lowering of the seafloor on which the structure was built by roughly 10 m in the 2 ½ millennia, or a long-term average annual subsidence rate that approximates 4 mm/year. This is a higher rate than that calculated for other submerged or buried sites at four locales off the Ionian margin of Calabria (about 1.0 to 3.0 mm/yr; *cf.* STANLEY *et al.*, 2007; STANLEY and BERNASCONI, 2009, 2010; TENNENT *et al.*, 2009; BERNASCONI and STANLEY, 2011). While high, however, this value is in the range of those calculated in other Mediterranean regions such as some tectonic sectors of the Hellenic Arc (FINETTI and MORELLI, 1973) and, surprisingly, even some of the more stable ones such as the subsiding Nile Delta margin (0.9 to 4.0 mm/yr; *cf.* STANLEY and TOSCANO, 2009; STANLEY, 2010; STANLEY and BERNASCONI, study in preparation).

The sharply-defined morphology of the Crotone peninsula shelf and the numerous large distinct tectonic offset features identified on its surface strongly suggest that submergence of the AE/AF targets did not take place as a single catastrophic event. Rather, it is more likely that subsidence occurred by means of multiple descent phases, or pulses, through time. Taking into account the continuous, physically unbroken nature of the elongate AE archaeological feature and the two large rectangular AF structures, we propose that the total minimal subsidence of 10 m at the top of the breakwater more likely occurred over time by a series of many small downward movements, rather than by a few more powerful destabilizing pulses.

Conclusion

MBS technology provides a number of advantages with which to study the seafloor in detail. Applications are useful not only for navigation, but also for geological, geographical and/or archaeological purposes. Data can be obtained rapidly over large areas in a manner that could not be as thoroughly covered by diving and ROV surveys. Among the major uses of this still underutilized system are detailed and precisely positioned images providing both 2-D and 3-D views that record features as small as a few centimeters in relief and length, or that cover areas as large as hundreds of square meters. Moreover, the MBS database can be reprocessed to provide more detailed, oblique, high-quality relief sections was well as larger-scale plan view images as needed for specific research and nautical purposes.

The present investigation focuses on the contested origin of two seafloor targets discovered in 2005 by MBS in the Capo Colonna-Punta Scifo study area off Calabria. These had first been interpreted as archaeological in origin, and then subsequently as of natural lithic formation. We proceeded here to determine if the larger of the two targets, an elongate high-relief structure, is possibly a breakwater and part of an ancient now-submerged harbor facility as initially suggested by ROYAL (2008), or whether it is of natural beachrock origin as more recently proposed by BARTOLI (2010). A beachrock or slump debris formation is ruled out. Detailed MBS images revealed the stacked, non-cemented and non-stratified nature of large calcarinite boulders that form the structure, indicating artificial construction. Rock-on-rock emplacement is confirmed by direct diver observation and comparison with other Greek coastal features examined in the Mediterranean.

The breakwater structure had been emplaced in a shallow marine environment near a former, but now submerged, coastline. MBS data provide information on how this anthropogenic structure came to rest on a deep seafloor surface that is presently 12.5-13 m below m.s.l. To be lowered to such considerable depth would have entailed remarkably rapid subsidence, especially taking into account that land lowering occurred since late Greek or Roman time, a period of less than 2500 years. The MBS images of the surrounding seafloor help identify some mechanisms that could have been involved in the lowering of the archaeological features. Seafloor structures of sedimentological origin, such as mass gravity flows and bottom currents, are distinguished from those produced by tectonic displacement. It is concluded that the former harbor features subsided primarily by structural motion of variable scale on the seafloor likely resulting from a number of extensional faulting and possible strike-slip events. Of note are two major axial trends of offset features on the narrow shelf platform (NW-SE, NE-SW) that are similar to those mapped on the adjacent Crotone peninsula land area. This suggests that both subaerial and submerged areas of this part of the Calabrian Arc were tectonically modified in similar fashion. The distinct, well-defined linear features we observe on the seafloor indicate that motion occurred as recently as the late Holocene by a series of seafloor lowering pulses and that this lowering probably still continues periodically. The MBS data collected in this investigation show that the shelf platform off the Crotone peninsula has been subject to the greatest amount of displacement measured on Calabria's Ionian margin east of the Strait of Messina since ancient Greek time.

As any single technology used offshore, the MBS system is not an end in itself. It is necessary to integrate MBS and diver data in the present study with results of high-resolution subbottom seismic profiles and cores to be obtained from future surveys in this area. Geotechnical properties determined from radiocarbon-dated sediment cores may help quantify the compaction factor in seafloor lowering of strata underlying the shelf surface, and seismic records will provide a means to detect structural displacement resulting from seismicity and plate contact affecting this area. MBS used with these other marine geological methods, and combined with future submarine archaeological observations, will further understanding of the causes and timing of tectonic offset and rapid subsidence in this part of the Calabrian Arc. This multibeam sonar technique is recommended for geoarchaeological problem solving and we expect its applications will likely bear fruitful results on continental margins of the Mediterranean and other world oceans.

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