Maerl-bed mapping and carbonate quantification on submerged terraces offshore the Cilento peninsula (Tyrrhenian Sea, Italy)

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ABSTRACT
On the continental shelf off the Cilento peninsula (eastern Tyrrhenian Sea) the occurrence of more than 13 km^2 of maerl beds was documented through acoustic surveys. Swath bathymetric data along with a dense grid of chirp-sonar profiles were acquired over more than 180 km^2. The maerl facies was characterized on the basis of the components analysis of 32 grab samples collected at selected sites. Mapped maerl-beds are predominant on submerged terraces located at variable water depth (wd) between 42 and 52 m. This preferred distribution on submerged terraces is probably associated with relatively vigorous bottom currents generated by local circulation that hinders the deposition of terrigenous sediments. Calcareous red algae result to be the most important producers of carbonates from 40 down to 60 m wd. We calculated the coralline carbonate accumulation from the percentage cover of coralline algae (thin section mapping) × 1 cm-thick layer of sediment × measured coralline density. The total coralline cover (living plus dead) in the Cilento area is 13.96 km^2, with a total 316 800 tons of algal carbonate in the surface 1 cm layer, that correspond to 20 430 g m^{-2}. Living maerl is recorded at a depth of 47 m, with a live coralline

cover of about 40% over a minimum area of about 1.2 km². This live maerl has a thickness of about 1 cm and is composed mainly of unattached branches of *Lithothamnion corallioides* (P.L.Crouan & H.M.Crouan) P.L.Crouan & H.M.Crouan, 1867. The molluscan association of the maerl bed is dominated by characteristic species of the Coastal Detritic Biocoenosis. The production of carbonate by living coralline algae has been calculated as weight of live corallines in 1 cm-thick layer × 100 y^{-1} × total $area^{-1}$ and corresponds to 90.8 g m^{-2} y^{-1}.

KEY WORDS
seafloor mapping,
submarine geomorphology,
marine terraces,
acoustic facies,
maerl distribution,
coralline carbonate,
Cilento peninsula.

RÉSUMÉ
Cartographie du maërl et quantification de la production carbonatée sur les terrasses sous-marines au large de la péninsule du Cilento (Mer Tyrrhénienne, Italie).
Des données de bathymétrie par balayage ainsi qu'une grille serrée de profils réalisés au « sonar chirp » ont été acquises dans une zone couvrant plus de 180 km² de superficie sur le plateau continental au large de la péninsule du Cilento (Mer Tyrrhénienne orientale). Ces reconnaissances hydro-acoustiques ont permis de détecter la présence de bancs de maërl dont l'extension dépasse 13 km². Le faciès du maërl a été caractérisé à partir de l'analyse de 32 échantillons prélevés dans des sites sélectionnés. Il abonde sur les terrasses submergées sises à des profondeurs variées entre 42 et 52 m. Cette distribution préférentielle est probablement liée à la dynamique locale des courants de fond qui empêche la sédimentation terrigène. Il en résulte que les algues rouges corallines sont la principale source de production calcaire entre 40 et 60 m de profondeur. Nous avons estimé la production nette de calcaire biogène par ces algues à partir de leur taux de couverture (cartographie à partir de lames minces), rapporté à un centimètre d'épaisseur de sédiment et à leur densité mesurée. Dans la région du Cilento, la couverture totale par les algues corallines, vivantes et mortes, correspond à 13,96 km², soit un total 316 800 tonnes de carbonate d'origine algaire dans le premier centimètre du fond marin, soit encore 20 430 g m^{-2}. Du maërl vivant, principalement constitué de branches libres de *Lithothamnion corallioides* (P.L.Crouan & H.M.Crouan) P.L.Crouan & H.M.Crouan, 1867 et dont l'épaisseur atteint environ 1 cm, a été récolté à une profondeur de 47 m. La couverture d'algues corallines vivantes est de 40 % environ pour une surface minimum de l'ordre de 1,2 km². L'association de mollusques des bancs de maërl est dominée par des espèces caractéristiques d'une biocénose de type « détritique côtier ». La production par les algues corallines vivantes a été estimée en calculant le poids d'une couche d'un centimètre d'épaisseur d'algues vivantes, rapporté à cent ans et à la surface mesurée ; le résultat de cette opération donne un taux de 90,8 g m^{-2} an^{-1}.

MOTS CLÉS
Cartographie sous-marine,
géomorphologie sous-marine,
terrasses marines,
faciès acoustique,
distribution du maerl,
carbonate produit par des algues corallines,
Péninsule du Cilento.

INTRODUCTION

Maerl beds are a kind of rhodolith deposit and represent a major natural calcium carbonate factory in non-tropical shallow environments (Milliman 1977; Carannante *et al.* 1988; Henrich & Freiwald 1995; Blunden *et al.* 1997; Foster *et al.* 1997; Birkett *et al.* 1998; James *et al.* 1999; Bosence & Wilson 2003; Vilas *et al.* 2005; Hetzinger *et al.* 2006; Konar *et al.* 2006; Hall-Spencer *et al.* 2008). Commonly, maerl beds occur in clear, shallow-marine waters, from tide-swept channels to sheltered areas of marine inlets with weak currents, usually away from important terrigenous sources (Scoffin 1988; Foster *et al.*

1997; Birkett *et al.* 1998; Wilson *et al.* 2004; Riul *et al.* 2008). Maerl can be preserved in sub-fossil and fossil deposits that represent a carbonate reservoir (Boyd 1986; Scudeler Baccelle & Reato 1988; Birkett *et al.* 1998; Toscano & Sorgente 2002; Basso *et al.* 2008). The deposits are principally formed by both living and dead unattached non-geniculate coralline algae that secrete a high magnesium calcite thallus (Cabioch 1969; Blunden *et al.* 1997; Peña & Bárbara 2009). The maerl beds were first described from the northern Brittany coast in the eastern Atlantic, where they occur in the shallow subtidal zone, 4-8 m below the low spring tide level (Cabioch 1969; Henrich & Freiwald 1995). More recent investigations demonstrated the occurrence of Atlantic maerl down to 41 m wd (Birkett *et al.* 1998; Peña & Bárbara 2009). The Atlantic maerl elements are mostly unattached, fruticose coralline plants or fragments of plants belonging to one or a few species. The maerl corallines form non-nucleated rhodoliths, of the *unattached branches* category (Bosellini & Ginsburg 1971; Bosence 1976; Basso 1998; Birkett *et al.* 1998; Basso *et al.* 2009). Mediterranean maerl has been identified to 65 m (Huvé 1956; Jacquotte 1962; Babbini *et al.* 2006) and coralline biodiversity is greater than that of most Atlantic and Pacific analogues (Birkett *et al.* 1998; Riosmena-Rodríguez *et al.* 1999; Bressan *et al.* 2001; Peña & Bárbara 2006; Babbini *et al.* 2006; Giaccone *et al.* 2009). The recent use of acoustic surveys techniques for seafloor mapping and remotely operated vehicles (ROVs) revealed recently the presence of maerl beds off the island of Ischia (Budillon *et al.* 2003; Gambi *et al.* 2009).

Maerl beds can be up to tens of square kilometer in area and several meters in thickness, with a living superficial layer over a thick sub-fossil deposit (Scoffin 1988; De Grave *et al.* 2000). Living maerl beds occur with variable surface cover: from square-meter, coarse-gravel patches composed of unattached, interlocking, fruticose coralline algae among rhodolith fragments and sand, to 100% algal cover (or even more, when stratified) over hundreds of m^2 (Hetzinger *et al.* 2006; Konar *et al.* 2006; Peña & Bárbara 2009). The bed profile can be gently sloping, or level with ripples and mega-ripples. Living maerl can be localized on ripple crests with current velocities of 37 cm sec^{-1} (Keegan 1974; Foster *et al.* 1997; Marrack 1999) or in ripple troughs, together with epiphytes, as documented in Galicia and in the Tyrrhenian Sea (Peña & Bárbara 2006; Gambi *et al.* 2009). Maerl associated with rippled sandy sediment is reported from the Mediterranean (Jacquotte 1962; Gambi *et al.* 2009), eastern and western Atlantic coasts (Keegan 1974; Bosence 1976; Scoffin 1988; Hall-Spencer 1995; Testa & Bosence 1999; Peña & Bárbara 2006), southern Indian Ocean (Collins 1988) and eastern Pacific coast (Foster *et al.* 1997). Maerl beds have an irregular areal shape. The borders of maerl beds correspond to the ecological breaking point of a delicate equilibrium of favourable oceanographic conditions, moderate hydrodynamics and sedimentary rate, avoiding excess sedimentation at one extreme and excess abrasion by frequent motion at the opposite (Steller & Foster 1995; Foster *et al.* 1997; Birkett *et al.* 1998; Barbera *et al.* 2003). Quantitative assessment of maerl beds distribution has been better achieved during the last decades thanks to recently developed seafloor mapping-technologies (Ehrhold *et al.* 2006; Hetzinger *et al.* 2006; Fournier *et al.* 2010). Quantitative mapping and assessment of worldwide maerl distribution are strongly needed because:

– maerl denotes a unique shallow-marine benthic facies that produces large deposits of biogenic calcium carbonate. It is distributed worldwide, and thus it contributes significantly to the global calcium carbonate budget. Maerl and other rhodolith beds are particularly important in temperate environments like the Mediterranean Sea, where other major carbonate (aragonite) producers, such as reef-building corals and green calcareous algae, are scarce or absent;

– coralline algae respond to marine acidification due to increasing atmospheric CO_2 by decreasing calcification, inhibition of spore production and partial dissolution of the Mg-calcite thallus (Kuffner *et al.* 2007; Cumani *et al.* 2010; Basso 2012). Therefore maerl is very sensitive to the ongoing global change;

– maerl-beds have a high conservation value: both the main bed-forming species and the habitat itself are listed in the EC Habitats Directive because of their high level of biological diversity. The Council Regulation EC 1967/2006 prohibits fishing with any kind of net or dredge over live or dead maerl beds. Maerl bed mapping is basic to marine resources management, that nowadays needs definitely to be considered (by the scientific community and by policy-makers) as an ecosystem-based management (BIOMAERL Team 2003; Hall-Spencer *et al.* 2008; Ballesteros 2009; Giaccone 2009; Hall-Spencer *et al.* 2010).

Our work mapped quantitatively the distribution of maerl facies in shallow marine soft bottom environments offshore Cilento peninsula (SW Tyrrhenian Sea; Fig. 1). It combined wide-area data sets (meso-scale geomorphologic maps derived from bathymetric data and seismic profiles) and point-based information (seabed samples) for "ground-truthing" the substrate and biota. It also provided a description and geomorphologic characterization of the morpho-acoustic facies associated with maerl. Moreover, we provided a first assessment of the algal carbonate contribution in the study area, by combining the mapped distribution of maerl with sedimentological and geobiological analyses of maerl samples.

STUDY AREA

The study area is located offshore the Cilento peninsula on the southeastern margin of the Tyrrhenian sea (Fig. 1). The Cilento peninsula is a part of the Apennine belt (Bartole 1984; Bartole *et al.* 1984; Malinverno & Ryan 1986; Mantovani *et al.* 1996) and it is located at the transition zone between the inner thrust belt and the peri-Tyrrhenian belt formed during the last stage in the opening of the Tyrrhenian Sea (Ghisetti & Vezzani 2002). Since late Pliocene times the tectonic evolution of the Campania margin has been characterized by extensional deformation coeval with the opening of the Marsili oceanic basin (Casciello *et al.* 2006). This tectonic activity generated numerous faults (dominantly NW-SE and NE-SW) determining the orientation of recent horst and graben structures. On land, horsts represent promontories that undergo frequent slides and erosion of active cliffs (Budetta *et al.* 2008); deep gulfs, in which Quaternary marine deposits are formed, evince tectonic depressions.

Therefore, the submarine Cilento margin (Fig. 1) has a complex morphology (Coppa *et al.* 1988; Ferraro *et al.* 1997; Pennetta 1996; De Pippo & Pennetta 2000), with a narrow shelf, slightly wider in the northwest than in the southeast. The shelf break is angled, ranging in depth laterally from 100 to 200 m. The upper rugged slope is tilted 2 to 4°, with intra-slope basins and ridges approximately parallel to the shelf-break, as a result of the recent tectonic activity (Trincardi & Field 1991).

The combination of locally-steep gradients, earthquakes (Rehault *et al.* 1987) and relatively high rates of sedimentation (due to uplift of the Apennine chain) cause the Cilento margin to be subject to frequent processes of resedimentation, and mass-wasting deposits are common in Quaternary strata (Trincardi & Field 1992). A sequence stratigraphic approach along the Cilento margin allowed the recognition of discrete mid-shelf and shelf-margin sedimentary deposits formed during sea-level falls and low stands. Such deposits vary greatly in shape and size owing to inherited shelf morphology and variation in the supply of sediment. They form marine depositional terraces along the shelf (Trincardi & Field 1991; Senatore 2004).

Detailed oceanographic studies for the area are still lacking. Available information on the present-day circulation pattern is obtained from general schemes of the Mediterranean-Tyrrhenian area (Millot 1999; Pinardi & Masetti 2000). The most relevant water mass flowing on the Cilento peninsula-continental shelf is surface water of Atlantic origin (MAW-Modified Atlantic Water). MAW occupies the whole Mediterranean as a 100-200 m surface layer and flows in the Tyrrhenian Sea with seasonal variability (e.g., Artale *et al.* 1994; Pinardi *et al.* 1997). During winter, MAW flows along the eastern Tyrrhenian margin from south to north (Fig. 1). In summer the flow weakens and is mostly confined, with an anticyclonic pattern, to the SE sector of the Tyrrhenian basin (Artale *et al.* 1994; Bignami *et al.* 1996; Pinardi & Masetti 2000) (Fig. 1).

METHODS

A total of 675 km of Very-High-Resolution (VHR) seismic profiles (GeoAcoustics GeoChirp II SBP system), 185 km^2 of swath bathymetry data (Multi-

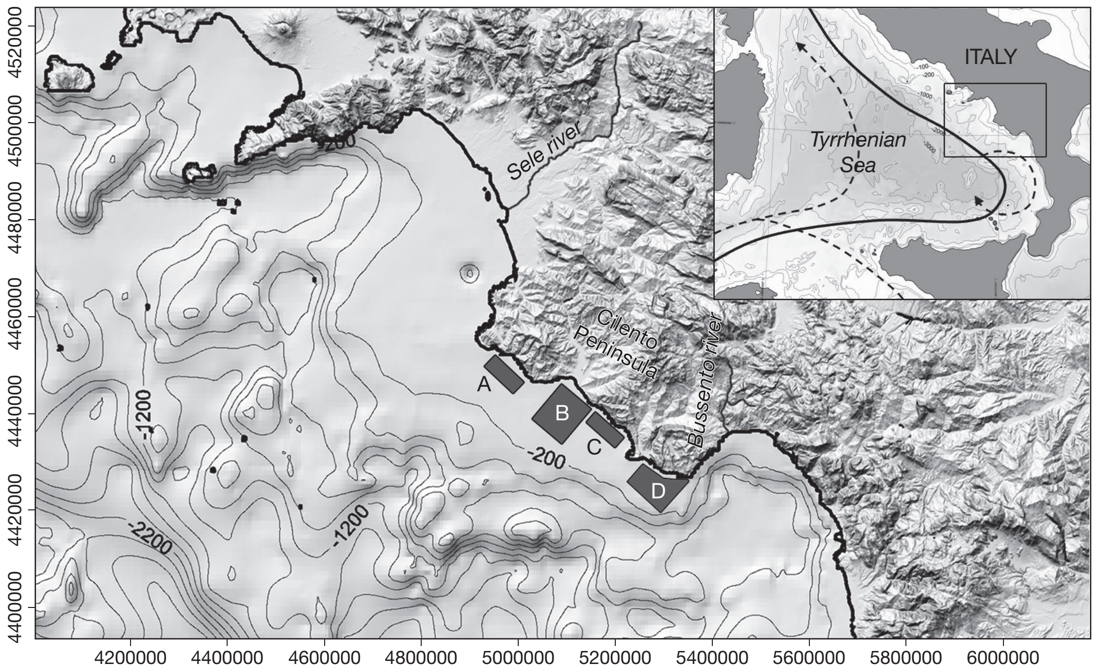


FIG. 1. — Geographical framework of the study area. The main figure shows the regional bathymetry (GEBCO Digital Atlas) and location of the 4 study areas (shaded relief of the mainland is computed by SRTM data). The upper right corner figure shows the existing pattern of surface water (solid line is winter circulation and the dashed line represents the summer circulation – from Millot 1999 and Pinardi & Masetti 2000).

Beam Eco-Sounder – MBES – Reson Seabat 8160) and 32 grab samples were collected on board R/V *Universitatis* in 4 areas of the continental shelf off the Cilento peninsula between 10 m and 130 m wd (Savini *et al.* 2005; Fig. 1).

The chirp-sonar employed (4 × 4 transducer array) uses advanced frequency modulation (FM) and digital signal processing (DSP) techniques to optimize seabed penetration and record resolution over the 1 to 12 kHz frequency range, providing a vertical resolution of approximately 1 millisecond. Chirp data were processed by Triton Elics International® software packages producing geotiff images of the investigated seismostratigraphy.

The acquired MBES data did not cover the investigated areas with 100% of coverage, and for this reason Digital Terrain Models (DTMs) were computed, for each area, at medium resolution (50 m cell size) instead of high resolution (i.e. 15 m cell size at 100 m wd). Terrain morphometric attributes (Wood 1996) were extracted from DTMs, using a 3 × 3 cell. Figures 2-5 are a bathymetric map and a slope gradient map with elevation histograms (statistical distribution of elevations) for each of the areas surveyed.

Grab samples were collected, using a 77 litres VanVeen grab, to verify the chirp-sonar echo-type identification, in order to characterize the general distribution of surface sediments (see location of samples in Figures 2A; 3A; 4A; 5A). The texture and fabric of each were described on board, using comparator charts and hand lens.

Dry grain size analyses were performed at the Geological Department laboratory of the Milano-Bicocca University on those samples of sediment composed mainly of sand or coarser grain size, using a 6 sieve vibrating column of decreasing meshes (2 mm, 1 mm, 0.5 mm, 250 μm, 125 μm and 63 μm). 300 grams of sediment per sample were used to pick up and investigate the molluscan death

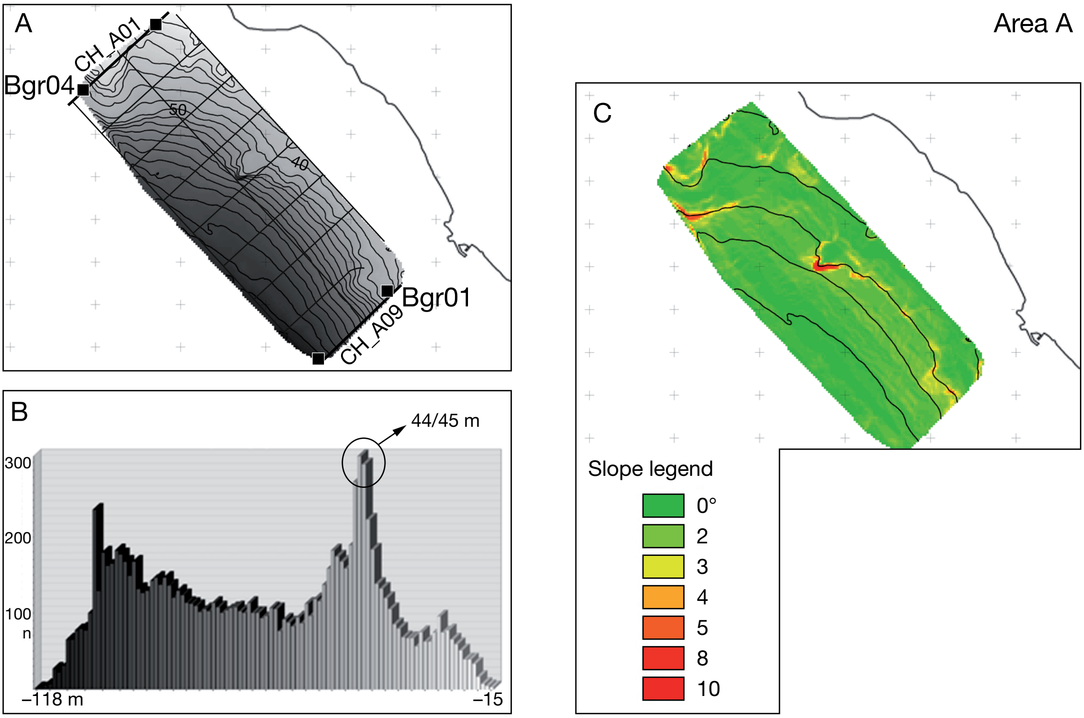


FIG. 2. — Area A: **A**, bathymetric map with location of chirp sonar and multibeam tracklines: bold tracklines show the location of the VHR seismic profiles shown in Figure 6; **B**, histograms of elevations for the digital terrain model (DTM); **C**, slope map. Abbreviation: **n**, number of cells.

assemblages. Only fragments larger than 1 mm were extracted and identified, following Basso & Corselli (2007).

The percentage cover of major benthic components of biogenic sediment samples was obtained by optical microscope analyses of thin sections. Representative sediment samples were poured into small cylinders filled with epoxy resin. The hardened sediment-resin block was removed, UV-glued to glass plates 4.5 cm × 2.7 cm and thinned to 80-110 µm (Bracchi & Basso 2012). Coralline identification was performed on selected algal fragments, embedded in epoxy resin and prepared as thin-sections. Seven categories of sediment were identified at 40 × magnification: 1) coralline algae; 2) bryozoans; 3) molluscs; 4) foraminifers; 5) echinoids; 6) indeterminate biogenic fragments; and 7) terrigenous matrix. The first 5 categories were recognized on the basis of their diagnostic features observable in thin section (Sholle 1978; Sholle & Ulmer-Sholle 2003); categories 6 and 7 were either as fragments showing typical calcite mineralization but lacking diagnostic features (6), or terrigenous fragments clearly derived from continental erosion (7). The distribution of the seven groups was mapped digitally and quantified on the thin sections (prepared from representative sediment samples) using AutoCAD and ArcView GIS (version 3.1) software (Bracchi & Basso 2012).

Coralline density was determined by hydrostatic balance. Coralline accumulation (weight × surface unit^{-1}) for the first centimetre thick layer was calculated as surface covered by coralline algae (Bracchi & Basso 2012) × 1 cm-thick layer of sediment × measured coralline density. Following Adey & McKibbin (1970) coralline production rate is calculated on the basis of a mean growth rate of 0.105 mm y^{-1} for *Lithothamnion coral-*

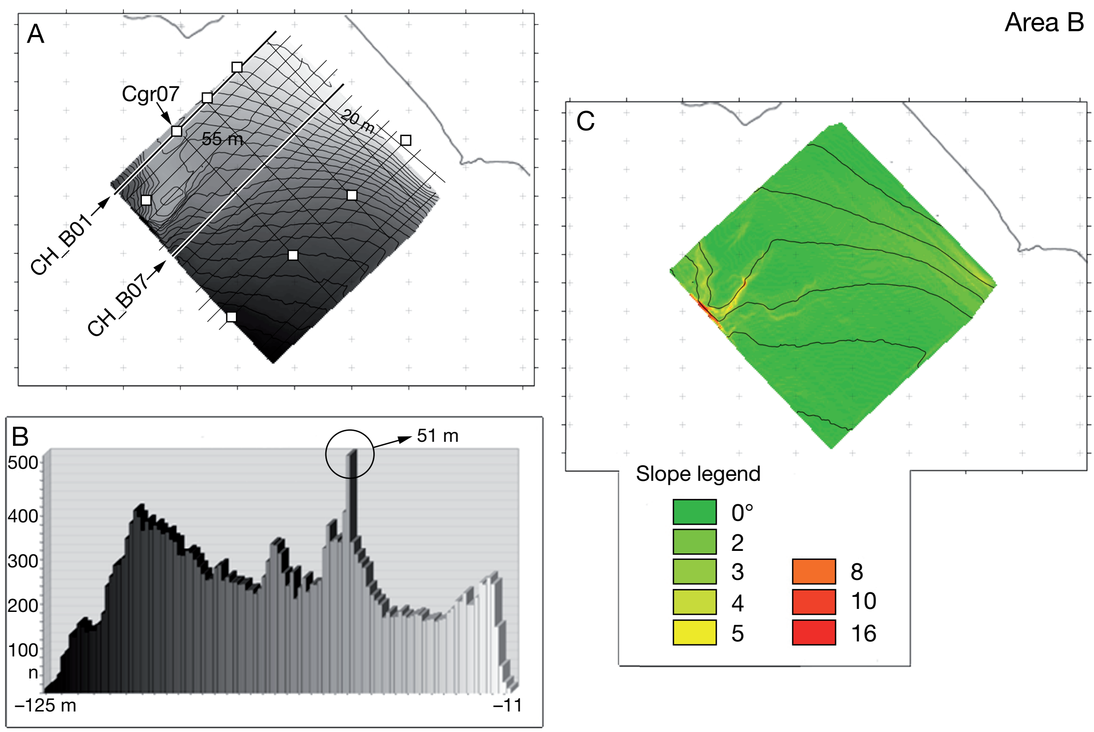


FIG. 3. — Area B: **A**, bathymetric map with location of chirp sonar and multibeam tracklines: bold tracklines show the location of the VHR seismic profiles shown in Figure 6; **B**, histograms of elevations for the digital terrain model (DTM); **C**, slope map. Abbreviation: **n**, number of cells.

lioides (P.L.Crouan & H.M.Crouan) P.L.Crouan & H.M.Crouan, 1867. Since the single branches of sampled *L. corallioides* had a maximum length of 1 cm, according to the mean growth rate of 0.105 mm y^{-1}, they took at least 100 years to grow up to 1cm. Therefore living coralline production rate was calculated as weight of live corallines in 1 cm-thick layer × 100 y^{-1} × total $area^{-1}$.

RESULTS

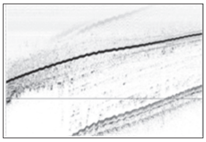
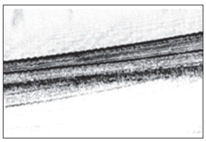
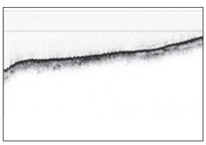
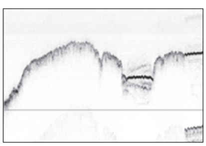
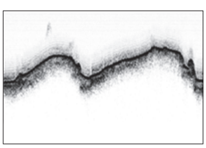
Bathymetry

The continental shelf of the Cilento peninsula is quite narrow with a seaward gradient of less than 1°. The shelf is a bit wider in the northwest than it is in the southeast and the shelf break generally follows the 120 m depth contour. The four areas investigated range in depth from about 10 to 130 m and occupy areas of 20 to 70 km^2, as DTMs and morphometry show (Figs 2-5).

Area A ranges in depth from 15 to 117 m wd and is 28 km^2 (Fig. 2). A change in slope occurs at the 55 m isobath that marks the boundary between the less sloping and irregular topography of the shallower area (where there are small scarps and other positive morphologies) from the smooth deeper zone that falls slowly to the southwest. The elevation histogram (Fig. 2) shows a well defined peak in elevation between 45 and 47 m. On the slope map, these peaks match a broad flat area at around 45 m wd. in the central sector (Fig. 2).

Area B ranges in depth from 11 to 126 m and is 70 km^2 (Fig. 3). In its northern sector a NE-SW sub-elongate and irregular positive feature occurs, its boundaries indicated by well marked breaks in slope, obvious on the slope map. These breaks outline a pronounced terraced area, which on the

Table 1. — Synopsis of the diagnostic features of the five echo types, grouped as distinct and indistinct bottom echoes, with the interpreted Sedimentology (right column) derived from grab sample analysis.

	Echo type example	Description	Distribution	Seafloor morphology	Interpretation/ ground truthing
Distinct					
I_1		Distinct moderate amplitude echo surface reflector with low diffuse penetration	Continuous patches occur at lower depth down to 30 m maximun	Smooth surface, gently sloping seaward	Fine to medium sand – Sediment samples: B_gr01, C_gr01, D_gr01, E_gr06 grab samples collected fine sand
I_2		Distinct parallel reflectors with low to moderate amplitude; from 20 to 30 ms in sound penetration	Wide areas along the outer continental shelf	Smooth surface, gently sloping seaward	Muddy sediment – Sediment samples: B_gr02, C_gr02, C_gr03, C_gr04, C_gr05, C_gr06, C_gr08, D_gr02, D_gr04, E_gr01, E_gr02, E_gr03, E_gr04, E_gr05, grab
Indistinct					
II_1		Strong echo surface reflector with no sub-bottom echoes, flat topography	Strictly distributed along topographic terraces, which characterizes all the investigated areas, from 40 to 50 m of water depth	Terraced areas with sharp seaward boundaries outlined by marked steps, which are from few to maximum 20 m high	Coarse biogenic sediment – Sediment samples: B_gr04, C_gr07, and D_gr03 grab samples (Maerl facies)
II_2		Nearly irregular indistinct and weak surface reflector, no penetration and diffuse tiny incision on the surface	Shallow sectors located between 10 and 30 m of water depth	Rough surface carved by tiny incision and lunate depressions (few meters wide)	The typical morphological pattern and the depth range in which the echo-type occurs, make evidence that it represent the distribution of Posidonia oceanica matte
II_3		Nearly irregular and indistinct surface reflector and diffuse acoustic unstratified sub-bottom echo, moderate to strong in amplitude	Discontinuous patches often located offshore of marked coastline promontories	Very rough surfaces	The morphological pattern (surface roughness and correlation to coastline promontories), the indistinct path of the surface reflector and the lack of penetration suggest that the echo-type is associated to rocky outcrops

histogram produces the peak in elevation values at 50 m wd (see histogram in Fig. 3B). Seaward of the 50 m contour line, the sea floor slopes regularly down to the south, as the isobaths approach a uniform spacing.

Area C ranges from 20 to 84 m wd and is 20 km^2 (Fig. 4). The 65 m contour marks the base of a nearly continuous break in slope that separates an irregular shallow area from a deeper regularly southwestward-sloping surface. The associated slope map

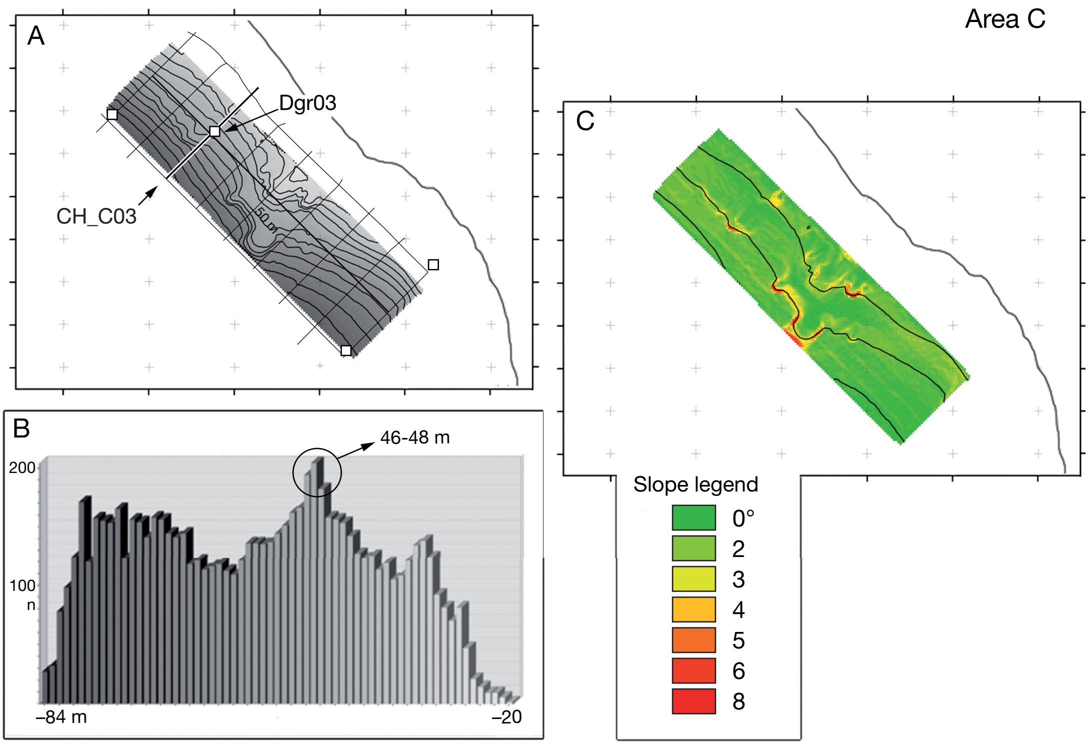


FIG. 4. — Area C: **A**, bathymetric map with location of chirp sonar and multibeam tracklines: bold tracklines show the location of the VHR seismic profiles shown in Figure 7; **B**, histogram of elevations for the digital terrain model (DTM); **C**, slope map. Abbreviation: **n**, number of cells.

and the elevation histogram (Fig. 4), show that in the central part of the shallower area, between 46 and 48 m wd, there is a narrow terrace.

Area D, the southernmost of the four areas, ranges from 11 to 130 m wd and is 67 km^2 (Fig. 5). The topography is significantly more complex than that of the other areas and a number of irregular positive features occur at the seafloor, more numerous in the eastern sector. The most striking feature is a central ridge, elongated southward with an almost flat top and a steep eastern slope with sub-vertical flanks up to 20 m high, the angle of slope attains 10°. This ridge clearly separates the eastern irregular surface from a relatively smooth seafloor to the west. Most of the irregular positive morphologies located to the east of the central ridge have flat tops. They are confined to two discrete intervals (53/60 m and 70/72 m) as the two peaks in values of the associated elevation histogram demonstrates (Fig. 5).

SEISMIC DATA

For each sub-area, a VHR seismic profile analysis was carried out mainly to identify significant echo-types. Each seismic profile was described and classified following the criteria proposed by Damuth (1980). Classification was based on parameters that include the clarity and continuity of echoes along with the presence or absence of a sub-bottom reflectors, and the amplitude of the surface reflector. Five echo-types, classed in 2 broad categories, were recognized:

– distinct echo-types (defined by continuous sharp bottom echoes): echo types I-1 and I-2;

– indistinct echo types (defined by continuous prolonged bottom echoes and/or hyperbolic-wavy echoes): designated as echo-types II-1, II-2 and II-3.

These echo-types are listed in Table 1, together with their sedimentological interpretation based on sediment sample ground-truthing (Table 2).

TABLE 2. — Location and depth of maerl samples collected by grab, along with the sediment type and grain size parameters. Classification of textures uses the Udden-Wentworth scale (Wentworth 1922).

Station	Depth (m)	Coordinates	Description	Medium diam. (Dm Φ)	Standard deviation (Φ)	Skewness
A_gr04	–52	40°16’29”N; 14°54’41”E	Muddy sand	03:01	01:23	00:56
A_gr05	–43	40°19’26”N; 14°55’31”E	Muddy sand	1.83	00:43	0.97
B_gr01	–44	40°10’11”N; 15°00’43”E	Muddy biogenic sand (Maerl)	2	01:07	–0.6
B_gr03	–24	40°13’20”N; 14°56’51”E	Muddy sand	2.88	0.44	1.53
B_gr04	–46	40°12’30”N; 14°55’36”E	Coarse biogenic sand (Maerl)	–0.1	01:04	1
C_gr01bis	–21	40°07’57”N; 15°09’34”E	Very fine sand	3.07	0.48	–0.11
C_gr07	–48	40°08’09”N; 15°03’49”E	Coarse biogenic sand (Maerl)	–0.3	00:09	00:07
D_gr01	–18	40°04’02”N; 15°15’52”E	Very fine sand	02:50	00:54	00:01
D_gr03	–47	40°05’48”N; 15°12’08”E	Coarse biogenic sand (Maerl)	00:04	01:03	00:08
E_gr06	–28	40°00’35”N; 15°18’21”E	Muddy fine sand	03:17	00:23	2.86

Distinct echo-types

Distinct echo-types are defined by a distinct surface echo.

Type I-1. An echo surface reflector with very low penetration. It is diffuse at shallow depths to a maximum depth of 30 m, in connection with a gently sloping and regular surface topography. A discrete and well-characterized surface echo together with the row penetration suggest that medium to coarse grained sediments such as sand and/or gravel produced this kind of echo. Grab samples (Bgr01, Cgr01, Dgr01 and Egr06) confirm the presence of sand in conjunction with this type of echo.

Type I-2. Low to moderate amplitude parallel reflectors. The surface echo reflects a nearly flat to gently sloping topography. Its penetration ranges from 20 to 30 ms. This type was found to exist over large portions of the outer continental shelf that have a smooth surface. Most of the grab samples were collected where this kind of echo exists. (Bgr02; Cgr02-Cgr06; Cgr08; Dgr02; Dgr04; Egr01-Egr05). All of them were mud-dominanted.

Indistinct echo-types

Type II-1. Prolonged echo surface reflector , sometimes bounded by a sharp erosional surface a few meters below. Associated topography is almost flat and regular. This type of echo occurs mainly between 40 and 60 m wd and in discontinuous patches in all four areas. The strong amplitude reflection with no internal reflectors suggests a predominance of coarse sediments. Grab samples (Bgr04, Cgr07 and Dgr03) confirm the presence of coarse biogenic sand and gravel in conjunction with this type of echo.

Type II-2. An indistinct and low amplitude echo surface reflector with no penetration. It occurs only in areas B and D, at shallow depths, ranging down to 30 m. The surface echo shows an irregular topography, weakly cut up by diffuse and tiny incisions. No grab samples were collected where this echo-type occurs, although the depth belt in which it is diffuse and the morphologic pattern observed at high resolution on MBES data, suggests it may be related to the occurrence of mattes of seagrass, *Posidonia oceanica* (Linnaeus) Delile, 1813.

Type II-3. An indistinct and irregular surface reflector with moderate to strong amplitude and no penetration. It occurs in discontinuous patches along the shelf associated with a rough topography, characterized by positive morphological sea floor features of different sizes, sometimes a few kilometres long. No grab samples were collected where this type of echo exists. The highly accidented seafloor, the morphological pattern and the lack of penetra-

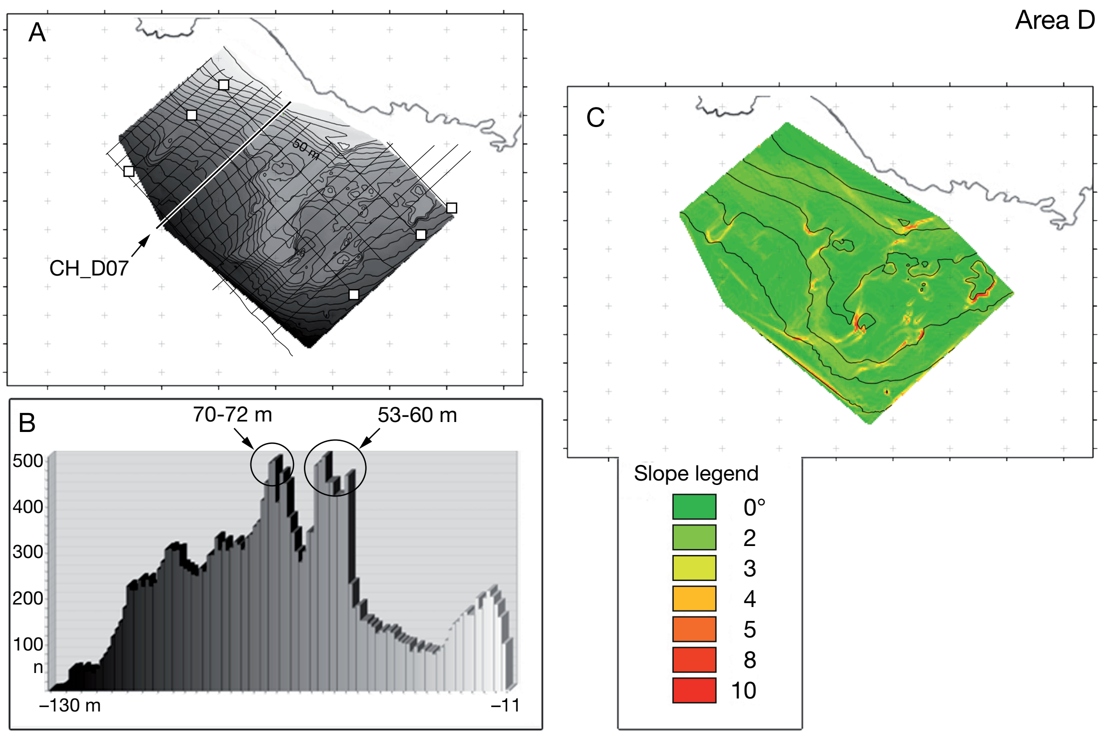


Fig. 5. — Area D: **A**, bathymetric map with location of chirp sonar and multibeam tracklines: bold tracklines plot the location of the VHR seismic profiles shown in Figure 7; **B**, histogram of elevations for the digital terrain model (DTM); **C**, slope map. Abbreviation: **n**, number of cells.

tion by the diffuse path of the echo-surface reflector, suggest that is probably related to outcrops of rocky-grounds.

The VHR seismic profiles presented in Figures 6 and 7 (crossing all 4 areas; see location of profiles on Figures 2 to 5) highlight the main erosional unconformities that outline the general depositional geometry of the Cilento continental shelf. In agreement with Trincardi & Field (1991), we observed that the present-day sedimentation (established when modern sea level was attained, approximately 5.5 ky BP) is represented, for over most of the shelf, by a seaward thinning seismostratigraphic unit. Overall the postglacial wedge overlies a marked unconformity (U01) along the whole shelf, except in localities where it is interrupted by outcrops of the acoustic basement (indicated by echo-types II-2 or II-3; Figs 6, 7). The unconformity U01, which commonly coincides with acoustic basement, marks the flat terraces that have been identified in all the four sub-areas by histograms of elevation computed by quantitative analysis of DTMs.

Sediments, macrobenthic assemblages and algal carbonate

Biogenic sediment in the form of maerl was recovered in four samples: Bgr01, Bgr04, Cgr07 and Dgr03 (Fig. 8). All but Bgr01 were acquired in areas marked by echo-type II-1, Bgr01 was sampled at the boundary between echo-type II-1 and echo-type I-2. The mean grain size of the four samples is that of sand or gravelly sand (Table 2). The gravel is entirely biogenic, consisting mainly of live or dead unattached coralline branches (maerl). The percentage of mud in these sediment semples ranges from 0.1 (Bgr04) to 31% (Bgr01). Grab Bgr01 is muddy

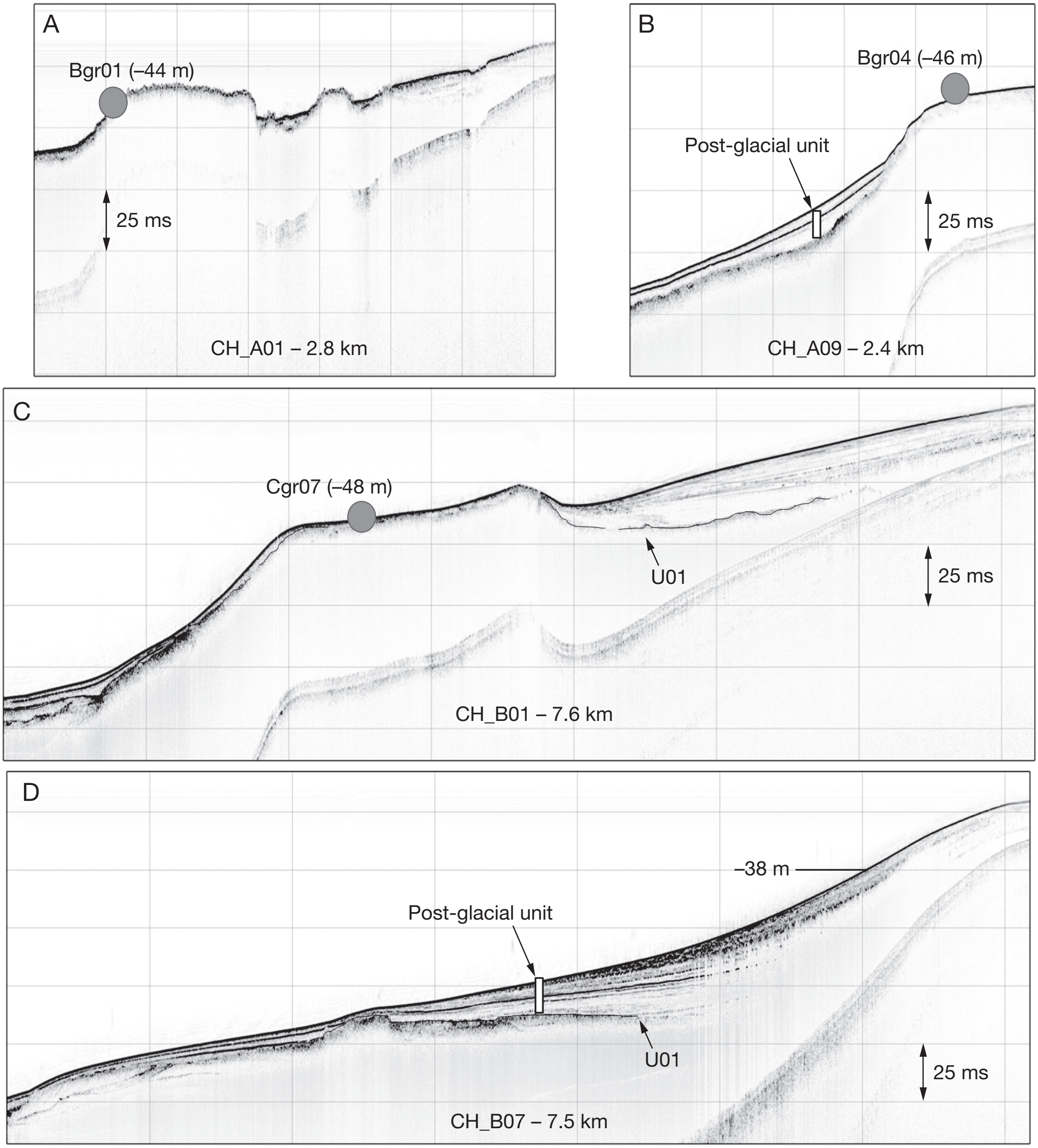


Fig. 6 – Chirp sonar profile of areas A and B. See Figures 2 and 3 for location of seismic profiles.

sand; it was taken at the transition between a sand facies and a maerl facies and free algal branches are here present only randomly. Samples Bgr04 and Cgr07 are accumulations of dead maerl, whereas grab Dg03 is an assemblage of free fine branches of both living (40%) and dead free maerl. In the latter, living maerl is only a 1 cm-thick layer of pink unattached coralline branches, overlying an unknown thickness of dead maerl in mud (7% of the volume).

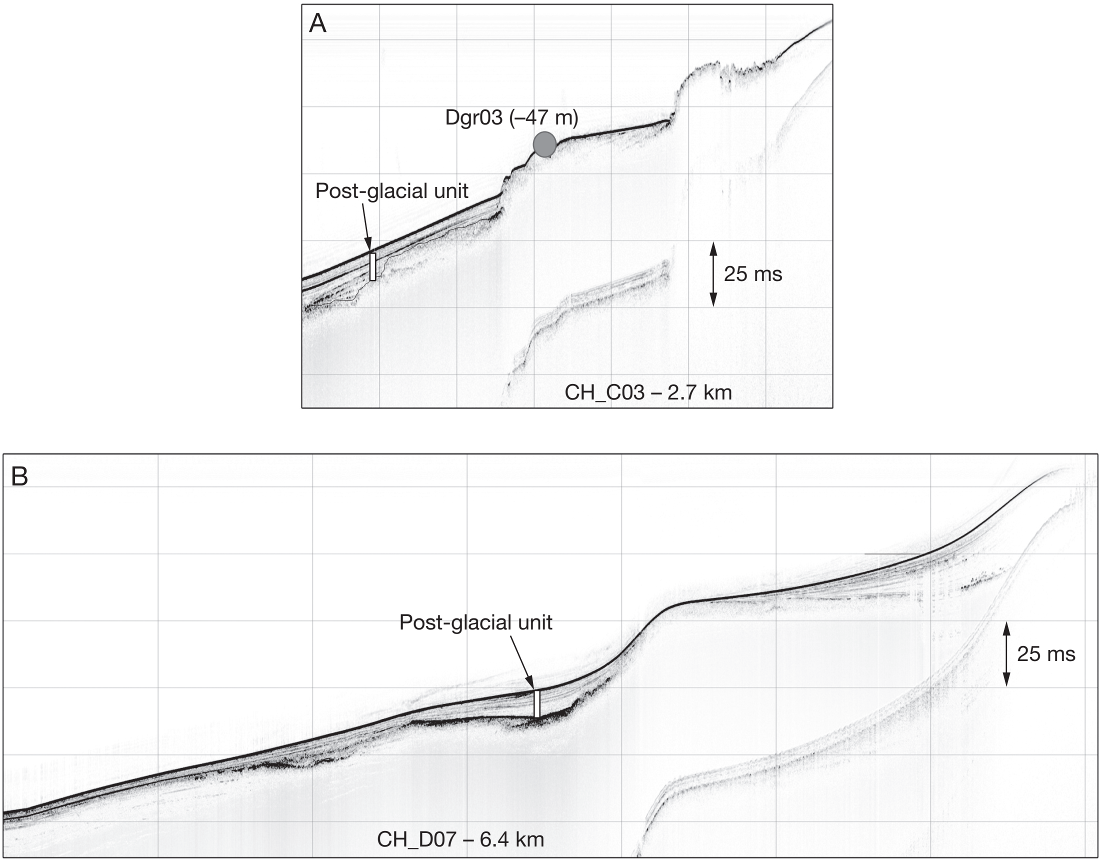


FIG. 7. — Chirp sonar profile of areas C and D. See Figures 4 and 5 for location of seismic profiles.

The molluscan death assemblage was qualitatively analyzed and proved to be homogenous in the four samples. We have identified four bivalves (*Pecten jacobaeus* (Linnaeus, 1758); *Tellina donacina* Linnaeus, 1758; *Plagiocardium papillosum* (Poli, 1795); *Pitar rudis* (Poli, 1795)) and two gastropods (*Melanella polita* (Linnaeus, 1758) and *Turritella turbona* Monterosato, 1877) that are exclusive or preferential characteristic species of the costal detritic biocoenosis (Pérès & Picard 1964; Pérès 1982), together with the current-loving species *Donax variegatus* Gmelin, 1791 (SGCF exclusive characteristic species; Pérès & Picard 1964; Pérès 1982). This attribution is confirmed by a report concerning the littoral fauna of the island of Elba (Basso & Brusoni 2004).

The recognized coralline species are *L. corallioides* and *Mesophyllum expansum* (Philippi) Cabioch & Mendoza, but also *Lithothamnion* sp., *Lithophyllum* sp. and *Titanoderma* sp. are recorded. *Lithothamnion corallioides* is maerl-characteristic species (Pérès & Picard 1964; Cabioch 1969; Birkett *et al.* 1998; Babbini *et al.* 2006).

The mapping of components on thin sections shows that free branches of coralline algae are the primary carbonate producer on the mapped portion of the Cilento sea floor. The cover of coralline algae ranges from 84 to 94%. Given a total sea-floor surface of 15.51 km^2 covered by maerl (echo-type II-1 from geoacoustic survey; Table 1, Fig. 9), we can assess that roughly 90% of the sediment on the sea floor is formed by free branches of coralline algae (according to thin section mapping). Thus, coralline debris covers a total of 13.96 km^2 in the investigated portion of the Cilento area.

The density of maerl corallines by hydrostatic balance is 2.27 g cm^{-3}. Considering only the coralline fraction of the sediment and 1 cm-thick layer, a very conservative figure for coralline (dead or alive) accumulation on the Cilento seafloor results to be about 20 430 g m^{-2} (for a total of 316 800 tons of algal carbonate).

Using the 40% live coralline cover seen in the Dgr03 sample, a mean growth rate of about 0.1 mm y^{-1} (Adey & McKibbin 1970) and the measured density of maerl (2.27 g cm^{-3}) we obtain (for the live coralline fraction of the sediment in 1 cm layer) a production rate of 90.8 g m^{-2} y^{-1}.

If we consider that the whole area of echo-type II in which we collected Dgr03 has an identical benthic facies, we can confidently argue that the area of living maerl is at least 1.19 km^2 (Fig. 9). Therefore, for this area only, using the calculated production rate of 90.8 g m^{-2} y^{-1}, carbonate production from living maerl is about 108 t y^{-1}.

DISCUSSION

The "Maerl-bed morpho-acoustic facies"

The study of selected samples has confirmed the occurrence of the maerl facies (*sensu* Pérès & Picard 1964) at three location between 40 and 50 m wd (Fig. 8). At all three sites there is a strong correlation between the echo-types (II-1) and morphometric parameters (nearly flat sectors). The histogram plots of elevation are a good morphometric indicator of the occurrence of nearly flat areas in a given DTM (according to Passaro *et al.* 2010). In our study they make evident the occurrence of flat and terraced areas in all the DTMs (Figs 2-5). The submerged terraces that were mapped occur in the following ranges of depth: 43-46 (area A), 50-52 (area B), 46-48 (area C), 53-60 and 70-74 (area D). VHR seismic profiles crossing these flat areas are predominantly characterized by indistinct echo-type II-1, which is formed by the exposures of unconformity U01 as flat and terraced surfaces. In all four of the areas the location and distribution of maerl was mapped on the basis of these findings (Fig. 9).

Marine terraces are coastal landforms formed by wave and current action and represent key targets for studies of Quaternary stratigraphy and eustatic changes (Emery 1958; Ferranti *et al.* 2006). Marine terraces are usually formed by an abrasion ramp (its seaward-dipping surface angle depends on the size and quantity of sediments produced by erosion on the platform) and by a cliff that delimits the terraces landward (Bird 2000). Terraced areas found in this study can be morphologically referred to marine terraces and show the following characters:

– most of the terraced area are bounded by a marked seaward step from 2 to 5 m high, that is associated with the II-1 echo type. The break in the slope of the terraces appears sharper when it trends southeastward (Figs 2-5);

– unconformity U01 is a well-defined erosional surface that developed during the last-glacial sea-level low-stand, and seaward it progressively truncates older progradational deposits (Trincardi & Field 1991; Senatore 2004) (Figs 6; 7). Units overlying unconformity U01 are a combination of both transgressive and high-stand marine deposits. The reflector that outlines the mapped terraces correllates well with the U01 unconformity. Overlying, the present-day high-stand drape is not resolvable on the terraces where maerl-beds were sampled (Figs 6; 7);

– the lack of penetration by the acoustic signal on the mapped terraces suggests that they are underlain either by consolidated sediment or by bedrock. That it is bedrock is consistent with the absence of important river systems to supply the Cilento offshore with sediments (in areas both north and south of offshore Cilento a contrary situation exists: to the north the Salerno gulf is fed by the Sele river and to the south the Policastro gulf is fed by the Bussento river; Fig. 1). With a lower sea level, terraces could be formed either by erosion at the new wave base or by deposition through expansion of deltas (Emery 1958). Therefore, the lack of penetration on the mapped terraces (echo-type II-1; Table 1) conforms with their interpretation as submerged relict shore platforms, formed when relative sea level was lowered. The depth range in which terraces are located is consistent with the hypothesis that they were formed during still-stand periods of

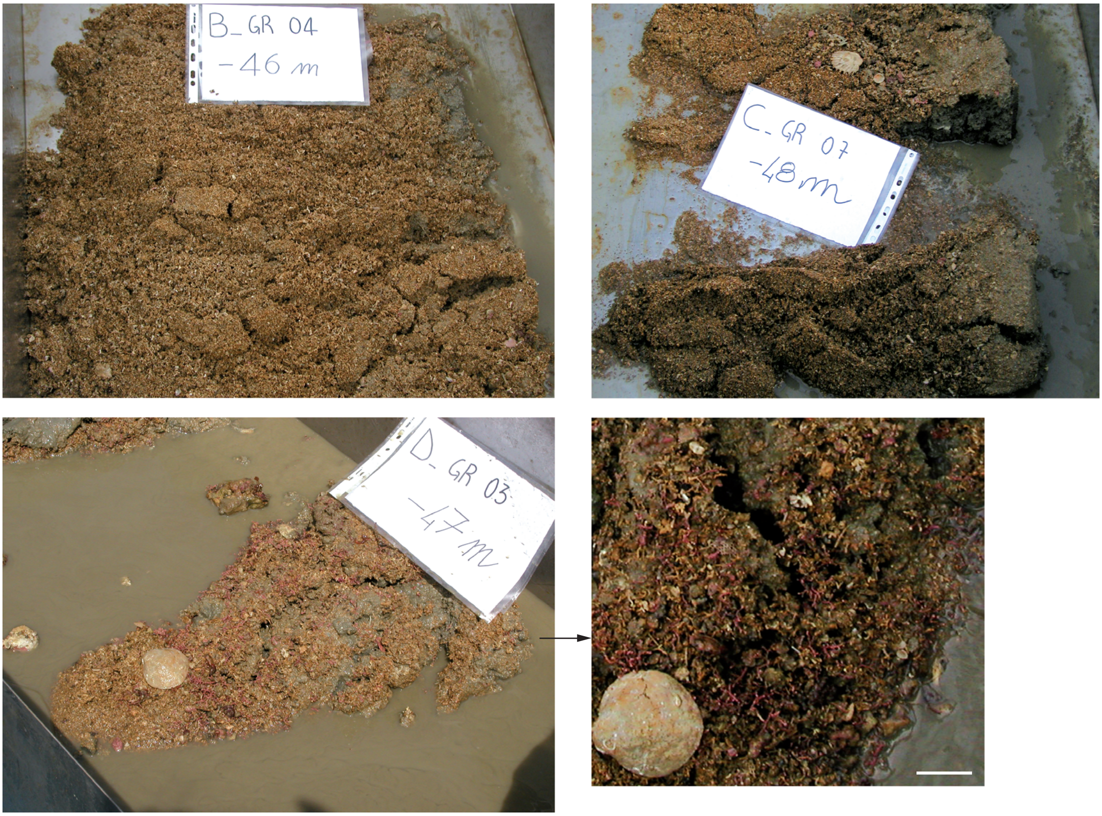


FIG. 8. — Grab samples from sub-areas A, B and C, collected on maerl beds. Scale bar: 2 cm.

the last transgression. Indeed, marine depositional terraces occur in other localities along the Tyrrhenian coasts: the seaward edges of Sardinian and Campanian terraces range in depth between 55 and 95 m (Chiocci *et al.* 2004). Further investigation is needed to ascertain the origin of these terraces and refer them to a precise phase of sea-level.

Rhodolith-bearing facies are often the first lithological unit laid down above major unconformities (Nalin *et al.* 2007). Although we have no precise information regarding the stratigraphic succession on the mapped terraces, over the whole of the Cilento continental shelf maerls are the unique facies found directly overlying these shelf terraces, well correlated to seismo-stratigraphic unconformities (U01; Figs 6, 7) that appear to have been bypassed by present-day high-stand deposits. Obviously a highstand drape is not completely absent on terraces, indeed maerls were sampled there. Our data suggests that the thickness of the highstand drape made by biogenic organisms (heteropic with terrigenous HST deposits amd that produce different discrete echoes) is indeterminate and possibly not resolvable on the VHR seismic profiles. This is mostly due to the reduced sediment aggradation on starved terraces along with the character of the returned echoes (II-1) which is characterized by a total lack of signal penetration.

Our seismostratigraphic interpretation infers that maerl facies aggraded on terraces after their formation. At the latest, maerl accumulation began when sea level attained more or less the present day position (i.e. from 6-4 ky BP or shortly before, during the final stage of sea-level transgression).

The elevation of these submerged terraces and their marked steps seaward suggest that they behave as obstacles to current flow, which is presumed to be enhanced on the terrace. If so, the presence of enhanced bottom currents is consistent with the fact that water movements is reported as being one of the most common environmental condition favouring the installation and accumulations of maerl (Toscano & Sorgente 2002). In addition, the seaward flanks of the terraces are more sharply defined when they are exposed toward SE, countering the northward currents along the eastern margin of the Tyrrhenian (Artale *et al.* 1994). So the preferential distribution of maerl on submerged terraces may be related to the role that terraces exert on the dynamics of circulation as obstacles to the regional flow of bottom currents. This hindrance, together with a more rapid flow locally over terrace floor, slows or prevents terrigenous sedimentation on terraces. This conclusion agrees with that of Ryan *et al.* (2007) in Esperance bay (western Australia), who idendified the exposure to wave energy as the dominant constrain to the distribution of unconsolidated substrate, and consequently the most useful regional predictor of rhodolith and seagrass habitats.

Carbonate budget

Calcareous red algae are the most important producers of carbonate in sediments laid down at depths of 40 to 60 m along the Cilento continental shelf. In general, data on the growth rate of temperate species of algae are scarce and were obtained using a suite of discrete methods (Adey &Vassar 1975; Potin *et al.* 1990; Garrabou & Ballesteros 2000; Frantz *et al.* 2000; Rivera *et al* 2004; Basso & Caragnano 2007; Basso & Rodondi 2007; Caragnano & Basso 2009). Data on the accumulation and productivity of coralline algae in non-tropical areas are also scarce (Farrow *et al.* 1984; Canals & Ballesteros 1997; Freiwald 1998; Bosence & Wilson 2003; Basso 2012).

Literature data on algal carbonate production rates in the Mediterranean range between 464.6 g m^{-2} y^{-1} for the coralligenous environment and 210 g m^{-2} y^{-1} for maerl beds (Canals & Ballesteros 1997). In the maerl facies, single unattached branches of the characteristic species *L. corallioides* and *Phymatolithon calcareum* (Pallas) Adey & McKibbin are 1-3 mm in maximum diameter. *Lithothamnion corallioides* is apparently the most abundant in our samples. Adey & McKibbin (1970) propose a mean growth rate of 0.105 mm y^{-1} for *L. corallioides* in the maerl beds of the Atlantic Ocean. With a maerl density of 2.27 g cm^{-3}, and according to the growth rate reported by Adey & McKibbin (1970) the production rate for a 1 cm-thick layer of the Cilento living maerl is 90.8 g m^{-2} y^{-1}.

Bosence & Wilson (2003), following Bosence (1980), report a production rate of 29-164 g m^{-2} y^{-1} for maerl, based on the rate of growth of individual thalli (expressed as g $CaCO_3$ y^{-1} $thallus^{-1}$) × the standing crop (numbers of thalli m^{-2}). If we use Bosence's calculation (1980) for the grab sample containing living maerl (Dgr03), we obtain a production rate of 66.74 g m^{-2} y^{-1}. The production rate of 90.8 g m^{-2} y^{-1}, found using our approach is within the range suggested by Bosence & Wilson (2003). So, calculation by both methods yields carbonate production rates of the same order of magnitude, and our figure is much lower than the rate of 210 g m^{-2} y^{-1} obtained by Canals & Ballesteros (1997) for maerl at comparable depths on the Mallorca-Menorca shelf. The Balearic maerl is apparently richer than the Cilento maerl, although the observed live coralline cover in our sample (40%) is well within the definition of a rhodolith bed (Steller *et al.* 2003).

CONCLUSION

The occurrence of maerl beds off the Cilento coasts (eastern Tyrrhenian Sea) is reported for the first time. The mapping of maerl beds and the accompanying geobiological analyses demonstrate that:

– maerl beds can be mapped and characterized by acoustic survey combined with analyses of the sediments mapped;

– maerl beds predominate on submerged terraces located at wd of 42 to 52 m. The preferred location of maerl beds on submerged terraces is associated with the role that terraces exert on the dynamics of local circulation, through the deviation of bottom currents preventing terrigenous sedimentation on terraces, and thus promoting maerl growth and accumulation;

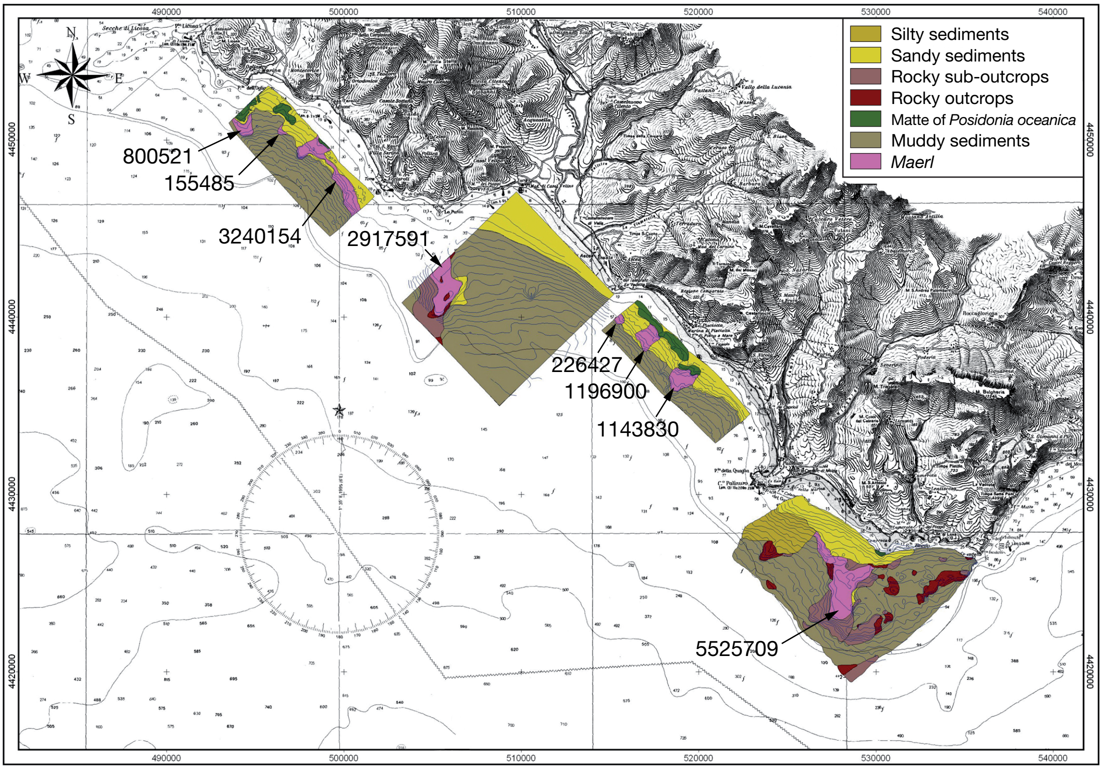


FIG. 9. — Distribution of morpho-acoustic facies mapped in the areas investigated. The size of these areas are indicated in m^2.

– living maerl is recorded at a depth of 47 m, with a live coralline cover of about 40% over a minimum area of about 1.19 km^2. This live maerl has a thickness of about 1 cm and is composed mainly of unattached branches of *L. corallioides*. The molluscan association of the maerl beds is predominantly that of the coastal detritic biocoenosis;

– habitat mapping together with sedimentological and geobiological analyses of selected seafloor samples is useful in the quantification of present-day carbonate accumulations, their rates of production, and the contributions of biogenic sediment;

– we calculate the accumulation of coralline carbonate by multiplying the percentage cover of coralline algae (from thin section mapping) by the density of 1 cm-thick layer of sediment. The total coralline cover (live plus dead) in the Cilento area is 13.96 km^2, that according to measured density gives a total of 316 800 tons of algal carbonate in the surface 1 cm-thick layer, that is to say 20 430 g m^{-2} over the whole acoustic facies that we identify as maerl-beds (15.51 km^2);

– living coralline production rate has been calculated as weight of live corallines in 1 cm-thick layer × 100 y^{-1} × total area^{-1} which gives 90.8 g m^{-2} y^{-1}. These results are consistent with those obtained from literature.

Our results suggest that the importance of coralline as carbonate deposits on the Mediterranean shelf has been underestimated, due to poor knowledge of their distribution. Further investigation, combining acoustic survey techniques and geobiological sample analysis over large areas, will provide a more realistic picture of the role of coralline algae in the Mediterranean carbonate budget.

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