The contribution of calcareous algae to the biogenic carbonates of the continental shelf: Pontian Islands, Tyrrhenian Sea, Italy

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ABSTRACT
This contribution discusses current carbonate deposition in the channel between the Ponza and Palmarola islands and along the western coast of Palmarola, focusing on the quantitative contribution of biogenic carbonate and in particular on the production and accumulation of carbonates by coralline algae. Seventeen out of 150 grab samples have been selected as representative of the main sedimentary features facies of the seafloor between 30 and 100 m of water depth (wd). They were analyzed using XRD and EDTA titration. Thin sections of the same samples were made to identify their biogenic components and to quantify the contribution of calcareous algae to the total sediment. Maximum carbonate production takes place between 40 and 70 m wd, with the percentage of carbonates ranging between 83.1 and 95.7%. of the total. Multidimensional statistical analyses found two different carbonate facies: the coralline algae facies (CA) occupies 38 km^2 between 30 and 70 m wd, and the carbonate matrix facies (CM) covers 24 km^2 between 70 and 100 m wd. An estimate of the current contribution of algal carbonates to seafloor sediments is about 80% in the CA facies and 15% in the CM facies. The accumulation of total carbonate sediments in the uppermost 2 cm interval of the CA facies is calculated to be 20 566 g m^{-2} and the fraction of coralline carbonate in the superficial 2-cm layer of the CM facies is calculated as 16 452 g m^{-2}. The production rate of the mean 7% live coralline covers ranges between 7.91 and 31.64 g m^{-2} yr^{-1}.

KEY WORDS
Western Pontian Islands,
Tyrrhenian Sea,
carbonate mineralogy,
calcareous algae,
carbonate accumulation,
coralline carbonate
production rate.

RÉSUMÉ

La contribution des algues calcaires aux carbonates biogéniques du plateau continental : îles Pontines, mer Tyrrhénienne, Italie.

Les dépôts de carbonates du canal entre les îles de Ponza et Palmarola et le long de la côte ouest de Palmarola ont été étudiés, en particulier la contribution quantitative du carbonate biogénique et la production et l'accumulation de carbonate par les algues rouges calcifiantes. Dix-sept échantillons ont été sélectionnés parmi 150 prélèvements par benne et analysés par XRD et titrages EDTA comme étant représentatifs des principales caractéristiques sédimentologiques du fond entre 30 et 100 m de profondeur. Des sections minces ont été préparées pour définir les composants biogènes et quantifier la contribution des algues rouges calcifiantes au sédiment total. La production de carbonate est maximale entre 40 et 70 m et le carbonate total varie entre 83,1 et 95,7 %. Deux faciès carbonatés différents ont été reconnus sur la base des analyses statistiques multivariées : le faciès des algues rouges calcaires (CA) occupe 38 km^2, dans un intervalle bathymétrique de 30 à 70 m, et le faciès de la matrice carbonatée (CM) occupe 24 km^2, entre 70 et 100 m de profondeur. L'estimation de la contribution actuelle du carbonate algal aux sédiments du fond est de 80% pour le faciès CA et de 15% pour le faciès CM. L'accumulation du carbonate total et du carbonate algal actuel dans les deux centimètres superficiels du faciès CA atteint respectivement 20 566 g m^{-2} et 16 452 g m^{-2}. Le taux de production des 7 % moyens d'algues rouges calcifiantes vivantes varie entre 7,91 et 31,64 g m^{-2} yr^{-1}.

MOTS CLÉS
Îles Pontines occidentales, mer Tyrrhénienne, minéralogie du carbonate, algues rouges calcifiantes, accumulation de carbonate, taux de production de carbonate algal.

INTRODUCTION

In the latest decades, the topic of non-tropical shelf carbonate deposits has become more and more important. Previously, in temperate non-carbonate areas, the deposition and accumulation of carbonate deposits was considered exceptional. Chave (1967) was the first to report that carbonate deposition could also occur on non-tropical shelves if terrigenous input is low. Modern non-tropical carbonate sediments are composed almost exclusively of heterozoan skeletal remains (*sensu* James 1997). The association is characterized by animals like molluscs, benthonic foraminifers, echinoderms, bryozoans, barnacles, sponges, ahermatypic coral, and by plants, like calcareous red algae (Lees & Buller 1972; Nelson 1988). In the Mediterranean and particularly in the Tyrrhenian Sea, shallow marine soft bottom environments are mainly formed by terrigeneous sediments supplied by fluvial systems and coastal erosion processes (Tortora 1996), although various skeletal assemblages can provide an important contribution to present-day shelf carbonate production (Pérès & Picard 1964; Carannante *et al.* 1998). Many authors have described modern carbonate depositional systems in the Mediterranean Sea (Pérès & Picard 1964; Carannante *et al.* 1988; Canals & Ballesteros 1997; Fornos & Ahr 1997, 2006; Betzler *et al.* 1997; Basso 1998). In this paper, we investigate temperate carbonate shelf sediments in the channel between the Ponza and Palmarola islands and along the west cost of Palmarola (Pontian Islands). The phytobenthic assemblages of the area and the living coralline algae were investigated by Basso (1992, 1994, 1996). An interpretation of coralline algal facies and major environmental factors in the framework of the Mediterranean benthic bionomy is reported in Basso (1998).

This study defines the major patterns of carbonate facies on the Pontian shelf, in order to attain a quantification of the contribution of red calcareous algae to those facies.

GEOLOGICAL SETTING AND OCEANOGRAPHY

The Pontian Archipelago is located on the outer margin of the continental shelf in the central Tyrrhenian Sea, seaward of Cape Circeo (Fig. 1). It is formed by five islands subdivided into a western group – Palmarola, Ponza, Zannone – and an eastern group – Ventotene and Santo Stefano (see Fig. 1). The position of the western islands is very critical because the area is disposed along the boundary between a stable platform and a still active slope. Plio-Pleistocene volcanic rocks form the archipelago. Rheolytic to trachytic subaerial and submarine volcanic units crop out in the western islands (Barberi *et al.* 1967). Volcanic activity started in the early Pliocene consequent on extensional tectonics at the Tyrrhenian margin. The western group formed the emergent portion of a structural high that separates the two intra-slope sedimentary basins of Ventotene and Palmarola (De Rita *et al.* 1986). A NS trending channel 7 km wide lies between the islands of Palmarola and Ponza. The channel ranges in depth between 28 and 120 m wd. The shelf break is between 105 and 160 m wd. The rate of sedimentation at the Pontian Islands' shelf break can be roughly calculated at about 0.7-0.8 cm yr^{-1} based on the AMS radiocarbon dating of four cores (Basso *et al.* 2006). Large instability phenomena have been recorded in the southwestern sector, on an extremely steep continental slope connecting the continental shelf to the Vavilov abyssal plain (Chiocci *et al.* 2003). The Mediterranean Sea is an enclosed basin, with thermohaline circulation and oligotrophic conditions, (Hopkins 1999; Pinardi & Masetti 2000; Bricaud *et al.* 2002). The Tyrrhenian Sea, one of the western Mediterranean basins, shows a wind-driven circulation and negligible tidal currents. The dominant wind directions and the major storms are directed W-NW (Istituto Idrografico della Marina 1978; Noli *et al.* 1996) but eastward winds in autumn and winter are reported (Noli *et al.* 1996).

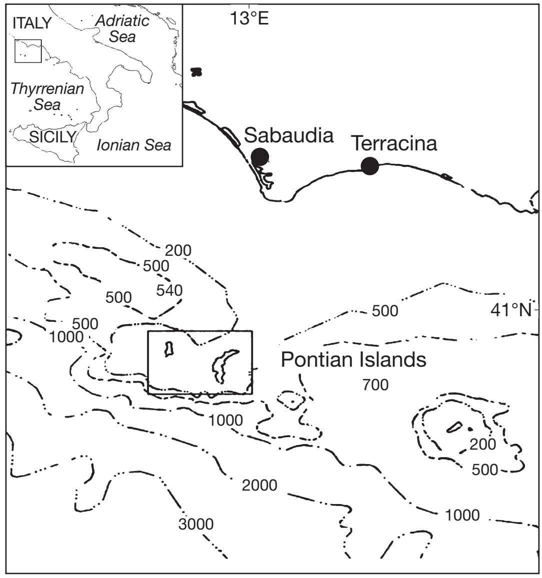

Fig. 1. — Location of western Pontian Islands, Tyrrhenian Sea, Italy. Numbers refer to water depth (in m).

MATERIAL AND METHODS

The project "Taphonomy and Sedimentology on the Mediterranean shelf" (TSM project) investigated the sedimentary processes along the Tuscany and Pontian Islands (Tyrrhenian Sea, Italy). During the summer and autumn 1989, two cruises of the RV *Minerva* sampled the seafloor around the Palmarola and Ponza islands. A total of more than 300 grabs, dredge and core samples were collected. Data on grain size and benthic associations are reported in Corselli *et al.* (in press). Here we considered two areas: the channel between the Ponza and Palmarola islands and the west Palmarola coast. Only the grab samples collected with a modified Van Veen apparatus 50 litres in volume, are considered here. Taking into consideration available data on location and grain size, 150 grab samples were used to define the major pattern of distribution of benthic assemblages and sediment textures (Fig. 2). Seventeen grab samples of the 150 were selected as representative of the variability of sediment textures and benthic assemblages across the investigated area (Fig. 2; Table 1) and have been analyzed to detect their biogenic components and carbonate phases. Samples were collected at depths ranging between 32 and 100 m wd.

Table 1. — Position data (UTM coordinates) and depth (in metres) of the 17 selected samples.

Samples	Position	Depth	Lat.	Long.
minau89be91	W Palmarola	47	405687	125018
minau89be92	W Palmarola	48	405663	125018
minau89be105	W Palmarola	60	405537	124938
mine89be107	SW Palmarola	104	405328	124964
mine89be108	SW Palmarola	78	405431	124956
mine89be109	SW Palmarola	78	405431	124956
mine89be118	Channel	98	405330	125107
mine89be119	Channel	98	405330	125107
mine89be141	Channel	81	405289	125295
mine89be143	Channel	81	405289	125295
mine89be144-146	Channel	68	405382	125314
mine89be151	Channel	32	405500	125168
mine89be159	Channel	46	405494	125208
mine89be160	Channel	54	405485	125226
mine89be163	Channel	61	405471	125262
mine89be164	Channel	61	405471	125262
mine89be181	S Palmarola	61	405466	125262

A portion of each sample was smashed ground up and analyzed by X-Ray Diffraction (XRD) and ethylene-diamine-tetraacetic acid (EDTA) titrations in order to determine the mineralogical composition of the sediment and to identify the crystalline structure of carbonates (calcite, Mg-calcite and aragonite) (Figs 3; 4). The sediments were poured into small cylinders filled with epoxy resin. The hardened sediment-resin block was removed, UV-glued to glass plates 4.5 × 2.7 cm and ground down to 80-110 µm. This technique formed artifacts: large aggregates (sand or gravel size) composed of fine particles (silt and clay size) may occur, but their origin is easily recognizable when magnified under binocular. The thin sections were examined under an optical microscope to obtain the percentages of cover derived from corallines and other major benthic components. Nine categories of sedimentary components were identified at 40× magnification (coralline algae, bryozoans, molluscs, foraminifers, sponges, echinoids, biogenic indeterminate detritus, biogenic carbonate matrix, terrigenous matrix) (Fig. 5). Coralline algae, bryozoans, molluscs, foraminifers, sponges and echinoids were recognized by diagnostic features observable in thin sections (Sholle 1978; Sholle & Ulmer-Sholle 2003). We defined the remaining groups as follows: biogenic indeterminate detritus for the fragments showing a typical calcite mineralization but lacking diagnostic features; biogenic carbonate matrix and terrigenous matrix for the detritus in which we could not distinguish and map the individual grains (under 40×), identifying the sediment as carbonate or terrigenous on the basis of EDTA results. The distribution of the nine groups was digitally mapped and quantified on the thin sections (AutoCAD 2008; ArcView GIS version 3.1) (Fig. 6). The identification of coralline algae genera or species was done on the thin sections (Fig. 7).

Hierarchical cluster analysis and non-metric Multidimensional Scaling (MDS) ordination based on the Bray-Curtis similarity of carbonate mineralogy and sediment components (percentage data) of the 17 sediment samples were performed with PRIMER 6 (version 6.1.12; Clarke & Gorley 2006) (Figs 8; 9). Results of the statistical analysis have been used to identify the major pattern of carbonate facies distribution across the area, and to produce a map of the areal distribution of these patterns (Fig. 10). Sediment density has been calculated as weight (g) × volume^{-1} (cm^3).

Available data on algal carbonate in Mediterranean sedimentary environments are reported as grams dry weight per unit of surface (Canals & Ballesteros 1997). In the gravelly sand of the studied area, the maximum diameter of most of the single algal particles (rhodoliths or unattached branches) is 1-3 cm. Therefore, the biogenic sediments currently forming on the seafloor should be confined to a 2 cm-thick layer of sediment used here to calculate the percentage accumulation of algal carbonates. Several authors have reported growth rates for various species of coralline algae in tropical environments or shallow-water (Adey & Vassar 1975; Potin *et al.* 1990; Garrabou & Ballesteros 1999; Frantz *et al.* 2000; Georgina-Rivera *et al.* 2004). Data on cultured Mediterranean algae are also available (Basso 1995; Basso & Caragnano 2007; Basso & Rodondi 2007; Caragnano & Basso 2009). Basso (1995) estimated a growth rate of 20-25 mm per 200 years for *Phymatolithon calcareum* (Pallas)

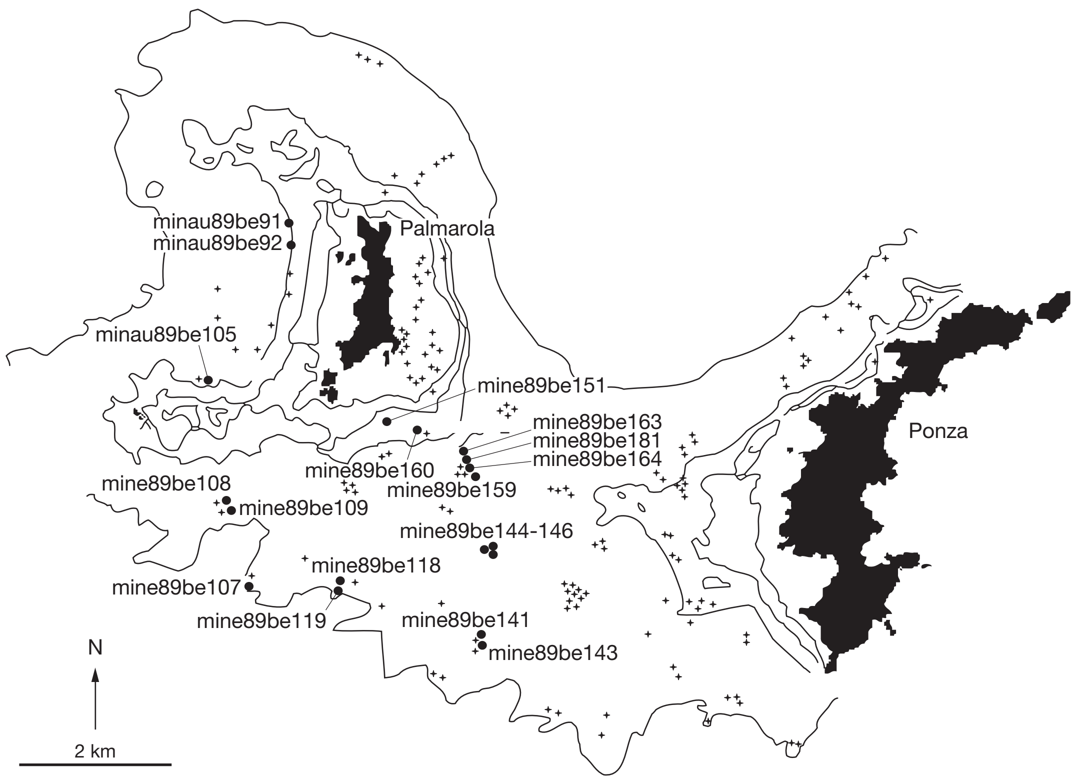

FIG. 2. — Location of samples. Daggers indicate all 150 grab samples. The 17 grab samples selected for study are indicated by circles and the name of the station.

Adey & McKibbin, 1970, sampled between 35 and 75 m wd. Caragnano & Basso (2009) show differences in marginal growth and thickening for *Lithophyllum stictaeforme* (J.E. Areschoug) Hauck, 1877 and *Mesophyllum expansum* (Philippi) Cabioch & Mendoza, 2003 (as *M. lichenoides* (Ellis) Lemoine, 1918), ranging from 1 cm per 200 years to 1 cm per 15 years.

The rates of algal production in the literature range between 464.6 g m^{-2} yr^{-1} for a coralligenous environment and 210 g m^{-2} yr^{-1} for maerl beds (Canals & Ballesteros 1997). We calculated the production rate at the seafloor now on the basis of the percentage cover of living calcareous algae (Basso 1992) and their growth rate. Given the wide range in literature of measured growth-rates of Mediterranean coralline algae, we considered a very conservative figure of 2 cm per 200 years and an alternative faster growth of 2 cm per 50 years.

RESULTS

EDTA TITRATIONS AND XRD

EDTA titrations indicate that all grab samples contain more than 40% carbonate (Fig. 3), excluding the samples minau89be92 (16.3%) and mine89be151 (22%) (Fig. 3). These two samples were taken on the western and southern coasts of Palmarola respectively. The other 15 samples have carbonate percentages ranging from 42.4% to 96.4%.

Semi-quantitative estimates of the mineralogical phases obtained by XRD analysis are given in Figure 4. High-Mg calcite is the most abundant phase in 14 out of 17 samples. The remaining 3 samples are richer in alkaline feldspars and quartz, with high-Mg calcite a secondary component (Fig. 4). Calcite seldom occurs throughout samples, whereas aragonite is always present in variable abundances.

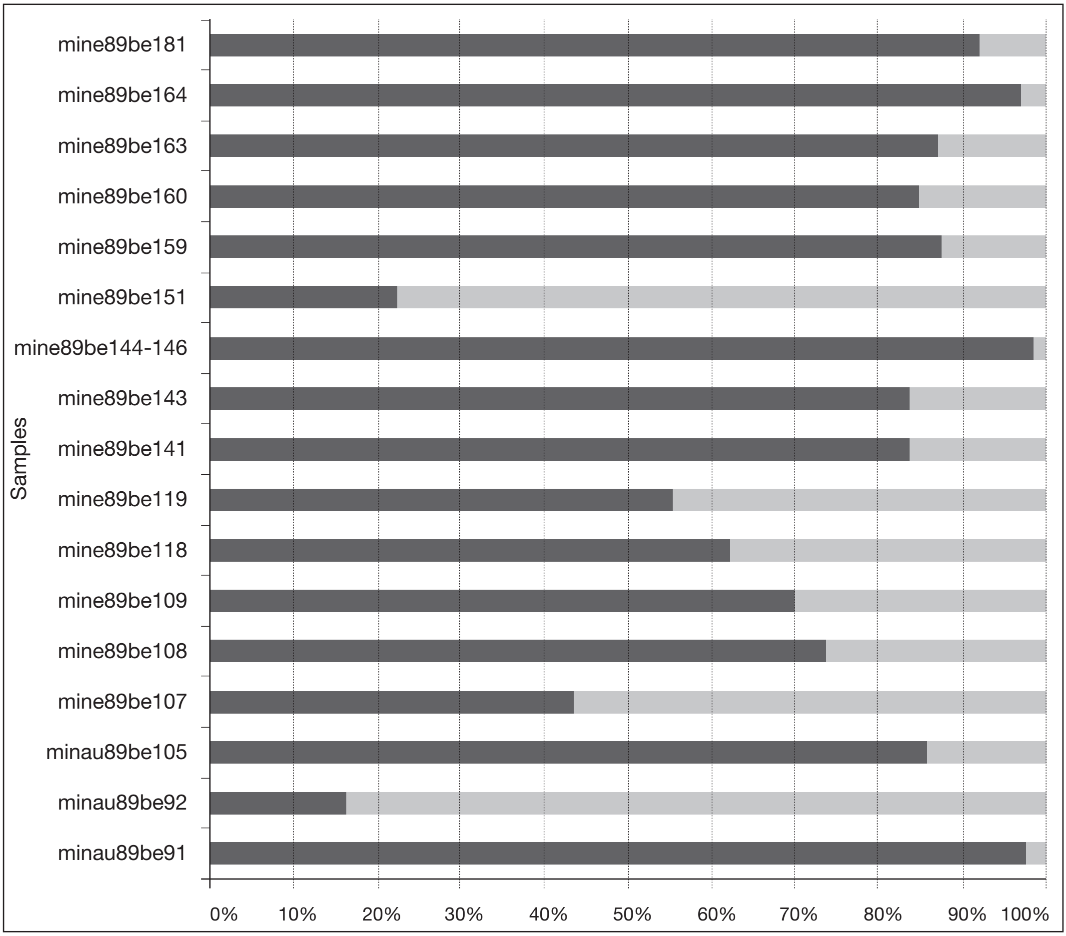

FIG. 3. — EDTA titrations results. Dark grey indicates carbonate percentage. Light grey indicates the percentage of residuals.

THIN SECTIONS

Samples can be ordered into two major groups on the basis of mapping and by calculation of the percentage of coverage for the 9 categories (Figs 5; 6). Recognizable fragments of dominant coralline algae characterize the first group, with percentage cover always exceeding 30%, and ranging up to 92.5% (Fig. 6; Table 3). The second group is characterized by a dominant matrix content: seven samples are more than 65% carbonate matrix, and two are more than 90% terrigenous matrix (Fig. 6; Table 3). Five species of coralline algae have been identified in thin sections: *Lithothamnion minervae* Basso, 1995, *Lithothamnion* sp., *Titanoderma* sp., *Mesophyllum* sp. and *Lithophyllum* sp. (Fig. 7).

MULTIVARIATE STATISTICAL ANALYSIS

Hierarchical cluster analysis and MDS ordination on data from carbonate mineralogy and sediment components show 3 groups, identified with a Bray-Curtis similarity of 70% (Figs 8; 9).

One group has been defined as "Terrigenous facies" (T facies). It was found in 2 samples: minau89be92 and mine89be151. They have low carbonate content (less than 22% on the basis of titrations) and are characterized by a terrigenous matrix (more than 90% of cover percentage).

The second group has been named the "calcareous algae facies" (CA facies) and comprises 7 samples:

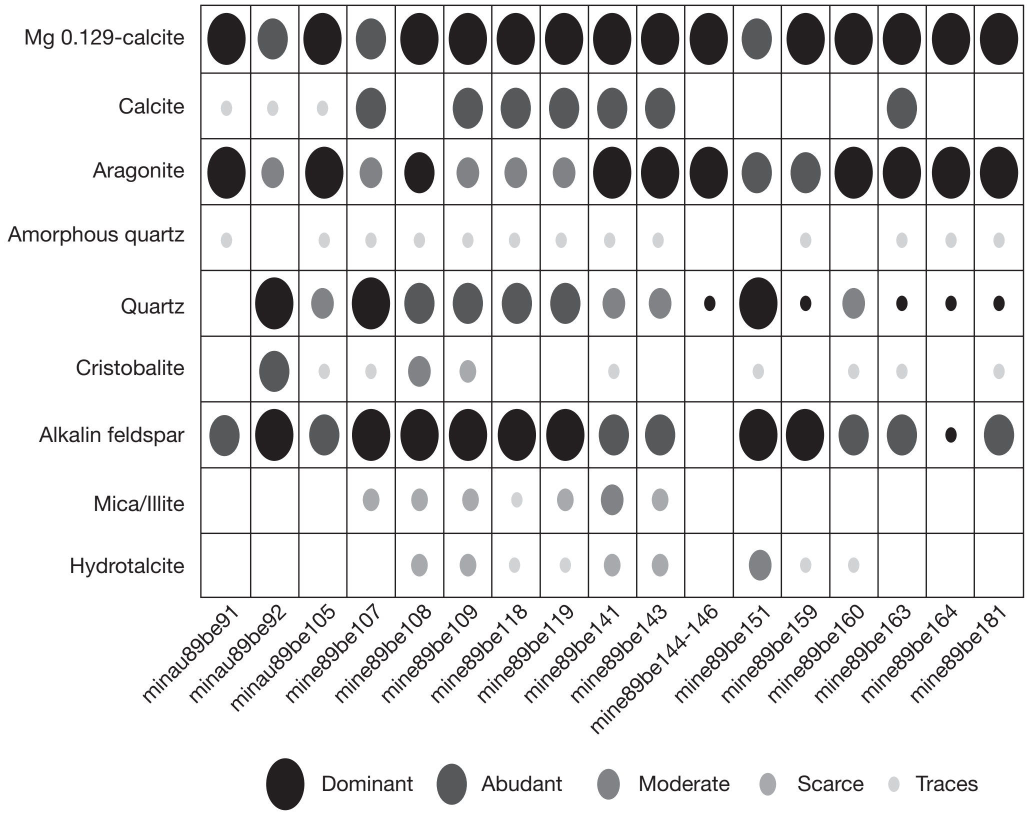

FIG. 4. — Semi-quantitative XRD results. The size of the circles indicates a semi-quantitative estimate of the mineralogical phases.

minau89be91, 105, mine89be159, 160, 164, 181 and 144-146). All have carbonate content higher than 80%, of which the calcareous red algae represent the most abundant group, with a percentage cover higher than 65% of the total content of carbonate particles, ranging up to 92.5%. The third group has been named the "carbonate matrix facies" (CM facies). Height samples comprise it: mine89be163, 108, 109, 141, 143, 107, 118 and 119. The CM facies is characterized by carbonates ranging from 42.4 to 84.2% of the total, but it was not possible to distinguish and map the individual grains. The same clusters have been identified in the MDS plot (Fig. 9).

MAPPING, DISTRIBUTION, ACCUMULATION AND PRODUCTION RATE OF CORALLINE ALGAE

Two distinct patterns for carbonate sedimentation have been identified, and mapped, corresponding in general to two bathymetric intervals (Fig. 10). The first bathymetric interval spans 40 to 70 m wd and delimits the areal distribution of the CA facies. The second interval ranges between 70 and 100 m wd and is coincident with the areal distribution of the CM facies. The CA facies occupies 38 km^2; the CM facies 24 km^2 (Fig. 10; Table 2). 80%, or 30.4 km^2, of the CA facies surface is covered by living and dead coralline algae, whereas coralline algae cover only 15% or 3.6 km^2 of the CM facies total surface.

EDTA-titration analyses show that 91% of the present surface sediment is carbonate, while 9% is non carbonate (Fig. 11). Coralline carbonate represents 80% of the total carbonate, including both living and dead coralline thalli and their fragments. The percentage cover of living coralline algae was estimated by Basso (1992) and for the CA facies

TABLE 2. — Data concerning coralline cover percentage, areal distribution, volume and production rate.

	Coralline algae facies			Carbonate matrix facies
Depth (m)	40-70			70-100
Granulometry	Gravelly sand			Muddy sand
Dominant component	Coralline algae			Carbonate matrix
Facies area (km^2)	38			24
Coralline algae percentage cover	80%			< 15%
Total coralline algae area (km^2)	30.4			3.06
Living coralline algae (km^2)	living 7% (2.66 km^2)			–
	living 32% (12.16 km^2)			–
Volume (m^3)	760000			480000
Density (g/cm^3)	1.13			0.066666667
Weight (tons)	858800			460800
% $CaCO_3$ per gram	91%			66%
Coralline algae weight (tons)	625206			45619
Total carbonatic sediment accumulation (g/m^2)	20566			12672
Total coralline algae accumulation (g/m^2)	16452			1900
Production rate g m^{-2} y^{-1}	all	2 cm/200 y	82	9.5
		2 cm/50 y	329	38.02
Production rate g m^{-2} y^{-1}	living 7%	2 cm/200 y	7.91	–
		2 cm/50 y	31.64	–
Production rate g m^{-2} y^{-1}	living 32%	2 cm/200 y	36.16	–
		2 cm/50 y	144.64	–

gives a mean value of 7% of the total area, with maximum values of 32% (sample minau89be105) (Fig. 11).

Considering the covering 2 cm-thick sediment layer, the present-day living biogenic interface, the accumulated volume of total coralline algae in the CA facies, both living and dead, is 608000 m^3. The accumulation of total carbonate sediments and the fraction of coralline carbonate presently in the covering 2-cm layer on the seafloor are calculated as 20566 and 16452 g m^{-2} respectively.

Using the 7% living coralline algae as a reference, and assuming a growth rate of 2 cm per 50 years, the algal production rate is 31.64 g m^{-2} yr^{-1}. Alternatively, with a much slower growth rate of 2 cm per 200 years, we calculate a present-day coralline carbonate production rate as 7.91 g m^{-2} yr^{-1}.

If the highest observed value of living coralline algae (32%) is used, the algal production rate is 144.64 m^{-2} yr^{-1} for faster growth rate, and 36.16 m^{-2} yr^{-1} for the lowest.

At a growth rate of 2 cm per 50 years, the rate of all coralline production, living and dead, is 329 g m^{-2} yr^{-1}.

DISCUSSION

The studied area of the Pontian Islands is a typical mobile substrate of the circalittoral zone, termed "détritique côtier" (DC) in the classification scheme of Pérès & Picard (1964) (Basso 1994, 1996, 1998). The DC sediment is composed of a mixture of sand, gravel and mud (Blanc 1968). The coarse fraction of the DC sediment is biogenic clasts, produced *in situ* or derived from nearby environments (coralligenous build-ups, *Posidonia* meadows, etc.) (Blanc 1968; Pérès 1982). Data on the distribution of benthic assemblages and sedimentary facies of the Pontian Islands (Basso 1998; Altobelli & Collins 2004; Sañe-Schepisi *et al.* 2004; Brandano & Civitelli 2007; Corselli *et al.* in press) at depths ranging between 30 and 100 m wd suggest a moderate variability of predominantly sand-sized sediments dominated by biogenic carbonates. Most of the Pontian sediments are a mixture of free algae branches, rhodoliths and coralligenous-derived fragments. In the bathymetric interval between

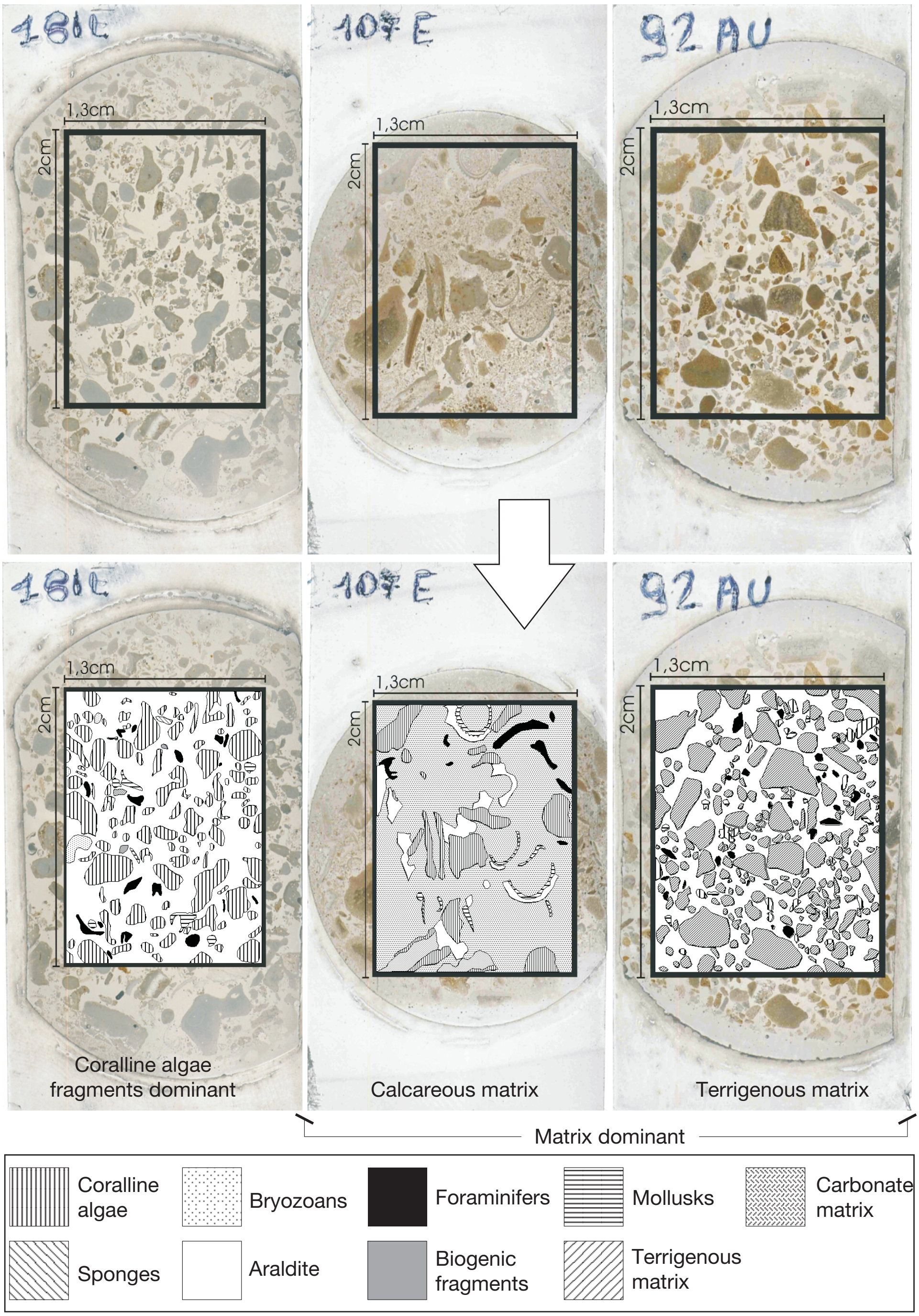

Fig. 5. — Example of thin section mapping. Three mapped thin sections showing the area selected for mapping (above) and the results (below). The textures in the legend indicate the biogenic components identified. On thin section 92AU the apparently coarse, unsorted terrigenous sand is an artifact caused by an Araldite inclusion (see Material and methods).

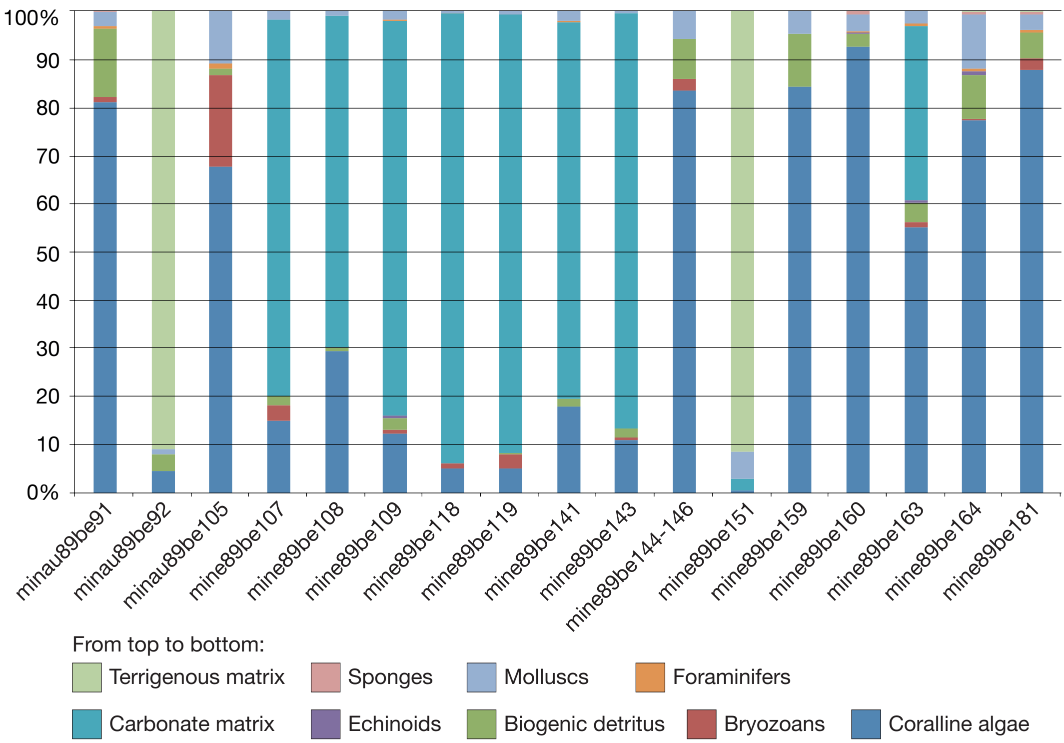

FIG. 6. — Percentage of the sediment cover provided by its components. The legend gives the significance of the several shades of gray. Grey tones indicate the identified biogenic components, as indicated in the legend. Percentages are given in the Table 3.

TABLE. 3. — Percentage of the sediment cover provided by its components. This Table corresponds to the Figure 6.

Sample	Coralline algae	Bryozoans	Biogenic detritus	Echinoids	Carbonate matrix	Foraminifers	Molluscs	Sponges	Terrigenous matrix
minau89be91	81.0	1.0	14.3	–	–	0.4	3.0	0.3	–
minau89be92	4.6	–	3.3	–	–	–	1.1	–	91.0
minau89be105	67.6	19.0	1.4	–	–	1.1	10.9	–	–
mine89be107	15.0	3.1	2.0	–	78.0	–	1.8	–	–
mine89be108	29.3	–	0.9	–	68.5	–	1.2	–	–
mine89be109	12.4	0.7	2.5	0.5	81.7	0.4	1.8	–	–
mine89be118	5.2	0.8	–	–	93.3	0.1	0.6	–	–
mine89be119	5.1	3.0	0.2	–	90.9	0.1	0.8	–	–
mine89be141	18.0	–	1.4	–	78.2	0.2	2.2	–	–
mine89be143	10.9	0.6	2.0	–	86.1	–	0.4	–	–
mine89be144-146	83.5	2.2	8.4	–	–	–	5.9	–	–
mine89be151	0.6	–	–	–	2.5	–	5.4	–	91.5
mine89be159	84.2	–	11.1	–	–	–	4.7	–	–
mine89be160	92.5	–	2.6	0.3	–	0.3	3.5	0.8	–
mine89be163	55.0	1.1	4.0	0.8	36.0	0.4	2.8	–	–
mine89be164	77.2	0.2	9.1	0.7	–	0.7	11.0	0.6	0.3
mine89be181	87.6	2.5	5.4	–	–	0.4	3.4	0.4	0.3

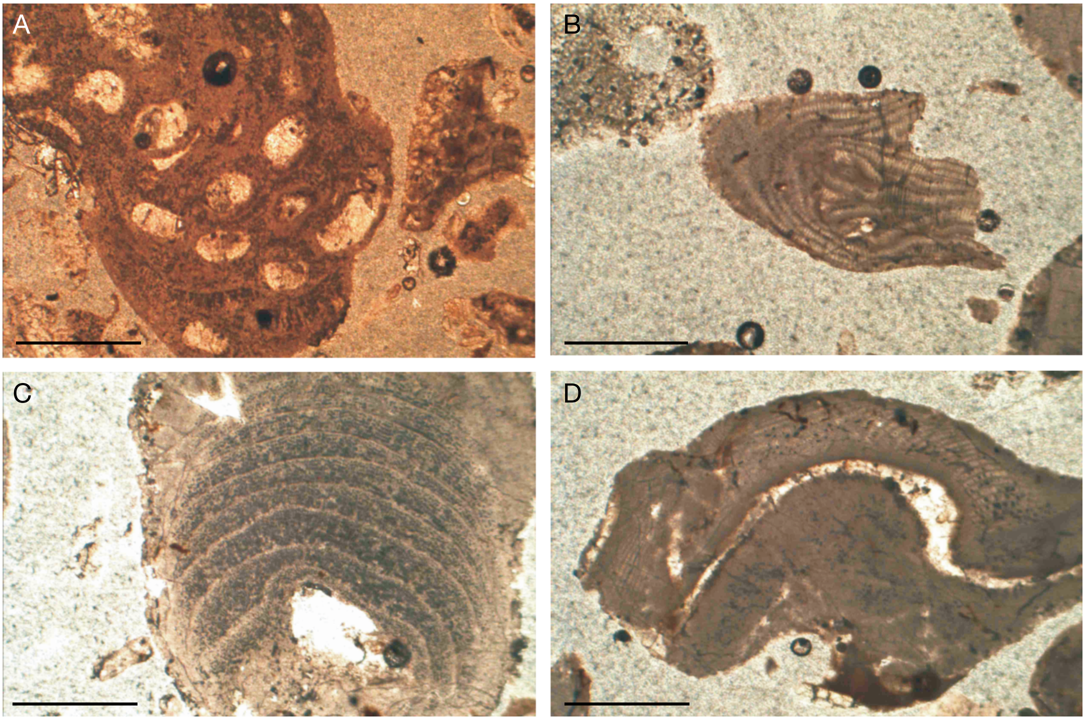

FIG. 7. — Species/genera of coralline algae: **A**, *L. minervae* Basso; **B**, *Titanoderma* sp.; **C**, *Lithothamnion* sp.; **D**, *Mesophyllum* sp. Scale bars: 500 µm.

32 and 100 m wd, the total carbonate is more than 80% of quasi-current sediment, and in particular, the highest percentages of carbonates were in samples collected between 49 and 81 m wd. On the contrary, erosion-derived terrigenous detritus is abundant close to coasts at depths shallower than 43 m wd. Two carbonate facies were identified: the CA facies and the CM facies (Fig. 10). These facies represent two aspects of the same carbonate-dominated sedimentary realm. Coralline algae play the major role in carbonate biogenic production and consequently the high-Mg carbonate phase is predominant. Coralline algae occupy 30.4 km^2 in the area comprised between 40 and 70 m wd.

The 70-100 m wd range in depth is characterized by the carbonate matrix (CM) type, although abundant coarse algal fragments occur, as reported in literature (Basso 1998; Altobelli 2002; Brandano & Civitelli 2007; Corselli *et al.* in press). The abundance of carbonate matrix in the deepest area of the continental platform may be related to the seafloor saddle morphology that is apt for the generation of gravitational mass movements (Chiocci *et al.* 2003). Moreover, the saddle morphology of the channel between Ponza and Palmarola islands conveys a water flow sweeping the seafloor. The shallowest and sub-planar portion of the saddle morphology is an optimal environment for the development of a coralline facies, because of the favorable depth and hydrodynamics, and the low input of terrigenous sediment. On the other hand, the steep slopes of the sea bottom to the North and South may be responsible for the sediment displacement in the deepest part of the studied area. It is possible that the CM content facies is partly composed of relict particles. The CM facies is not continuous, for rock outcrops reported in the mapped area (Altobelli 2002; Sañe-Schepisi *et al.* 2004).

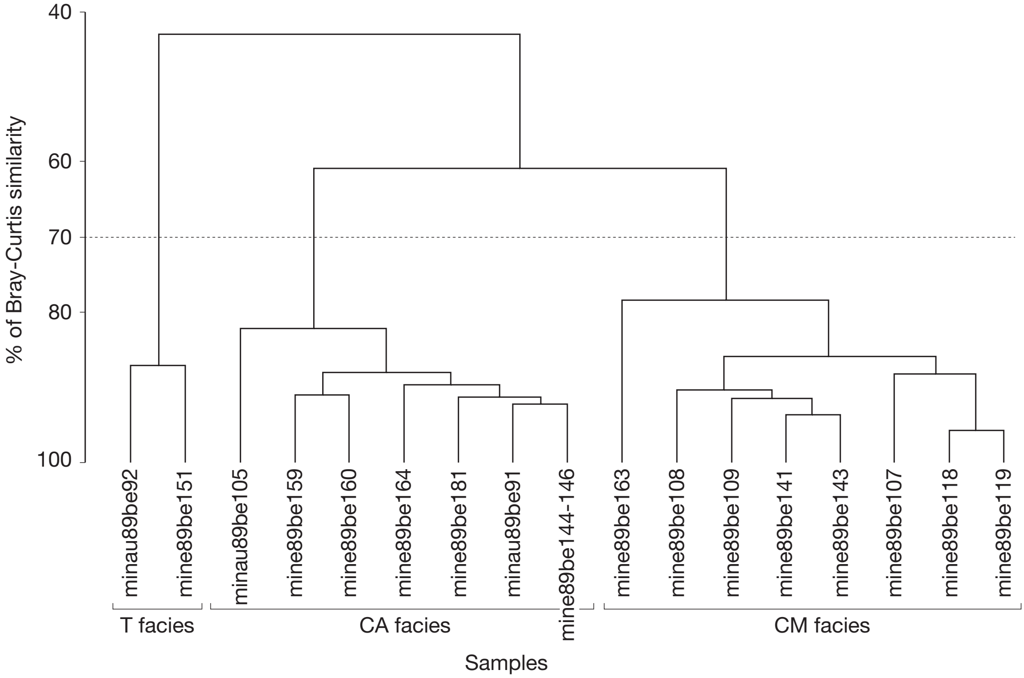

Fig. 8. — Dendrogram from cluster analysis based on Bray-Curtis similarity. A line indicates the level of 70% of Bray-Curtis similarity. Three clusters have been identified and the name of the corresponding facies is indicated below. Abbreviations: **CA**, coralline algae; **CM**, carbonate matrix.

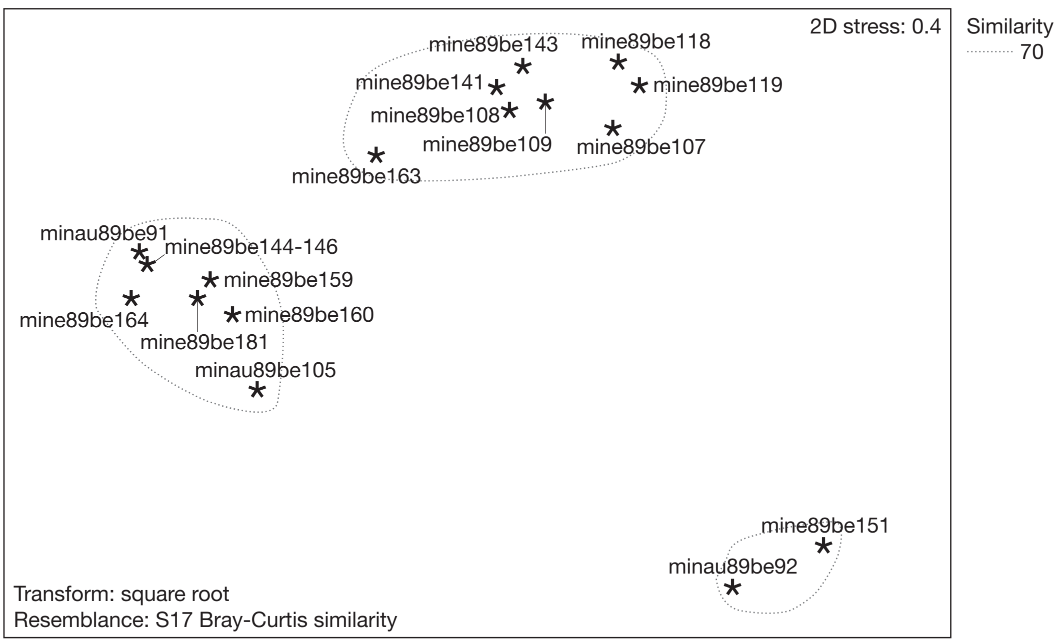

Fig. 9. — Non-metric MDS analysis based on the Bray-Curtis similarity of Figure 8. The override clusters correspond to those of Figure 8.

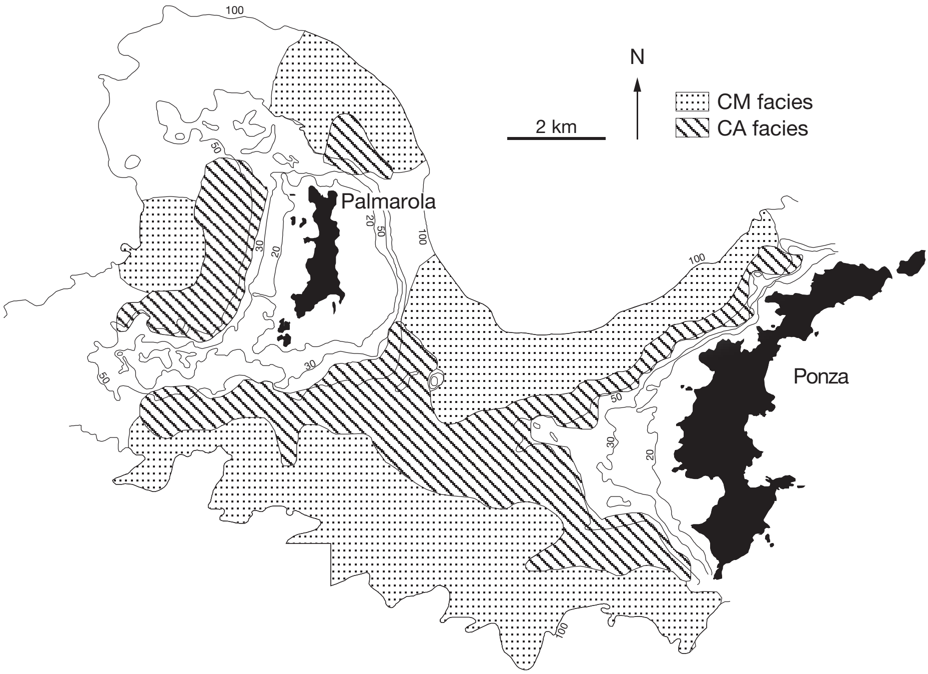

FIG. 10. — Map of the calcareous algae (**CA**) facies and carbonate matrix (**CM**) facies. Numbers refer to water depth (in m).

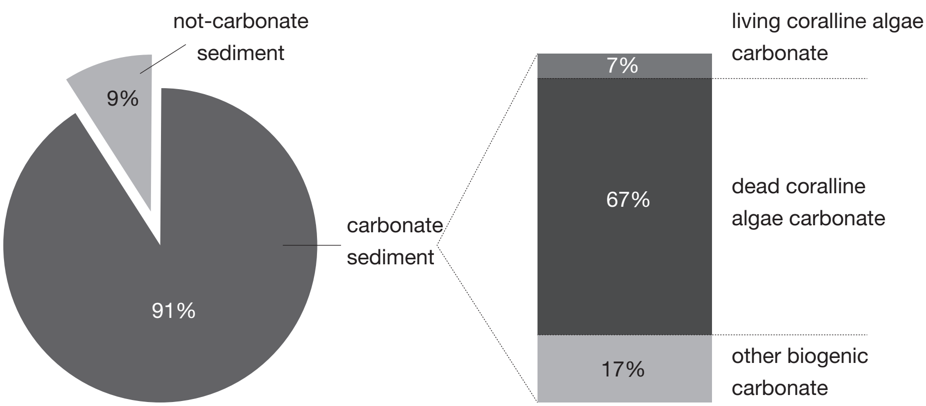

FIG. 11. — Sediment mineralogy and carbonate components: **left**, sediment mineralogy from EDTA analyses; **right**, carbonate components from thin section analyses.

Four of the ten facies and sub-facies identified by Brandano & Civitelli (2007) can be recognized in our analyses of the biogenic components of the western Pontian Islands. The CA facies corresponds to F4 (“unattached coralline algal branches gravel”), F2a (“poor sorted skeletal sand”) and F5b (“siliciclastic skeletal sand”). In particular, Brandano & Civitelli (2007) recognized facies

F4 as the environment with the highest rate of carbonate production rate. The CM facies corresponds to F2a ("poorly sorted skeletal sand") and F5 ("relict sand").

The sedimentary facies of Brandano & Civitelli (2007) was aimed at provide a detailed description of seafloor sediments, whereas we focused on the total carbonate content and its mineralogy in order to produce an areal and volumetric quantification of coralline algae. Thus, our carbonate facies include more than one of the sedimentary facies of Brandano & Civitelli (2007).

The production rate of the 7% mean cover of living coralline algae in CA would yield from 7.91 to 31.64 g m^{-2} yr^{-1} depending on the rate of production. If we choose the highest level of living coralline algae in CA (32%), this rhodolith bed (Steller *et al.* 2003) has an algal production rate between 36.16 g m^{-2} yr^{-1} and 144.64 g m^{-2} yr^{-1}. Canals & Ballesteros (1997) reported a production rate ranging between 210 g m^{-2} yr^{-1} for maerl beds and 464 g m^{-2} yr^{-1} for coralligenous assemblage. Our calculated values of coralline production rate, though lower than those of Canals & Ballesteros (1997), seem reasonable because we did not investigate the hard substrates, and true maerl does not occur in the area of our investigation. Moreover, the depth range of our CA facies is broad enough to accept the existence of a variable rate of algal carbonate production.

CONCLUSION

The western Pontian Islands shelf is an area of temperate carbonate deposition. Two carbonate facies (CA and CM) have been identified and represent continental shelf deposition between 40 and 100 m wd. In particular the CA facies occupies the bathymetric interval from 40 to 70 m wd, and the CM facies is present only between 70 and 100 m wd. The contribution of continental sediments is confined to shallow-water, near the islands coasts. On the continental shelf, biogenic activity produces most of the sediments. Sand is the dominant class of the grain-size distribution. Gravel particles are present, especially in samples of CA facies where mud content increases below the 80 m wd.

Maximum carbonate production takes place between 40 and 70 m wd, with carbonate content ranging between 83.1 and 95.7%.

Coralline algae are the most important carbonates producer in the area, attaining a cover of 80% in water depths between 40 and 70 m (CA facies), that occupies alone more than 30 km^2 of the seafloor. Free branches and rhodoliths 1-3 cm in diameter form the algal assemblage. In the 2 cm-thick layer of sediment that constitutes the current living biogenic interface, the cumulative volume of both alive and dead coralline algae is 608 000 m^3. In the current 2 cm layer, the total of carbonate sediments and the fraction of the total made up of coralline carbonate are respectively 20 566 and 16 452 g m^{-2}. Significant living coralline algal cover occurs only in the CA facies, for which we calculated a production rate of 7.91-31.64 g m^{-2} yr^{-1}.

In the deeper bathymetric interval (CM facies) calcareous red algae occupy 3.6 km^2 of seafloor, in muddy sand characterized by abrasion, bio-erosion and recrystallization (Brandano & Civitelli 2007). The percentage of biogenic carbonate in this interval has a mean value of 66%. The recognized algal contribution is lower than 15% of total carbonates.

We quantified the areal distribution, the production rate and the sediment contribution of coralline algae in the Pontian area, in order to demonstrate their role in the carbonate budget of the present Mediterranean shelf. In non-tropical environments, coralline algae must be considered one of the most important producers of biogenic sediment, particularly in areas where terrigenous input is minimal.

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