

Neogene non-tropical carbonate sedimentation in a warm temperate biogeographic province (Rethymnon Formation, Eastern Crete, Greece)

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Abstract

The Apostoli Basin, in the central-west part of Crete, was formed as a fore-arc type basin related to the convergent plate boundary between the African and the Eurasian plates. Most of the Neogene sediments filling the basin were deposited in a terrestrial to shallow marine environment. The succession is a transgressive cycle, which culminates in the alternation of Rethymnon bioclastic limestones with marls, documenting the important Tortonian marine transgression. The Rethymnon limestones are classified as a typical non-tropical carbonate lithofacies. Two particular lithofacies have been recognized: (a) a *rhodalg*-type lithofacies, characterized by predominance of encrusting coralline algae and bryozoans, and (b) an *echino*-type lithofacies, characterized by predominance of echinoderms and/or benthic foraminifera. The coralline algae occur mostly as in situ spheroidal or branched rhodoliths, whereas benthic foraminifera are mainly represented by larger foraminifera. In both lithofacies, typical tropical carbonate elements are lacking. Skeletal elements consisted of low- and high-Mg calcite. Although the observed lithofacies possess many similarities with facies of non-tropical carbonates, the presence of large benthic foraminifera suggests development in a warm temperate biogeographic province. The depositional environment corresponds to a shallow ramp, the sediments being deposited in a nearshore environment and under conditions analogous to those prevailing in the present-day circalittoral bottoms of the Mediterranean Sea. The main carbonate accumulation area is located at the factory area itself (rhodalg-type sediments), and downslope from the factory area (echino-type sediments). In the classic zonation of Mediterranean benthic assemblages of Peres and Picard [Rec. Trav. Stn. Mar. (1964)], the rhodalg-type sediments of the Rethymnon Fm correspond to the “Facies a Pralines”, developed in areas strongly controlled by currents (e.g., tops of plateaus), and the echino-type sediments to the “Detritique Cotier” bioclastic deposits, derived mostly by bioerosion and fragmentation of local and adjacent calcareous benthic communities.

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1. Introduction

Warm-water tropical shelf carbonate sediments are well-known and provide modern facies analogues for many limestones in the geological record (Wilson, 1975; Scholle et al., 1983; James, 1984). Less is understood about the facies of modern non-tropical

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shelf carbonate sediments and they are rarely used as models for interpreting ancient rocks (Chave, 1967; Lees and Buller, 1972; Lees, 1974; Nelson, 1978, 1988a,b; Rao, 1981; Nelson and Hancock, 1984; Scoffin, 1988; Nebelsick, 1989; James, 1997).

As Lees and Buller (1972) and Lees (1975) defined, the chlorozoan association (hermatypic corals, calcareous green algae and non-skeletal carbonate grains) characterizes the tropical oligotrophic carbonate platforms, whereas in the tropical–subtropical zones the chloralgal association develops (calcareous green algae). Instead, the modern temperate–subtropical open shelves are characterized by the foramol association (molluscs, benthic foraminifers, bryozoans, barnacles and encrusting coralline algae).

A wide range of textures, with variable component of average and importance, characterizes the foramol association. For that reason, Carannante et al. (1988) attempted a further distinction between a lithofacies rich in encrusting coralline algae and bryozoans (rhodagal) and a lithofacies in which echinoids, barnacles, serpulids and bryozoans are associated by molluscs and arenaceous foraminifera (molechfor). Recently, Hayton et al. (1995) proposed a new classification system for non-tropical carbonate deposits, identifying seven major skeletal assemblages that maybe regarded as subdivisions of the single foramol skeletal association as defined by Lees and Buller (1972).

Due to the fact that deposits characterized by foramol association are abundant in the modern tem-

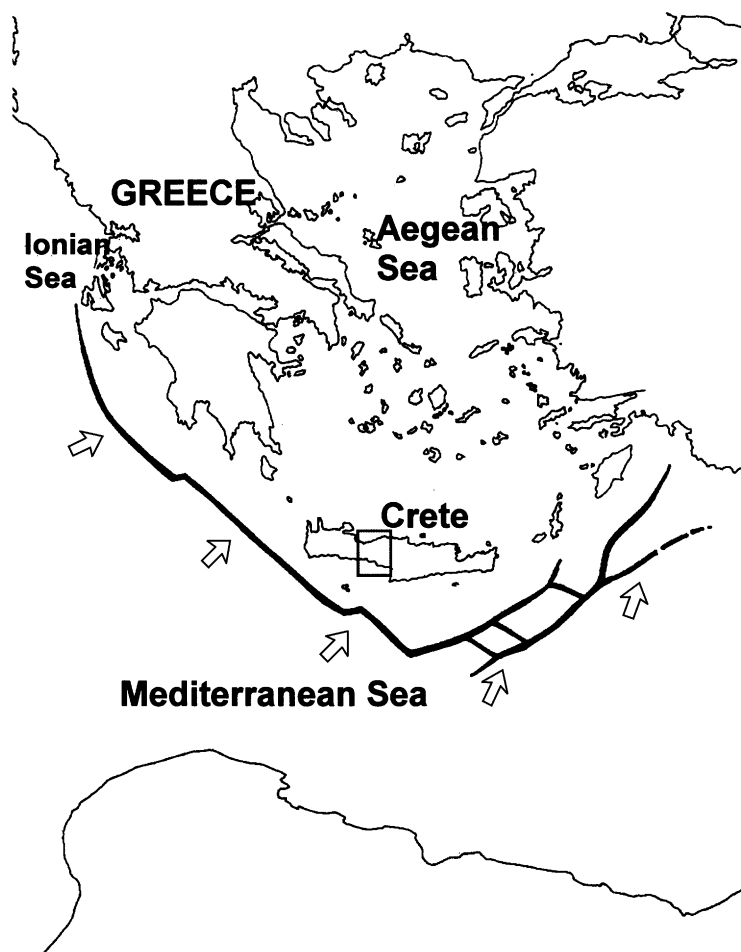


Fig. 1. Geographical position of the studied area in central-west Crete, southern Greece, eastern Mediterranean Sea.

perate to subtropical open shelves, it becomes dangerous to interpret a priori all ancient carbonate deposits, with an assemblage similar to the foramol association, as having been formed in the temperate climatic zone. For this reason, [Betzler \(1997\)](#) suggested that, from a biogeographic point of view, the easiest distinction is to subdivide the associations by using the concept of temperate (cool and warm temperate) and the tropical waters. Furthermore, trying to discuss the problems of delimitation of the tropical and non-tropical carbonate realms, stressed upon the significance of the warm temperate biogeographic province, which comprises the link between the tropical and the cold-water realm and is characterized by foramol, chloralgal, rhodalgal and molechfor associations.

The Rethymnon limestones are not comparable with the well-known shallow tropical–subtropical modern carbonates, rather possessing similarities with the temperate carbonate sequences, which are mostly characterized by the “foramol association”. For that reason, the principal goal of the present paper is to classify the studied lithofacies-type according to their skeletal assemblage association, as well to determine

the climatic zone and the environment in which they were deposited.

2. The study area

The island of Crete in the eastern Mediterranean represents an emerged part of the Hellenic Arc ([Fig. 1](#)). The Late Cenozoic evolution of Crete has been controlled by the final stage of northward subduction of the African plate beneath the Aegean lithosphere ([Makris and Vees, 1977](#); [Le Pichon and Angelier, 1979](#)).

In the Rethymnon region, two Neogene basins occur: the Rethymnon Basin to the north and the Apostoli Basin to the south. An elevated pre-Neogene relief separates these basins ([Fig. 2](#)). The Apostoli Basin was formed as a fore-arc type basin related to the convergent plate boundary between the African and the Eurasian plates. During Late Serravallian to Late Tortonian times, the tectono–sedimentary setting was one of a graben, with most of the sediments being shed from a fault-bounded upland area to the north.

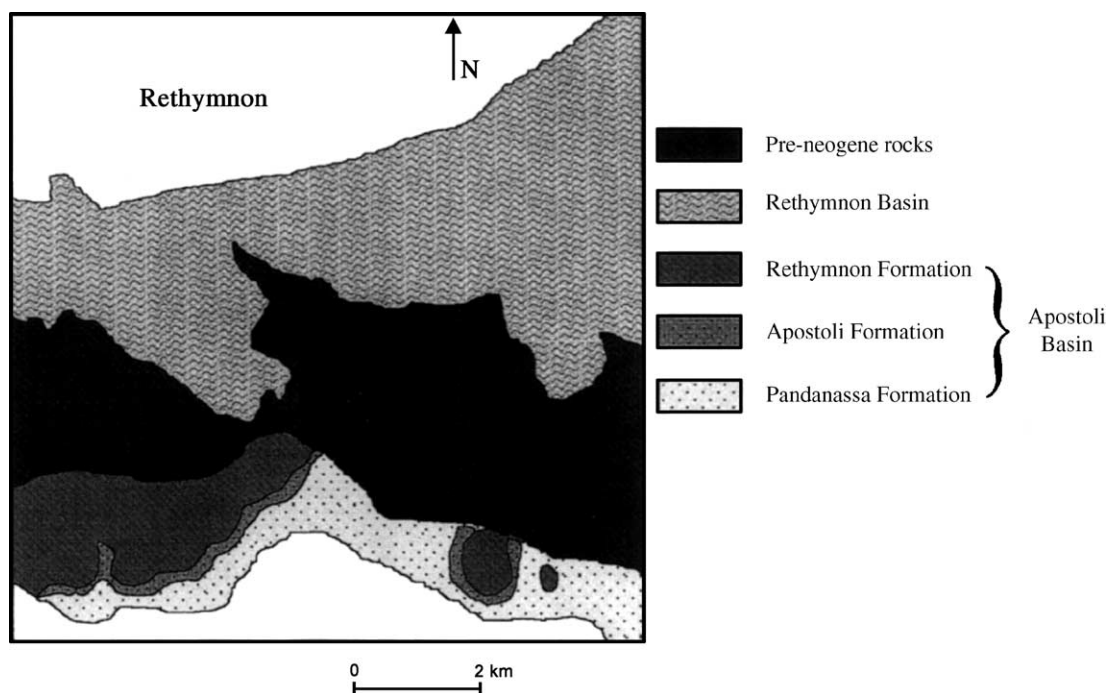


Fig. 2. Geological map of the studied area (after [Meulenkamp, 1969](#) and [Drinia, 1996](#)).

Alluvial fan conglomerates from active faults or fault zones located mainly on its northern margin accumulated in the Apostoli Basin, being interfingered with coastal plain and marginal marine facies. The marginal marine facies become more abundant upward in the succession and culminate with bioclas-

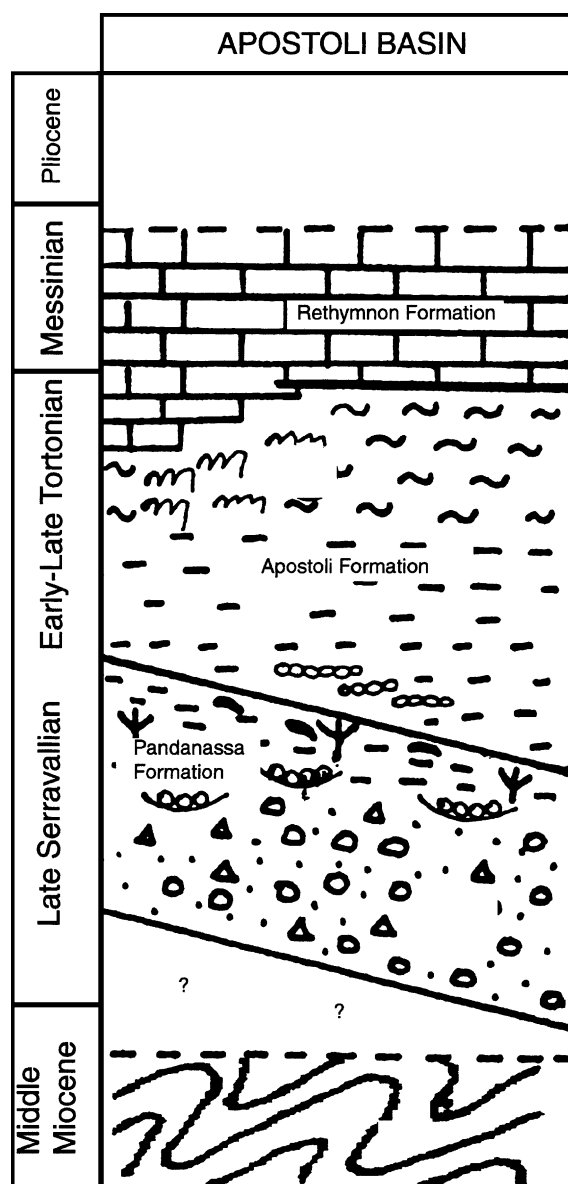


Fig. 3. Composite lithostratigraphical column of the sedimentary fill of Apostoli Basin.

tic limestones, documenting an important Tortonian marine transgression in the region.

The Apostoli Basin consists of the following three principal formations (Fms, Facies Sequences), (Fig. 3, Meulenkamp, 1969; Drinia, 1996, 2000): the Pandanassa Fm (Facies Sequence A), generally consisted of alluvial fan and floodplain deposits (debris flow and braided stream conglomerates); the Apostoli Fm (Facies Sequence B), consisted of marine deposits (upper shoreface sandstones, *Heterostegina* sands and grey-bluish fossiliferous marine marls); and the Rethymnon Fm (Facies Sequence C), consisted of alternations of bioclastic limestones with marls.

The Rethymnon Fm always forms the cap of the sediment infill of the Apostoli Basin, onlapping the nearshore deposits of Apostoli Fm and the continental deposits of Pandanassa Fm. It is up to 60 m thick, bedding being defined by sharp erosional, irregular to scalloped, contacts (Fig. 4). No unconformities have been noticed. Calcareous nannofossil biostratigraphy which has been carried out in the marly intervals of the bioclastic limestones suggested a Middle–Late Tortonian age (Drinia et al., 2001).

3. Sedimentological analysis of the Rethymnon limestones

The Rethymnon Formation consists of alternation of bioclastic limestones with marls.

Although the Rethymnon limestones are classified as a typical “foramol” lithofacies sensu Lees and Buller (1972), they show distinctive features that permitted the recognition of the following two particular lithofacies-types.

(a) A rhodalgal-type lithofacies sensu Carannante et al. (1988) (e.g., predominance of coralline algae and bryozoans in relation to foraminifera and molluscs; Fig. 5A and B). This lithofacies possesses also analogies with the rhodochor assemblage, according to the recent classification of Hayton et al. (1995), as the coralline algae occur mainly as in situ developed rhodoliths (boundstones/biolithites), and in lesser extent as abraded fragments of articulate and crustose corallines (floatstones/biomicrodites). Locally, bryozoans can be very abundant (bryorhodagal lithofacies). The matrix is a bioclastic packstone consisting of abundant fragments of coralline algae, foraminifera,

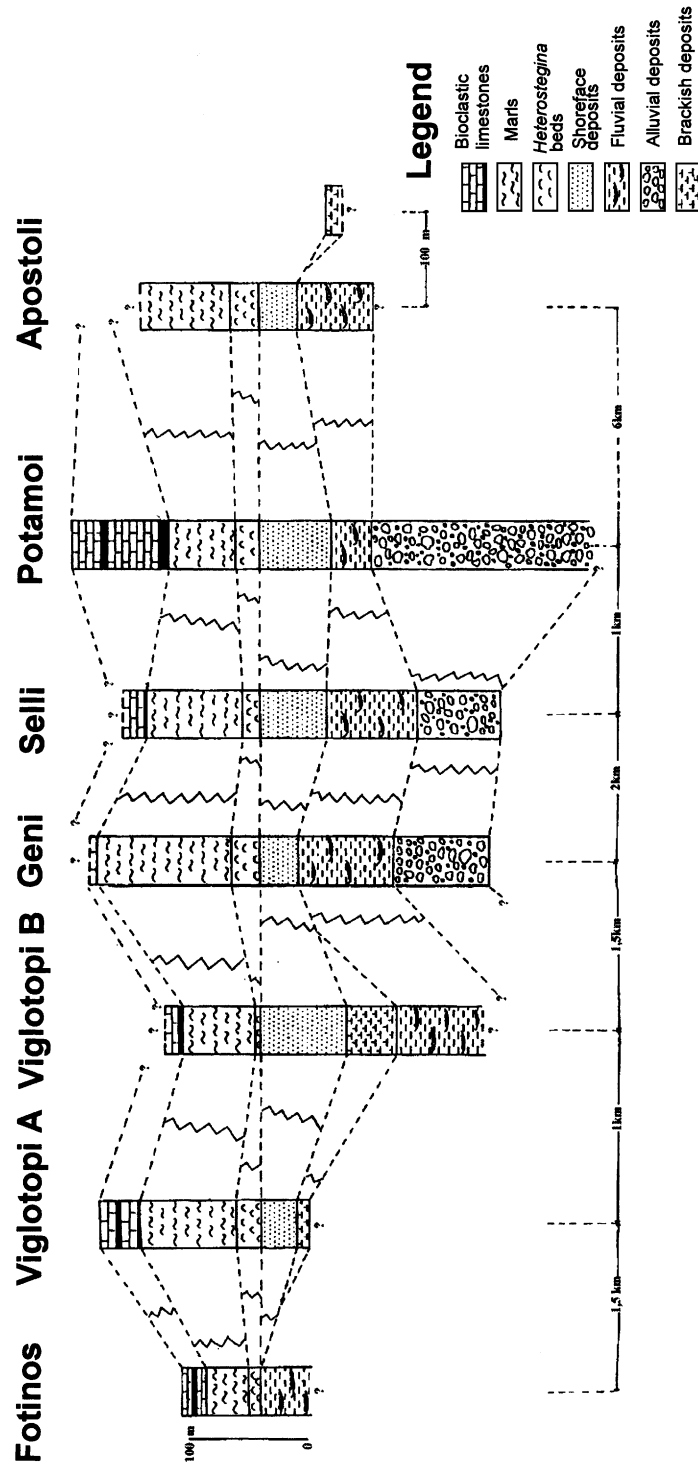
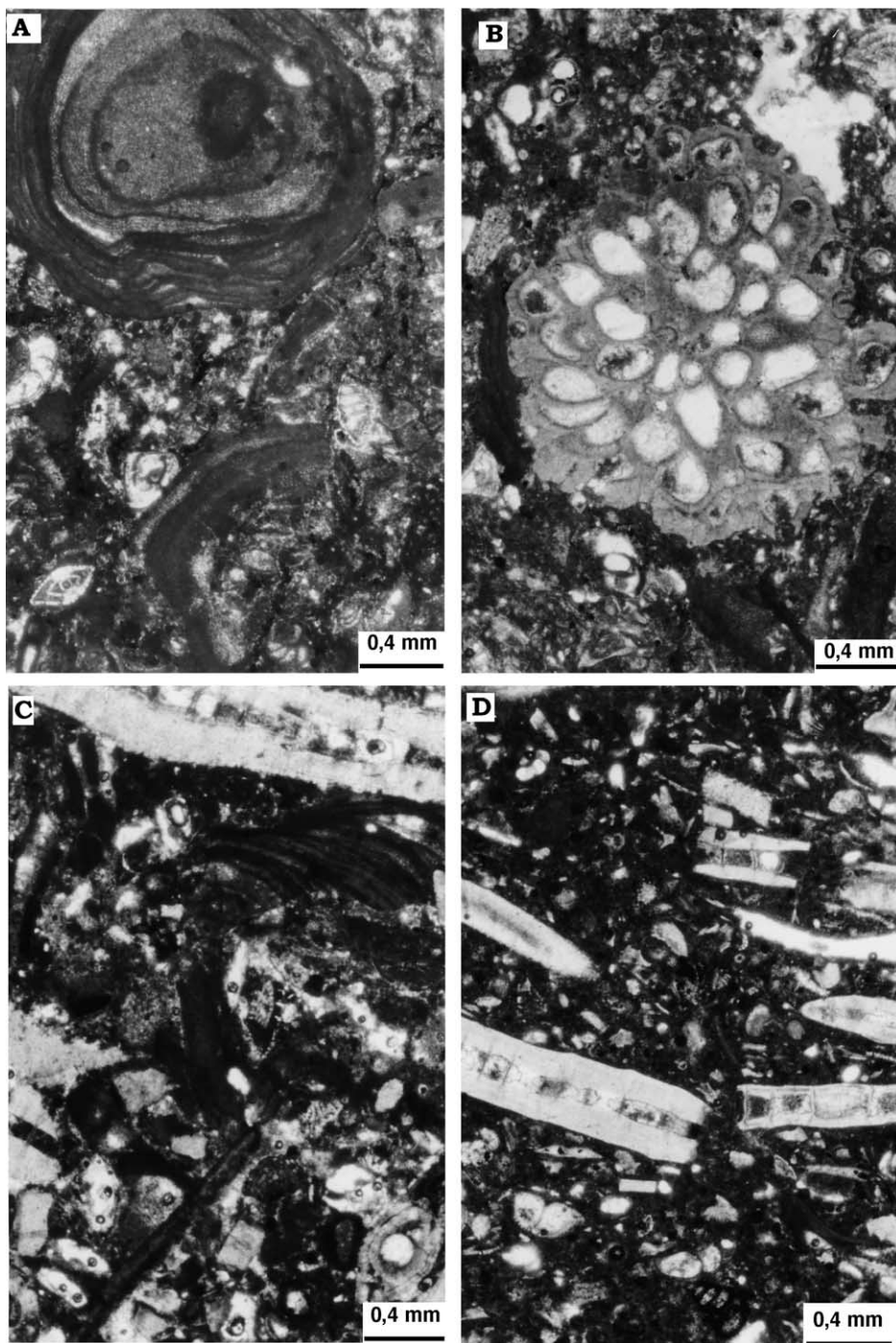


Fig. 4. Lithostratigraphical correlation of the studied sections.



fera, bryozoans, echinoids, molluscs and often planktonic foraminifers. Scattered quartz crystals and quartzitic fragments, of detrital origin, are rare.

The coralline algae (Rhodophyta) prevail towards bryozoans and occur mostly as in situ spheroidal or branched rhodoliths. Rhodoliths average in diameter and show concentric to botryoidal-columnar morphologies. Coralline algae often encrust bryozoans (Fig. 5B). Sessile foraminifera often grow on rhodoliths, as well as on bryozoans. The bryozoans have not been systematically described in places where bryozoans of encrusting type have been observed.

(b) An echinofor-type lithofacies (floatstones) sensu Hayton et al. (1995) (e.g., predominance of echinoderms and/or benthic foraminifera Fig. 5C and D). In places where molluscs occur dispersed but in lesser amounts, bryozoans and coralline algae are observed.

Benthic foraminifera are mainly represented by large, thin, discoidal *Heterostegina*, *Cibicides*, *Elphidium* and *Uvigerina*. Sessile or encrusting foraminifera occur, as well. The large benthic foraminifera are abraded and locally broken, suggesting a certain degree of reworking. Planktonic foraminifera occur in small amounts. Molluscs are represented by pectinids and oysters and echinoids by *Clypeaster* and *Echinolampas*.

Scattered quartz grains of silt size and quartzitic fragments, derived from the crystalline rocks of the substrata, are observed in places.

This lithofacies is comparable with the molechfor-type lithofacies sensu Carannante et al. (1988) (e.g., characterized by abundant mollusc fragments, benthic foraminifera and echinoids), but this facies indicates the predominance of molluscs, which is not the case for the Rethymnon limestones.

In both lithofacies, typical tropical carbonate elements are lacking (e.g., corals, calcareous green algae, ooids, grapestones, micritic rims, cements, etc.).

4. Diagenesis

Early diagenetic processes are of “destructive” type, involving mainly processes such as pronounced grain bioerosion and dissolution, rather than “constructive” cementation (James and Clarke, 1997).

The primary mineralogy of the skeletal elements was generally dominated by low- and/or high-Mg calcite. Aragonite skeletal elements and molds are not preserved. High-Mg calcite is transformed diagenetically to low-Mg calcite. However, micromorphology of skeletal particles is well preserved. Some bioclastic components are heavily impregnated by Fe-oxides. Compaction features such as microstylolites are not observed.

No evidence for primary marine cement exist. In fact, absence or scarcity of sea-floor marine cements has been suggested for most temperate, non-tropical carbonates (Nelson, 1988b). However, Nelson and James (1995, 2000) have documented early sea-floor lithification in cool-water shelf limestones. Sparry calcite cement is generally lacking or is restricted to syntaxial cement overgrowth of echinoderm debris. According to Walkden and Berry (1984), this is the first cement generation formed through the change from high-Mg calcite to low-Mg calcite.

Intraparticle pore spaces of coralline algae are surrounded by a thin fringe of scalenoedric cement (dog-tooth type), the rest space usually remained empty or filled by blocky cement.

Particularly, inter- and intraparticle spaces of coralline algae (conseptacles) are filled by microbioclastic–micropeloidal micrite, texturally similar with internal sediment washed into pore spaces during early marine cementation. Microbioclastic micrite is heterogeneous, being composed by micrite and silt-sized skeletal detritus. On the other hand, micropeloidal micrite is composed by micritic clots set in a microsparite matrix. Micropeloidal micrite is inter-

Fig. 5. (A) **Rhodalgal-type lithofacies.** Floatstone with coralline algae in the form of in-situ developed rhodoliths. Rhodoliths are characterized by concentric structure. On the right, an abraded fragment of coralline algae is observed. The matrix is a bioclastic packstone rich in benthic foraminifers, echinoderms and fragments of coralline algae. (B) Bryozoan partially encrusted by coralline algae. Intraparticle pores are surrounded by a thin generation of scalenoedric cement, the rest space remained open or filled by blocky cement. **Echinofor-type lithofacies.** (C) Floatstone (biomicrudite) with abundant echinoderms and large benthic foraminifers. Coralline algae occur as well. (D) Floatstone (biomicrudite) with abundant large benthic foraminifers (*Heterostegina* sp.) dispersed in a bioclastic matrix rich in small benthic foraminifers and echinoderms. Large benthic foraminifers show a tendency of parallel orientation achievement.

puted as cryptocrystalline cement (Reid et al., 1990; Nelson and James, 2000).

Coralline algae are commonly transected by a net of sinuous, hair-like cracks, interpreted as desiccation cracks. Coralline algae particles show traces of intensive boring activity. Bioerosion was responsible for the in situ fragmentation of the coralline branches and possibly for the production of micrite (Akran and Farrow, 1985).

5. Paleoeecology

Although the rhodalgal and echinoform lithofacies of the Rethymnon Formation possess many similarities with facies of non-tropical carbonates, the occurrence of large benthic foraminifera suggests development in a warm temperate biogeographic province (Brachert et al., 1996; Betzler, 1997).

Environmental conditions prevented the development of hermatypic corals and calcareous green algae and favoured the development of foramol-type shelves. According to Simone and Carannante (1988), particular hydrological conditions such as cold current regimes, cold nutrient-rich upwelling waters and/or variations in salinity, or nutrient content may have been responsible for the suppression of the chlorozoan association. Hallock and Schlager (1986) made recognition of the negative influence of nutrients on reef communities and carbonate platforms growth. As it was discussed by Carannante et al. (1988), high-nutrient areas of the tropics may be characterized by foramol association, which “mimic” non-tropical conditions.

Organism diversity and abundance can be also related to trophic resource levels at the time of deposition. In fact, it has been proven that changes in the trophic resource continuum (TRC) from nutrient-rich, relatively eutrophic states to nutrient-poor, relatively oligotrophic states affect the character of the substrate and turbidity of the water column (Hallock and Schlager, 1986; Hallock, 1987; Lukasik et al., 2000).

Lithofacies of rhodalgal-type are known to develop in warm temperate–subtropical zones, considered to occur at the transition between the typical cold temperate zone (molechfor lithofacies) and the tropical zone (chlorozoan and chloralgal lithofacies) (Carannante and Simone, 1986; D’Argenio et al., 1987; Carannante

et al., 1988; Giscler et al., 1994). The bryorhodalgal-type (e.g., predominance of bryozoans) is considered to occur in the transition towards colder areas. Rhodalgal-type lithofacies has been referred to be very common to the tropical–subtropical climatic zone of Middle Miocene in the Mediterranean area, representing a transitional environment between the chlorozoan/chloralgal and molechfor association (Carannante et al., 1988).

Although modern larger benthic foraminifera are considered among the best known algal symbiont-bearing taxa, which are adapted to tropical, oligotrophic environments (Hottinger, 1983; Hallock, 1988), they often occur in cooler environments. The occurrence of large benthic foraminifera in sediments rich in sciaphile and cooler skeletal components is considered to indicate an intermediate position between the «chlorozoan» and cooler water systems (Carannante et al., 1988; Brachert et al., 1993; Betzler et al., 1995) in the warm temperate biogeographic realm (Betzler, 1997). According to Brachert et al. (1996), the occurrence of larger foraminifera could point to water temperatures close to the lower temperature threshold of reef systems.

The studied sequence shows a well-expressed upward-deepening tendency, proven by the presence of planktonic foraminifera in the described bioclastic limestones, as well as by the alternation of the bioclastic limestones with hemipelagic marls. According to Simone and Carannante (1988), the «temperate-type platforms» of tropical–subtropical areas exhibit low rates of sedimentation and can be expected to be easily drowned. Drowning of the platform is very well expressed in the southern Apennines of Italy, where Early to Middle Miocene «foramol-type» sediments pass upwards into hemipelagic marls. Simone and Carannante (1988) made the important statement that at present, under rising of sea level, the low rate of sedimentation ultimately resulted in the drowning of temperate foramol platforms, even though tropical chlorozoan platforms may persist because the normal growth rates of organisms therein can keep pace with the rise of sea level.

6. Depositional environment

Our depositional interpretation is that the Miocene Rethymnon bioclastic carbonates are formed on

a gentle shallow ramp. The energy level was relatively low, suggesting that sedimentation took place all along the ramp. Our sedimentary model is analogous to that documented by Martin et al. (1996) for the uppermost Miocene temperate carbonates of Agua Amarga Basin (southern Spain). However, in our case the main accumulation area was located not only on the downslope of the factory area (echinofor lithofacies), but also in the factory area itself (rhodalgial lithofacies). Most organisms lived below the fair-weathered wave base and from that site, they were redeposited on the downslope along the ramp.

The Miocene deposits of the Rethymnon Formation possess many similarities with the recent bioclastic sediments of the circalittoral bottoms of the Mediterranean Sea as described by Walther (1985) and Walther and Schritz (1986) and thoroughly studied by Simone and Carannante (1985) and Carannante et al. (1988).

According to the classic zonation of Mediterranean benthic assemblages of Peres and Picard (1964), the rhodalgial-type sediments of the Rethymnon Formation correspond to the biocoenosis of the “Facies a pralines”, which are developed in areas exposed to stronger current regimes (e.g., tops of plateaus), whereas the echinofor-type sediments to the sediments of the “Detritique Cotier”, which resulted from bioerosion and fragmentation of local and adjacent calcareous benthic assemblages and are characterized by low sedimentation rates. The echinofor-type sediments show evidence of formation under conditions of, affected by currents, circalittoral bottoms. This is a common characteristic of non-tropical carbonate sediments, which mostly lack significant in situ rim construction. Because of this, as Nelson et al. (1988) have pointed out, sediments of this type frequently consist of «skeletal hash» and form through amalgamation and redistribution by currents or waves.

In the Mediterranean examples, in situ coralline algal growths extend from the shore down to depths of 100 m that are associated with molluscs, bryozoans and benthic foraminifers, and bioclastic sediments; and accumulate in local hollows at depths between 50 and 100 m. In contrast, the areas of maximum carbonate production and accumulation of the Cenozoic and modern deposits of South Australia, due to high-

energy swell waves and associated shelf currents, are located further down the ramp, at depths of 180–400 m (shelf margin and upper slope environments; James and Bone, 1991; James et al., 1992).

7. Conclusions

The Rethymnon limestones, consisted of alternations of bioclastic limestones and marls, are classified as a typical non-tropical carbonate lithofacies, consisting of:

- (A) a rhodalgial-type lithofacies characterized by predominance of in situ developed rhodoliths and bryozoans (boundstones), and in lesser extent as abraded fragments of corallines (floatstones), and
- (B) an echinofor-type lithofacies characterized by predominance of echinoderms and/or large benthic foraminifera mainly represented by *Heterostegina* (floatstones).

In both lithofacies typical tropical carbonate elements are absent. The primary mineralogy of the skeletal elements was dominated by low- and/or high-Mg calcite. Early diagenetic processes are of destructive-type involving pronounced grain bioerosion and dissolution.

Although the rhodalgial and echinofor lithofacies of the Rethymnon Formation possess many similarities with facies of the non-tropical carbonates, they are considered to have developed in the warm temperate biogeographic province because of the occurrence of large benthic foraminifera.

The depositional model corresponds to a gentle shallow ramp. The energy level was low, suggesting that all sedimentation took place along the ramp. The main carbonate production and accumulation area was located at the factory area itself (rhodalgial lithofacies), as well as downslope from the factory area (echinofor lithofacies).

The Rethymnon Fm bioclastic sediments were deposited in a nearshore environment, under conditions analogous to those prevailing on the present-day circalittoral sea floor of the Mediterranean Sea. According to the classic zonation of Mediterranean benthic assemblages, the rhodalgial-type sediments correspond to the rhodoliths of the “Facies a pralines”

and the echinofor-type sediments to the “Detritique Cotier” bioclastic deposits.

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