Microfacies evidence for the evolution of Miocene coral-reef environments in Cyprus

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Abstract

Cyprus is one of the few areas of the Mediterranean where lower and upper Miocene coral-reefs occur in close proximity and thus is well suited to investigate how environmental and geological changes affected reefs and the associated shallow-marine facies. The prevailing environmental conditions of the lower Miocene Terra Member and of the upper Miocene Koronia Member are reconstructed here, using detailed microfacies comparisons of the skeletal, foraminiferal and calcareous algal assemblages. The lower Miocene reefs were characterised by a higher biodiversity of coralline algae, large benthic foraminifera and corals, and mainly developed in slightly deeper water (20 - 40 m; lower euphotic zone) than the upper Miocene reefs (< 15 m; upper euphotic zone). The reduced late Miocene biodiversity was probably caused by destabilization of the Mediterranean marine environment, possibly in response to global cooling, increased latitudinal gradients and progressive isolation of the basin. The upward shift of the reef environment could be connected to a reduced risk of bleaching in the upper euphotic zone due to late Miocene cooling. Similarities between the Miocene carbonate facies of Cyprus and the Eratosthenes Seamount directly to the south, and elsewhere in the Mediterranean region (e.g., Corsica; Italy; Spain), suggest that the environmental changes inferred for the Miocene of Cyprus operated on a Mediterranean-wide scale.

Key words: Carbonate factories; Large Benthic Foraminifera; Coralline algae; Burdigalian; Tortonian; Climate change.

1. Introduction

The production of bioclastic sediments is closely connected to environmental conditions, including temperature, water-depth and nutrients, and thus narrowly constrained in space (Wilson, 1975; Schlager, 2003). The realisation that different modes of carbonate production occur in different
depositional areas has led to the concept of the “carbonate factory”. Carbonate factories represent the
space where biological carbonate sediments are produced and the associations of carbonate producing
organisms (Tucker and Wright, 1990; Wright and Burchette, 1996; Schlager, 2003). Carbonate factories
change through time (i.e., a certain association of carbonate producers is typical of a certain time
period) and they are significantly influenced by the interaction between the sediment produced by the
factory and sedimentary processes, which include basin physiography, accommodation space and
resedimentation processes (Pomar and Ward, 1995; Pomar and Hallock, 2008). The nature and
distribution of carbonate factories are thus commonly used as environmental indicators (Kiessling et
al., 2002; Bosence and Wilson, 2003; Halfar and Mutti, 2005; Bosellini and Perrin, 2008; Wilson,
2008; Van Buchem et al., 2010; Perrin and Kiessling, 2012; Pomar et al., 2017; Pomar, 2020). Modern
coral-reefs are the best known examples of shallow-water oligotrophic tropical carbonate factories (e.g.
Wilson, 2008), however, it has been proposed that modern reefs developed from the late Miocene
onwards (Pomar and Hallock, 2007; Pomar et al., 2012; Pomar et al., 2017).

Cyprus is a key area of the Mediterranean for the study and understanding of reefs, mainly
because both lower and upper Miocene reefs are exposed in close spatial proximity (Fig. 1). Reefs and
related shallow-water carbonate facies occur in several different tectonic settings, in different parts of
the island, facilitating insights into the potential controls of reef formation, including local to global
sea-level change, tectonics and other environmental factors (Follows, 1992; Eaton and Robertson,
1993; Cannings et al., 2021). The geological framework and the geometries of Miocene reefs and
related facies of Cyprus were largely established in the 1990s, based on field mapping, facies analysis,
petrographic and isotopic studies (Follows, 1990, 1992; Follows and Robertson, 1990; Follows et al.,
1996) (Fig. 1). Well-constrained models were developed for the lower and upper Miocene reefs and
associated sedimentary facies. Relatively little new information on these shallow-water carbonates has
been published during the intervening years. Recently, understanding of the lower and upper Miocene
reefs in the northwest of Cyprus has improved based on a combination of calcareous nannofossils, planktic foraminifera, large benthic foraminifera (LBF) biostratigraphy and strontium isotopic dating of associated hemipelagic facies (Cannings et al., 2021). In this paper, we build on and extend the previous research by providing a detailed microfacies analysis of the lower and upper Miocene coral-reefs and related facies, focusing on LBF and calcareous algae. Our main objective is to determine whether foraminiferal and algal assemblages indicate a water-depth-related change in coral-reef environment during the Miocene. Such depth-related changes have been suggested based on the studies of key outcrops, such as in southern Turkey, Central Italy and the Balearic Islands (Pomar and Hallock, 2007; Pomar et al., 2012; Pomar et al., 2017), and are here tested and developed based on our microfacies results from Cyprus.

2. Geological Setting

The Eastern Mediterranean Basin is a remnant of the Southern Neotethys Ocean (Robertson, 1998b; Schettino and Turco, 2011; Robertson et al., 2012a; Granot, 2016) (Fig. 2). Since the Late Cretaceous, this region, including the structural development of Cyprus, has been greatly influenced by the northward movement of the African-Arabian plate (Robertson and Dixon, 1984; Ben-Avraham and Ginzburg, 1990; Eaton and Robertson, 1993; Robertson, 1998b; Mart and Ryan, 2002). Cyprus can be broadly divided into a ‘northern’ and a ‘southern’ region. The ‘northern region’ is characterised by the Kyrenia Range, which mainly relates to the development of the Anatolian plate (Robertson et al., 2012b, 2013a) (Figs. 1, 2). The ‘southern region’, where the present research is focused, is dominated by the Upper Cretaceous Troodos ophiolite massif (Pearce and Robinson, 2010) and its Upper Cretaceous to Recent sedimentary cover (Figs. 1, 2). From the Maastrichtian to the Oligocene, the Troodos massif was covered by deep-sea sediments (Robertson and Hudson, 1974; Robertson, 1976; Kähler and Stow, 1998; Miguez-Salas and Rodríguez-Tovar, 2019; Rodríguez-Tovar
et al., 2019; Hüneke et al., 2021). During this time interval, the Southern Neotethys was closing due to northward subduction beneath a largely amalgamated continental area to the north (Aktaş and Robertson, 1984; Robertson 1998b; Robertson et al., 2012a; Barrier et al., 2018). By the early Miocene, the opposing continents were colliding in SE Turkey, ending deep-water circulation between the palaeo-Mediterranean Sea and the palaeo-Indo-Pacific Ocean, although shallow-water current interchange probably continued into the late Miocene (Robertson, 1998b; Rögl, 1999; Robertson et al., 2004; 2016; Hüsing et al., 2009; Cornacchia et al., 2018; Bialik et al., 2019). In the Kyrenia Range of northern Cyprus, the regional plate convergence was associated with Oligocene-Miocene deep-water siliciclastic deposition and late Miocene thrusting (Weiler, 1969, 1970; Baroz and Bizon, 1974; McCay and Robertson, 2012; Kinnaird and Robertson, 2013; Robertson et al., 2019). In southern Cyprus, tectonic processes, related to northward subduction and incipient continental collision, helped to create the topography and sedimentary accommodation space for the development of the Miocene coral reefs and associated carbonate facies.

The Miocene successions in the ‘southern region’ of Cyprus are divided into the Pakhna Formation and the Kalavasos Formation (Fig. 1). The Pakhna Formation (type locality: Pakhna village, south of the Troodos Massif; Henson et al., 1949) (Fig. 1C) is composed of hemipelagic marls and calcareous chalks that are interbedded with redeposited neritic bioclastic material, that are interpreted as gravity flow-deposits (Follows and Robertson, 1990; Robertson et al., 1991; Follows, 1992; Eaton and Robertson, 1993; Follows et al., 1996; Reolid et al., 2020). Two intervals of shallow-water carbonates are differentiated within the Pakhna Formation (Fig. 1D). The first is the Terra Member (type locality: Terra Village, SW Cyprus), which comprises lower Miocene reefs and related shallow-water carbonates (Henson et al., 1949; Banner et al., 1999; BouDagher-Fadel and Lord, 2006) (Fig. 1C) and is widely exposed and best developed near Cape Greco in SE Cyprus (Follows and Robertson, 1990; Follows, 1992; Follows et al., 1996). The second is the upper Miocene Koronia Member (type locality: Koronia
Hill, northwestern periphery of the Troodos Massif; Bear, 1960; Constantinou, 1995) (Fig. 1C). This member is better exposed at Kottaphi Hill along the northern Troodos margin (Fig. 1C). The lower Miocene Terra and the upper Miocene Koronia members vary considerably between the different areas and no one area shows the two reef-related members simply stacked one above the other. The Terra Member is exposed in the Cape Greco area as relatively well preserved build-ups and related shallow-water facies (Follows and Robertson, 1990; Follows, 1992; Follows and Robertson, 1996). In contrast, in western Cyprus the Terra Member almost entirely consist of talus deposits that sedimented on an older and irregular substratum (Cannings et al., 2021; E. Balmer, unpublished data). The Koronia Member is represented by both in situ build-ups and related talus in its type area along the northern margin of the Troodos massif (Follows and Robertson, 1990; Follows et al., 1996) (Fig. 1C). In addition, the Koronia Member is also exposed on both the east and the west flanks of the Polis graben (Follows et al., 1996; Cannings et al., 2021; E. Balmer, unpublished data) (Fig. 1C). There are also small exposures of the Koronia Member near Cape Pyla in SE Cyprus (Follows and Robertson, 1990; Constantinou, 1995). Elsewhere, around the southern periphery of the Troodos Massif, the former existence of in situ reefs can be inferred from gravity-flow material including detached blocks and debris-flow deposits within interbedded deeper-water carbonate sediments (e.g. near Tochni village and in Happy Valley) (Robertson, 1977; Eaton and Robertson, 1993).

This paper focuses on outcrops near Cape Greco (CG1-6; CG1= 34°58'30"N, 34°04'33"E; CG2= 34°57'55.5''N, 34°04'17.5"E; CG3= 34°57'48.5"N 34°04'01.7"E; CG4= 35°00'17"N, 34°02'12"E; CG5= 34°58'56.8"N 34°01'53.0"E; CG6= 34°59'09"N 34°01'16"E), near Cape Pyla (CP= 34°57'40.5"N, 33°50'2.5"E), on Kottaphi Hill (KH1, 2; KH1= 35°02'52.5"N 33°09'15.5"E; KH2= 35°02'59"N 33°08'25"E) and near Tochni village (TC; 34°47'02.5"N 33°19'13"E) (Fig. 1), therefore, more detailed information on the stratigraphy of these localities is provided below.
2.1 Cape Greco

In SE Cyprus (Fig. 1C) the oldest exposed mappable unit is the Late Cretaceous Paralimni Mélange which is composed of a wide variety of exotic Mesozoic lithologies, including quartzose sandstone, pelagic limestone, radiolarite, basalt and minor serpentinite, all set in a soft-weathered clay-rich matrix. The melange is interpreted as subaqueous debris-flows related to the emplacement of Mesozoic oceanic and continental margin material, similar to the Moni Melange in central southern Cyprus (Follows and Robertson, 1990 and references therein). The melange is overlain by the pelagic chalks and cherts of the Lefkara Formation, also exposed near Cape Greco (Constantinou, 1995). The Lefkara Formation is in turn overlain by the Terra Member, although the contact is not well exposed in the Cape Greco area. Benthic and planktic foraminiferal assemblages of the Terra Member at Cape Greco indicate an early Miocene age (Follows and Robertson, 1990; Follows, 1992; Follows et al., 1996). This is consistent with the results of recent Sr isotope stratigraphy from the Polis Graben area of western Cyprus (Fig. 1C), which suggest that the Terra Member sedimentation ended before 14 Ma (Cannings et al., 2021). The Terra Member is locally overlain by hemipelagic chalk of probable middle Miocene age (poorly exposed), and then, above a low-angle unconformity, by upper Miocene chalk (Follows, 1990; Follows and Robertson, 1990).

2.2 Kottaphi Hill

Along the northern margin of the Troodos ophiolite, Miocene shallow-water carbonates form several, generally elongate, outcrops, including the type locality of the Koronia Member at Koronia Hill in the west (Fig. 1C). In the west, including at Koronia Hill, Miocene shallow-water facies are transgressive on the Troodos ophiolite, whereas further east they overlie the deep-water sedimentary cover of Late Cretaceous-Oligocene age (Perapedhi and Lefkara formations). The succession named KH1, were most of the Koronia Member samples were collected, is well exposed on
the southeastern slopes of Kottaphi Hill, near Agrokipia village (Fig. 1C). The Neogene succession begins with lower Miocene chalks, that are separated from the overlying middle Miocene chalk by a highly-burrowed manganese-rich layer (Davies, 2001). Above this, the chalk is interbedded with fine-grained, dark-coloured, micrite-rich packstones, followed by normal-graded bioclastic carbonates (Robertson, 1976; Follows, 1990; Morse, 1996; Davies, 2001). Initially, thin bedded (<5 cm) and sand-sized, these bioclastic sediments become thicker bedded and increasingly coarse grained upwards, and are interpreted as calciturbidites (Davies, 2001). Above this come matrix-supported breccia-conglomerates with abundant neritic carbonate debris, interpreted as debris-flow deposits (Davies, 2001). Tortonian calcareous nanofossils were identified at the base of the major breccia-conglomerate interval (Davies, 2001), consistent with the late Miocene age that was proposed for the Koronia Member by previous authors (Follows and Robertson, 1990; Follows, 1992; Robertson et al., 1991; Follows et al., 1996). Recent research in NW Cyprus, mainly based on integrated nanofossil and strontium isotope stratigraphy, indicates that the Koronia Member reefs mainly grew between c. 9.1 and c. 6.1 Ma (Cannings et al., 2021).

2.3 Tochni

Tochni outcrop consists of an old quarry, c. 400 m north of Tochni village in south-central Cyprus (Fig. 1C). The exposed Koronia Member deposits form part of a N-S trending, sediment-filled submarine channel that developed along the northern periphery of the Maroni Basin (gullied-slope facies of Eaton and Robertson, 1993) (Fig. 1C). The channel and the related facies are placed within the upper Miocene (Tortonian) (Bagnall, 1960; Eaton and Robertson, 1993). The basal part of the succession consists of massive mixed siliciclastic-carbonate deposits (c. 35 m thick), forming lenticular beds up to several m thick interpreted as mass-flow deposits (i.e., gravity-controlled grain-flow deposits) (Eaton and Robertson, 1993). These layers contain abundant bioclastic fragments. Some of
the thicker beds include abundant clasts (up to c. 1 m in size) of pelagic chalk derived from the underlying Lefkara Formation. The mass-flow layers are incised by channels infilled by a clast-supported conglomerate (c. 30 m thick). The clasts of this conglomerate include rounded pebbles (several cm in size), mainly basalt and jasper (iron-rich chert), that were eroded from the Troodos ophiolite and its related deep-sea deposits, chalks from the Lefkara Formation, and Miocene neritic limestones (Eaton and Robertson, 1993).

2.4 Cape Pyla

Cape Pyla is located c. 20 km west of Cape Greco (Fig. 1). Here the Koronia Member consists of fine-grained bioclastic calcarenites with large, irregular echinoids overlain by planktic foraminiferal wackestones (Henson et al., 1949). Towards the top of the succession, the wackestones are interbedded with rudstones layers rich in rhodoliths and interpreted as mass-flow deposits (Henson et al., 1949).

3. Previous studies of the reefs and reef-related facies

Follows (1990, 1992) and Follows et al. (1996) provided detailed field observations and interpretations of the Terra and Koronia members coral-reefs, including their structure, facies distribution and depositional environment. Following tectonic uplift, the Terra Member in SE Cyprus developed on a relatively stable shallow-water substrate, isolated from large landmasses and thus from sources of siliciclastic material. Of the various exposed reef-bodies, the largest one, exposed in the Cape Greco Area (CG2 and CG3), is up to 80 m high by 500 m long. According to Follows (1990), the morphology of the coral colonies of the Terra Member reefs indicates a relatively calm environment and intermediate water depth (up to 20 - 30 m), furthermore, there is no evidence that Terra Member
reefs reached the sea-level. The bioclastic deposits that surrounds the reefs are dominated by coralline algae and LBF.

The development of the Koronia Member was strongly influenced by local tectonic processes. Differently from the Terra Member, the Koronia Member formed a belt of fringing reefs around the periphery of the uplifting Troodos Massif, with well-developed fore-reefs and relatively narrow back-reefs. The morphology of the coral colonies indicates that the Koronia Member reefs formed in a turbulent, shallow-water setting (Follows, 1990). The fore-reef facies were characterised by large volumes of neritic-derived talus together with abundant rhodoliths, molluscs and benthic foraminifera. Minor intercalations of ophiolite-derived material were derived from the nearby, emerging Troodos massif.

Previous studies recognised colonial corals, LBF and coralline algae as important carbonate producers in both the Terra and Koronia members (Eaton, 1987; Follows, 1990; Follows and Robertson, 1990; Follows, 1992; Follows et al., 1996), although quantification of the skeletal assemblages was not attempted until now. The coral fauna in the lower Miocene Terra Member include several taxa of major frame builders (Porites spp., Favia aquitaniensis, Favites neugeboreni) as well as several taxa of secondary builders (Favia melitae, Hydnophora provincialis, Goniastrea sp., Heliastrea grandis, Solenastrea tizeroutinensis, Tarbellastrea carryensis, Lithophyllia michelotti, Leptomussa falloti, Actinastrea tarbellensis, Stylophorida reussiana, Acropora sp., Gonioporta sp., Siderastrea sp.) (Follows 1990, 1992; Follows and Robertson 1990; Follows et al., 1996). In contrast, the coral assemblage of the upper Miocene Koronia Member consists of only a few taxa of major frame builders (Porites sp., Tarbellastrea reussiana) and secondary builders (Monastrea sp., Tarbellastrea carryensis) (Follows, 1990; Follows and Robertson, 1990; Follows, 1992; Follows et al., 1996). Similarly, a diversified LBF assemblage, including Operculina, Amphistegina, Sphaerogypsina, Spyroclupeus, various lepidocyclinids and miogyspinids, were recorded in the Terra Member, whereas only
Operculina, Amphistegina and Borelis were reported from the Koronia Member (Mantis, 1969, 1970; Eaton, 1987; Follows, 1990; Follows et al., 1996).

4. Material and Methods

For each outcrop investigated at Cape Greco (CG1-6), Cape Pyla (CP), Kottaphi Hill (KH1, 2) and near Tochni village (TC) (Fig. 1C), representative samples were collected, followed by the preparation of 92 polished thin sections. Carbonate rocks were classified based on Dunham’s (1962) classification, expanded by Embry and Klovan (1971) and Insalaco (1998). The petrography, skeletal assemblage and foraminiferal assemblage were investigated in each thin section, whereas coralline algal assemblages were studied only in algal-rich samples. The skeletal assemblage in each thin section was examined using point-counting (200 μm mesh; >800 points per section) (Flügel, 2010). To avoid oversampling of large elements, six randomly selected fields, with no overlap between them, were analysed in each section. The reconstruction of the prevailing environmental conditions is based on the results of the microfacies analysis, focused on coralline algal and foraminiferal assemblages (unprocessed data are included in Supplementary Table 1). The proposed palaeo-water depths rely on comparisons with the life occurrences of modern taxa of coralline algae and foraminifera and on the correlation between carbonate production and light penetration. According to Pomar (2001) the photic zone is divided in an upper part and a lower part. The upper part, referred to as the euphotic zone, is dominated by organisms that need relatively intense sunlight (e.g., green calcareous algae; large symbiont-bearing miliolids), i.e., up to 40 - 50 m in very clear water. The lower part, referred to as the oligophotic zone, is dominated by organisms that can thrive in low-light conditions (e.g., Hapalidiales; several taxa of nummulitids), i.e., typically from 40 - 50 m up to 100 - 140 m in very clear water.
Foraminiferal assemblages were studied using area-counting, identifying all of the specimens to the lowest reasonable taxonomic level in each thin section. The relative abundance of the most common LBF (miogypsinids, lepidocyclinids, heterosteginids, nummulitids and amphisteginids) was recorded. The ratio of rotaliids to miliolids, and the ratio of planktic to benthic taxa were also calculated. Taken together, these ratios were used to infer the approximate water depths of deposition following well-documented methodologies (e.g. Hallock and Glenn, 1986; Van der Zwaan et al., 1990; Beavington-Penney and Racey, 2004).

Coralline algal assemblages were investigated following the methods of Coletti et al. (2018). The algae were identified in the thin sections using a light microscope; the sections were then scanned, and the raster images uploaded to Inkscape (release 0.91). The outlines of each specimen were then traced in the vector graphic editor, and the area covered was measured using the path-measuring extension of the program. In order to compare our dataset of coralline algae accurately with those previously published, a simplified high-rank taxonomic scheme was used, based on algal reproductive anatomy, following Coletti and Basso (2020). This scheme recognises three major groups of coralline algae: 1) Corallinales (*sensu* Rösler et al., 2016 and Caragnano et al., 2018), i.e., algae with sporangial thalli, characterised by uniporate conceptacles; 2) Hapalidiales (*sensu* Nelson et al., 2015), i.e., coralline algae with sporangial thalli, characterised by multiporate conceptacles; 3) Sporolithales (*sensu* Le Gall et al., 2009), i.e., coralline algae with sporangial thalli, characterised by sporangi grouped in sori. Following Braga et al. (1993) and Hrabovský et al. (2016), coralline-algal genera have been identified based on the major morphological characters highlighted as useful by modern phycology and preserved in fossil material. Following Coletti et al. (2020), the genus *Chamberlainium* (introduced by Caragnano et al., 2018) has been separated from the genus *Spongites* based on its mainly dimerous organisation, usually displaying in tangential sections a basal layer of palisade-like cells, and its small conceptacles (< 300 μm in diameter) characterised by a thin roof (< 8 cells thick).
Similar to benthic foraminifera, coralline algal distribution is related to water depth; in particular, the ratio of Hapalidiales to Corallinales is positively correlated with increasing water depth, both in modern and Miocene settings (Adey and Macintyre, 1973; Minnery et al., 1985; Adey, 1986; Iryu, 1992; Rasser and Piller, 1997; Cabioch et al., 1999; Aguirre et al., 2000; Brandano et al., 2005; Benisek et al., 2009; Braga et al., 2009; Coletti and Basso, 2020).

5. Results

5.1 Terra Member – Cape Greco

Stratigraphically significant genera were identified during this study, including Miogypsina (possibly Miogypsina globulina), Miolepidocyclina, Miogysinoides, and Nephrolepidina, confirming an early Miocene age, no younger than the Burdigalian (Cahuzac and Poignant, 1997; Özcan and Less, 2009; Özcan et al., 2009). This is consistent with previously proposed early Miocene age for the Terra Member (Follows and Robertson, 1990; Follows, 1992; Follows et al., 1996; Cannings et al., 2021).

5.1.2 Facies

Observations during this study show that the Terra Member at Cape Greco is characterised by hermatypic-coral-dominated domestones (outcrops CG1, CG2, CG3) and LBF-coralline-algal packstones (outcrops CG4, CG5, CG6). The domestones form large frame-reefs up to 80 m high and several hundreds of meters across (CG2, CG3) (Fig. 3A). The growth fabric of these frame-reefs (sensu Riding, 2002) is dominated by a diversified assemblage of colonial corals (mostly domal colonies), associated with coralline algae that encrust and bind the corals (Fig. 3B-F). Borings made by endolithic bivalves (probably still in life position) are also common (Fig. 3E). Pockets of LBF-rich packstone (up to 1 m
across and several 10s cm deep) were locally observed among the colonies of CG1 and CG2 (Fig. 3F), whereas pockets of well-sorted grainstone (several decimeters in size) were observed in CG3. The overall skeletal assemblage is dominated by colonial corals, associated with abundant coralline algae and large rotaliids (Table 1; Fig. 4A, B). Encrusting foraminifera are mainly acervulinids, associated with rare encrusting miliolids; small benthic foraminifera, bryozoans (Fig. 4A-C), molluscs, and echinoderms are minor additional components (Table 1). Green calcareous algae (mainly *Halimeda*) and serpulids are also present (Fig. 4D). Planktic foraminifera occur very rarely. The benthic foraminiferal assemblage is dominated by miogypsinids, mainly *Miogypsina*, although *Miogypsinoides* also occurs (Fig. 5A, B). *Amphistegina* is common (especially in CG3). *Borelis* and *Peneroplis* are also present (Fig. 5C). *Sphaerogypsina*, agglutinated foraminifera, small miliolids and small rotaliids occur rarely (Table 1; Fig. 5D). Coralline algae are mainly present as thin (∼100 μm) and thick crusts (several mm) attached to corals and other skeletal grains or as bioclasts amongst coral colonies (Fig. 6A, B).

Articulated coralline algae are very rare. The algal assemblage is diverse and commonly includes the genera, *Phymatolithon*, *Mesophyllum*, *Spongites*, *Chamberlainium*, *Lithophyllum* and *Lithoporella* (Fig. 6C-H). The thin crusts are commonly characterised by cell fusions, beautifully preserved trichocytes and a coaxial hypothallus, suggesting assignment to the genus *Neogoniolithon* (Fig. 6B). Overall, the algal assemblage is almost equally represented by Corallinales and Hapalidiales (Table 1).

LBF-coralline-algal packstones crop out extensively in the Cape Greco area, forming the low ground and small hillocks between the frame-reefs (Fig. 7A). These are characterised by a diverse LBF assemblage, associated with abundant fragments of echinoderms and coralline algae (Fig. 7B). Two different facies were recognised: a LBF and echinoderm facies and a coralline algal and LBF facies.

The LBF and echinoderm facies was observed around a small mound in the center of the Cape Greco peninsula (CG4), and the coralline algal and LBF facies along the SE margin of an
The LBF and echinoderm facies is characterised by moderately sorted packstones, with small amounts of micrite; this is dominated by LBF and echinoderms, together with abundant coralline algae, mainly occurring as fragments of crusts and branches (Table 1; Fig 7C). Molluscs and planktic foraminifera occur as minor components; bryozoans and serpulids (mainly Ditrupa) occur rarely (Fig. 7D, E). The benthic foraminiferal assemblage is dominated by lepidocyclinids (including Nephrolepidina; Fig 7F), Operculina, Amphistegina, common Miogypsina, Miolepidocyclina and other large rotaliids; small benthic rotaliids, mainly Cibicides and Neoconorbina (with rare Lenticulina), are very common, whereas miliolids and textulariids are rare (Table 1). Coralline algal specimens are either too small or too fragmented to allow taxonomic identification.

The coralline algal and LBF facies (observed in CG5 and CG6) comprises poorly sorted, micrite-rich packstones that are dominated by coralline algae and LBF, associated with fragments of corals, small benthic foraminifera and encrusting miliolids (nubecularids) (Table 1; Fig. 8A). The benthic foraminiferal assemblage is dominated by Miogypsina, Miolepidocyclina and small miliolids (mainly Triloculina and Quinqueloculina), associated with common Borelis and small rotaliids (Table 1; Fig. 8A, B). Amphistegina, Lepidocyclina, textulariids and soritids are rare. The few identifiable coralline algae include Corallinales and Sporolithales (Fig. 8A), whereas Hapalidiales are absent.

5.2 Koronia Member – Kottaphi Hill

Two different neritic carbonate facies are recognised at Kottaphi Hill (9A). The flat heterosteginid facies characterises the dark-coloured packstone layers located below the debris flows (Fig. 9B). The coral-reef facies characterises the large sheetstone clasts that are embedded in the breccia-conglomerates (debris-flow deposits) of KH1 and KH2 outcrops (Fig. 9C, D).
The skeletal assemblage of the packstones is dominated by poorly preserved specimens of very thin and flat heterosteginids (Table 1; Fig. 10A, B). These LBF are associated with small benthic rotaliids including common Elphidium, Neoconorbina, Cibicides, Lenticulina, and rare bolivinids and lagenids (Table 1; Fig. 10C, D). Planktic foraminifera are also quite common (Fig. 10B, D).

Echinoderms, molluscs, serpulids and finely fragmented coralline algae are also present in minor amounts.

Sheetstone clasts within the debris-flows range from cobbles to megaboulders (several m across) and are embedded in a fine-grained micritic matrix. Encrusting colonies of Porites, coralline algae and endolithic mollusc borings can be recognised in the field (Fig. 9C, D). The skeletal assemblage of the sheetstones of both KH1 and KH2 is dominated by coralline algae, colonial corals and encrusting miliolids (nubecularids) (Table 1; Fig. 11A-C). Porites fragments are often encrusted by coralline algae (Fig. 11A), nubecularids (Fig. 11B), or both. Nubecularids also developed crusts around other bioclasts (Fig. 11C). Non-skeletal grains are also abundant, mainly sand-sized peloids (Table 1; Fig. 11D). Micrite locally fills the spaces between larger bioclasts. Mollusc shells and gastropod moulds are relatively common (Fig. 11E). Echinoderms, encrusting rotaliids (mainly Homotrema), green calcareous algae (mainly Acetabularia) and small benthic foraminifera are less common (Fig. 11F, G). Serpulids occur locally (Fig. 11H), whereas bryozoans and ostracods are rare. The benthic foraminiferal assemblage, excluding encrusting taxa, is relatively sparse, dominated by small miliolids, mainly Triloculina, Quinqueloculina and Pyrgo, associated with common small rotaliids, mainly Elphidium and rare Cibicides (Table 1; Fig. 12A-B). The coralline algal assemblage is largely dominated by Neogoniolithon sp. (Fig. 13A-D). Titanoderma, Lithophyllum sp. and Lithophyllum dentatum occur as minor components (Fig. 13E-H). Neogoniolithon sp. occur as thick crusts (up to 1 cm) with large (several mm in diameter) thick protuberances. Titanoderma and Lithophyllum dentatum
mostly form thin crusts (~100 μm). *Titanoderma* mostly occur as thin monostromatic crusts (Fig. 13F).

Overall, the coralline-algal assemblage consists almost entirely of Corallinales (Table 1).

### 5.3 Koronia Member – Tochni, Cape Pyla

The Koronia Member was investigated in two other areas, one in south-central Cyprus (Tochni, TC) and the other in SE Cyprus (Cape Pyla, CP), to allow comparisons and to test for variations within the Koronia Member (Fig. 1).

In the Tochni area the base of the Koronia Member is represented by large lenticular beds of mixed siliciclastic-carbonate deposits (Fig. 14A). These include abundant bioclastic fragments (Fig. 14B): heterosteginids (thin and flat specimens), small rotaliids, small miliolids, fragments of coralline algae, molluscs and echinoderms. These mixed deposits are incised by lenticular clast-supported conglomerate (c. 30 m thick) (Fig. 14A), interpreted as a submarine channel, that includes large clasts (up to 10s cm across) of well-preserved poritid corals (Robertson, 1977; Eaton and Robertson, 1993).

Two main types of Miocene neritic limestone clasts were recognised in the conglomerate during this study: packstones/rudstones dominated by coralline algae and grainstones dominated by large miliolids (Table 1; Fig. 14C-H). The LBF assemblages, observed in the mixed siliciclastic-carbonate deposits and in the limestone clasts of the conglomerate, are dominated by heterosteginids and *Borelis melo* *melo*, and lacks miogypsins or lepidocyclinids, which suggests a middle to late Miocene age (i.e. SBZ26 of Cauhzac and Poignant, 1997).

Coralline algal packstone/rudstone clasts are characterised by thin crusts (< 1 mm), crust fragments, and fragments of coralline algal branches. The algal assemblage is largely dominated by Hapalidiales (mainly *Phymatolithon*) (Fig. 14C), whereas Corallinales (mostly *Titanoderma*) are rare (Table 1). The algae are associated with abundant benthic foraminifera, bryozoans, common echinoderms and also rare green calcareous algae, molluscs and planktic foraminifera (Table 1).
Benthic foraminifera are mainly represented by small rotaliids, of which the most easily recognisable are Cibicides, Neoconorbina and Elphidium (Table 1; Fig. 14D). Miliolids are also common, mainly Triloculina and Borelis melo melo (Table 1). Textulariids and bolivinids are also present (Fig. 14E).

Planktic foraminifera are also common. The large miliolid grainstones are well-sorted and dominated by tests of porcellaneous foraminifera, mainly Borelis melo melo and Dendritina, associated with Triloculina and Quinqueloculina, whereas Peneroplis only occurs rarely (Fig. 14F-H). Small rotaliid specimens (of uncertain taxonomic identification) are also common, whereas thin and flat heterosteginids, textulariids and Sphaerogypsina are rare (Table 1; Fig. 14F, H). In addition to benthic foraminifera other skeletal grains include articulated coralline algae (Fig. 14G), corals, molluscs, echinoderms, bryozoans and nubecularids. Sand-sized grains of basalt also occur indicating a subordinate input from the Troodos ophiolite (Fig. 14H).

Near Cape Pyla (Fig. 1), the shallow water deposits of the Koronia Member include two thin rhodolith rudstone beds (c. 5 cm thick), interbedded with planktic foraminiferal wackestones (Fig. 15). The presence of Orbulina universa in the wackestone bed located between the rhodolith rudstones suggests a post-early Langhian age (Fig. 15A). A coralline-algal facies characterises the rudstones, with the algae mainly occurring as small rhodoliths and branch fragments (Table 1; Fig. 15B). Echinoderms, bryozoans and Halimeda are relatively common, whereas benthic foraminifera are mainly small rotaliids, miliolids and very rare textulariids (Fig. 15B-C). Most of the benthic foraminifera belong to Elphidium, Neoconorbina and Cibicides, whereas Borelis melo melo and Planorbulina are rare (Table 1; Fig. 15B). The algal assemblage is dominated by Hapalidiales (poorly preserved thalli of either Lithothamnion or Phymatolithon), with common Corallinales (mainly Titanoderma) (Table 1).

6. Discussion
6.1 Facies interpretation

The different facies recognised in the Terra and Koronia members are here interpreted in a comprehensive framework based on microfacies evidence, namely skeletal, benthic foraminiferal and coralline algal assemblages (Table 1; Supplementary Table 1). The palaeoenvironmental reconstruction also takes account of previously published data and relevant case histories.

6.1.1 Coral-reef facies - lower Miocene Terra Member

This facies is characterised by abundant large rotaliids, both free-living and encrusting, with miogypsinids as the most abundant free-living taxa. Several studies of Miocene limestones from across the world suggest that Miogypsina and Miogypsinoides should be considered similar to living baculogypsinids; Miogypsina probably lived between 0 and 80 m, while Miogypsinoides between 0 and 50 m (Chaproniere, 1975; Hallock and Glenn, 1986; Drooger, 1993; Geel, 2000; BouDagher-Fadel, 2018; Renema, 2018). Borelis, Peneroplis and other small miliolids, although less abundant than miogypsinids, also occur within the coral-reef facies (Table 1). Analyses of modern foraminiferal assemblages indicates that miliolids are usually more abundant in the shallow inner parts of the platform. In particular, large taxa like Borelis and Peneroplis are usually related to high-energy environments and water depths of < 70 m and commonly of < 40 m (Hohenegger, 1995; Saraswati, 2002; Murray, 2006). Encrusting rotaliids are secondary builders in modern reefs, where they generally occur in water depths of 25 - 60 m and commonly in the 40 - 60 m range (Hottinger, 1983; Rasser and Piller, 1997). The coralline algal assemblage of the Terra Member is dominated by Corallinales, but Hapalidiales are nearly as common. In modern tropical environments, Corallinales generally dominate very shallow-water settings (< 20 m; especially < 10 m), whereas Hapalidiales dominate at > 60 m; from 20 to 40 m both groups can be relatively common (Adey & Macintyre, 1973; Minnery et al., 1985; Adey, 1986; Iryu, 1992; Rasser and Piller, 1997; Cabioch et al., 1999; Aguirre et al., 2000).
similar pattern is observed in Miocene tropical carbonates related to oligotrophic settings (Brandano et al., 2005; Benisek et al., 2009; Braga et al., 2009; Vescogni et al., 2014; Coletti and Basso, 2020).

Assuming that the Miocene foraminiferal and coralline algal assemblages lived at similar water depths to their modern counterparts, taking both assemblages together, water depths of 20 - 40 m can be inferred for the lower Miocene coral-reef facies. The proposed depth range of 20 - 40 m is in agreement with the water-depth estimate proposed by Follows (1990) based on his analysis of coral morphology.

Given the oligotrophic conditions prevailing nowadays in the Eastern Mediterranean and seawater transparency (Basso et al., 2004; Sisma-Ventura et al., 2017), this depth range would be within the lower part of the euphotic zone and thus above the lower limit of green algae and of large symbiont bearing miliolids. Neodymium isotopes record of the basin suggests that during the early Miocene the Eastern Mediterranean was still influenced by water inflow from the oligotrophic Northwestern Indian Ocean (Bialik et al., 2019), indicating that oligotrophic conditions were probably prevailing during the early Miocene.

6.1.2 LBF and echinoderm facies - lower Miocene Terra Member

This facies is characterised by a benthic foraminiferal assemblage dominated by lepidocyclinids and Amphistegina, with common miogypsinsids and nummulitids, together with additional large benthic rotaliids, abundant small rotaliids, relatively common planktic foraminifera and very rare miliolids (Table 1). Overall, this facies has a higher rotaliid/miliolid ratio and a higher planktic/benthic ratio than the coral-reef facies. Compared to miogypsinsids, lepidocyclinids were probably more widely distributed throughout the platform environment, possibly from shallow-water, up to the lowest limit of the euphotic zone (Chaproniere, 1975; Hallock and Glenn, 1986; Geel, 2000; Beavington-Penney and Racey, 2004; BouDagher-Fadel, 2018; Briguglio, 2018). Lepidocyclinid-dominated facies, similar to those of the Terra Member, were common during the Oligocene - early
Miocene of the Tethyan and Indo-Pacific realms (e.g., Bosellini et al., 1987; Bosellini and Perrin, 1994; Tomassetti et al., 2013). In Somalia, Bosellini et al. (1987) interpreted lepidocyclinid facies as fore-reef deposits that developed at water depths of 30 - 60 m based on geometrical evidence, specifically the vertical distance between lepidocyclinid rich layers and the coral-reef deemed by the authors to have reached sea level. The 30 - 60 depth range is consistent with the presence of both miogypsinids, lepidocyclinids, minor planktic foraminifera, and with the lack of common large symbiont-bearing miliolids and green calcareous algae. Since both symbiont bearing miliolids and green calcareous algae are relatively more common in euphotic-zone carbonate factories (e.g. Pomar, 2020: fig. 12.9c), their absence suggests a water depth below or close to the lower limit of green algae. A similar lepidocyclinid and echinoderm- dominated facies, with a nearly identical skeletal assemblage and similar inferred depth range (30 - 60 m), has been reported from the lower Miocene of the Eratosthenes Seamount, south of Cyprus (Fig. 1A; Table 2) (Coletti et al., 2019).

6.1.3 Coralline-algal and LBF facies - lower Miocene Terra Member

This facies is rich in coralline algae and coral fragments, contains more abundant miliolids, including common Borelis and rare soritids, has more miogypsinids and less planktic foraminifera than the LBF and echinoderms facies (Table 1). The few coralline algae identified belong to the shallow-water group of the Corallinales, suggesting a shallower setting compared to both the LBF and echinoderm facies and possibly also of the coral-reef facies. The foraminiferal assemblage includes several taxa which, in modern environments, are known to occur associated with marine vegetation (e.g. Quinqueloculina, Triloculina and soritids; Langer, 1993; Murray, 2006; Mateu-Vicens et al., 2014). Modern and ancient meadows are characterised by similar poorly sorted sediments (see Reich et al., 2015 for a review of palaeo-seagrass indicators). It is quite possible that this facies represents the remains of a vegetated seafloor, as already proposed for a large portion of Cape Greco inter-reef
bioclastic deposits (Follows, 1990: fig. 6.4); it probably accumulated at < 30 m within the euphotic zone.

6.1.4 Coral-reef facies - upper Miocene Koronia Member

The algal assemblage of the reef consists almost entirely of Corallinales including *Lithophyllum dentatum*, a still-living Mediterranean species that inhabits intertidal and infralittoral settings (Bressan and Babbini, 2003). A similar coralline algal assemblage characterises the upper Miocene coral-reef and lagoonal facies of the Eratosthenes Seamount (Table 2), where it is interpreted to have formed at water depths of < 20 m (Coletti and Basso, 2020). The calcareous green alga, *Acetabularia*, although never abundant, occurs in several samples (Fig. 8F). Living representatives of this genus are generally abundant at tropical latitudes at water depths < 15 m (mostly < 10 m; Marszalec, 1975; Manuel et al., 2013) and at < 5 m in the Mediterranean Sea (e.g., Fornos et al., 1992). The encrusting foraminiferal assemblage is dominated by nubecularid miliolids (Table 1). Recent representatives of this group are extremely common at water depths of < 10 m and rarely occur at > 25 m (Cann et al., 1988, 1993; James and Bone, 2007). The dominance of miliolids amongst the non-encrusting taxa also supports shallow-water conditions (Hallock and Glenn, 1986; Beavington-Penney and Racey, 2004). Peloids are another important component of the Koronia Member reef carbonates (Table 1; Fig. 11D). These grains commonly occur within tropical carbonate systems in shallow-water protected settings (e.g., < 10 m on Great Bahama Bank; Tucker and Wright, 1990; Harris et al., 2015). Based on modern comparisons, water depths of < 15 m are thus likely for the coral-reef facies of the Koronia Member. A water depth of < 15 m is also consistent with Follow’s (1990, 1992) analysis based on coral morphologies that indicates shallow and turbulent water for the reefs of the Koronia Member. This depth range indicates that the reefs of the Koronia Member most likely developed within the upper euphotic zone.
6.1.5 Flat heterosteginid facies - upper Miocene Koronia Member

This facies characterises the fine-grained packstones that are interbedded with pelagic chalks at the base of the KH1. Large, flat nummulitids with partitioned chambers (e.g., *Cyclocypeus*, *Planostegina*), favour the oligophotic zone, which today is located at about 80-120 m below the surface in the open ocean (Hallock, 1987; Hohenegger, 2000; Hohenegger et al., 2000; Renema, 2006, 2018). Thin-tested LBF are usually related to deep water settings (Hallock et al., 1986; Mateau-Vicens et al., 2009). *Lenticulina* is also relatively abundant in the foraminiferal assemblage of this facies; in modern environments this genus is usually related to outer shelf and bathyal settings (Murray, 2006). A relatively deep environment is also consistent with the abundance of planktic foraminifera (Van der Zwaan et al., 1990). Since the heterosteginid-bearing packstones are interbedded with planktic foraminiferal chalks and most of the observed LBF specimens display common orientation and are poorly preserved (Fig. 10), the LBF and the associated finely fragmented coralline algae, are likely to represent material that was transported down-slope from the lowermost part of the photic zone (~ 100-120 m of water depth) to a distal outer shelf setting.

6.1.6 Large miliolid facies - upper Miocene Koronia Member

The large miliolid facies is largely dominated by the well-sorted tests of large imperforate genera, such as *Borelis* and *Dendritina*, and small imperforate genera, such as *Quinqueloculina* and *Triloculina* (Table 1). Modern representatives of *Borelis* and *Dendritina* usually occur at depths of < 70 m; their abundance peaks in < 30 - 40 m (Betzler and Schmitz, 1997; Hohenegger, 2004; Murray, 2006; Renema, 2006). Articulated coralline algae are particularly common in this facies. In contrast to encrusting coralline algae, articulated coralline algae mostly grow in shallow-water; therefore their abundance in the large miliolid facies also points to a shallow-marine setting. Given the well-sorted
texture and the composition of the skeletal and foraminiferal assemblage, this facies probably accumulated within the euphotic zone, in a high-energy setting (possibly < 15 - 20 m). A separation from the coral-reef facies is suggested by the low abundance of coral fragments.

6.1.7 Coralline-algal facies – upper Miocene Koronia Member

Coralline-algal facies of both Cape Pyla and Tochni outcrops display algal assemblages dominated by Hapalidiales. In modern tropical oligotrophic settings, Hapalidiales are common below 40 m of water depth and dominate below 60 m (Adey and Macintyre, 1973; Minnery et al., 1985; Adey, 1986; Iryu, 1992; Rasser and, Piller 1997; Cabioch et al., 1999; Aguirre et al., 2000). The benthic foraminiferal assemblages of these facies include various rotaliid genera (e.g., Elphidium, Neoconorbina and Cibicides) and miliolid genera (Borelis, Triloculina), that are common in modern shelfal settings (Murray, 2006), often clinging to marine vegetation (Langer, 1993; Mateu-Vicens et al., 2014). In both outcrops, planktic foraminifera and bryozoans are relatively common; there are also rare fragments of the calcareous green alga Halimeda. Overall, this facies is characterised by the co-occurrence of elements typical of the euphotic zone (e.g., Borelis and Halimeda) and oligophotic zone (e.g., Hapalidiales). It is possible that the coralline-algal dominated facies developed at intermediate depths, from below the coral-reef facies and the large miliolid facies, to above the flat heterosteginid facies. As indicated by the Cape Pyla outcrop, the depositional environment of the coralline-algal facies was also characterised by reedimentation processes resulting in the mixing of skeletal grains from the euphotic zone and oligophotic zone.

6.2 Distribution of carbonate production

Previous field-based research indicated that Cyprus carbonate systems were rather small (less than 10 km wide; see Follows, 1990: fig. 6.4, 6.6, 7.5, 7.6), and thus hardly comparable to much
larger carbonate depositional systems like the modern Great Bahama Bank (>100 km wide). Local and regional tectonics has been highlighted as an important control on these small carbonate depositional systems (Robertson et al., 1991; Bosence, 2005). The Terra Member in SE Cyprus developed on a shallow-marine substrate, isolated from terrigenous input. As the carbonate system developed on a relatively flat substratum, reef and off-reef facies developed as build-ups surrounded by bioclastic sediments (Follows et al., 1996) (Fig. 16). During deposition of the Koronia Member around the periphery of the Troodos massif, regional uplift allowed reefs to colonise firm substrates commonly provided by the emerging ophiolite. In addition, the northern margin of the Troodos ophiolite was characterised by rotational block-faulting, allowing the reefs to form on elongate topographic highs, fringed by off-reef facies (Follows and Robertson, 1990). Fore-reef facies were well developed, whereas the back-reef facies were restricted to a relatively narrow tract by the ophiolitic hinterland (Follows et al., 1996) (Fig. 17).

Our research provides important quantitative information on skeletal assemblages and water-depth reconstructions that support and develop previous depositional models based mainly on field observations (Follows, 1990; Follows et al., 1996). The lower Miocene carbonate systems, as studied at Cape Greco, comprised three main carbonate factories, corresponding to the coralline algal and LBF facies, the coral-reef facies and the LBF and echinoderm facies (Fig. 16). The coral-reef factory, located in the lower euphotic zone, was dominated by colonial corals associated with abundant Hapalidiales and Corallinales, and benthic rotaliids. The LBF (mainly lepidocyclinids) and echinoderm factory was located in slightly deeper settings. The coralline algal (mainly Corallinales) and LBF (mainly miogypsinids and miliolids) factory was instead located in shallow-water shoals between the reefs and landward of them. Coralline algae and free-living LBF were important producers in both the euphotic zone and the oligophotic zone. On the other hand, colonial corals were mainly restricted to the lower part of the euphotic zone.
The upper Miocene carbonate system, as studied at Kottaphi Hill and near Tochni, was characterised by four main carbonate factories, corresponding to the coral-reef facies, the large miliolid facies, the coralline-algal facies and the flat heterosteginid facies (Fig. 17). The reef factory, located in the upper euphotic zone, was equally dominated by corals, encrusting foraminifera and Corallinales. Towards the coastal ophiolitic hinterland a narrow and shallow back-reef is inferred, characterised by coral fragments associated with abundant micrite and scattered green-calcareous algae. A similar setting prevails along the modern coast of Okinawa-Jima (Japan), where the fringing reef protects an intertidal platform, several hundreds of meters across, with muddy ponds where calcareous green algae grow over coral-rubble (Ohba et al., 2017). Basinwards, carbonate production was dominated by Hapalidiales. Deeper, in the lower oligophotic zone, flat heterosteginids were the main carbonate producers. The large miliolid factory was probably located in shallow-water along coastal stretches that were not dominated by corals. In modern settings, strong currents and waves can promote the development of similar foraminiferal shoals by inhibiting coral growth (Doropoulos et al., 2017). Within the upper Miocene carbonate system, coral production was restricted to the upper part of the euphotic zone, whereas coralline algae were important producers in the entirety of the photic zone. Free-living LBF, although possibly less abundant than in the lower Miocene system, were still significant contributors in most carbonate factories (except within the reef), but they only dominated in very shallow (i.e., large miliolid-dominated) and deep settings (i.e., flat heterosteginids-dominated).

The above-mentioned model for carbonate facies distribution also finds support in the Miocene succession of the Eratosthenes Seamount. The Eratosthenes Seamount consists of fragmented and thinned continental crust that rifted from the North African margin and is presently subducting beneath Cyprus (Robertson, 1998a, c). The sedimentary cover of the Eratosthenes Seamount includes both lower and upper Miocene carbonates and displays several facies that are similar to those in Cyprus (Table 2). In particular, the lower Miocene LBF and echinoderms facies of the Terra Member and of the
Eratosthenes Seamount are extremely similar, as are the upper Miocene coral-reef facies of the Eratosthenes Seamount and of the Koronia Member (Table 2). The benthic foraminifer and mollusc facies of the Eratosthenes Seamount, interpreted to represent a shallow lagoonal setting, also resemble the large miliolid facies of the Koronia Member (Table 2). These similarities, based on point-count analysis of the skeletal assemblages, indicate that the patterns observed in Cyprus may well be relevant regionally.

6.3 Lower Miocene vs. upper Miocene reefs

Our microfacies analysis of skeletal, foraminiferal and algal assemblages is based on a wide variety of samples and, therefore, provides a time and space averaged picture of the prevailing environmental conditions during the development of Terra and Koronia reefs. The results suggest that lower Miocene coral reefs were generally flourishing in slightly deeper water (c. 20 m deeper) than their upper Miocene counterparts (Table 1; Figs. 16, 17). Lower Miocene reefs also display a higher number of taxa of coralline algae, LBF and corals (Follows, 1990; Follows et al., 1996), than the upper Miocene reefs.

As suggested by Cannings et al. (2021) and supported by the present results, the Miocene carbonate systems of the Cyprus-Eratosthenes area are remarkably similar to many others of the Mediterranean region. Corsica exposes lower Miocene reefs (e.g., Tomassetti et al., 2013) that display facies similar to those of the Cyprus-Eratosthenes area, i.e. reefs characterised by a wide variety of coral taxa associated with abundant LBF and surrounded by LBF and coralline algal dominated facies. The Tortonian to Messinian carbonate systems of Malta (e.g., Bosence and Pedley, 1982), southern Italy (e.g., Bosellini, 2006; Braga et al., 2009), northern Italy (Bossio et al., 1996), Balearic islands (e.g., Pomar et al., 2012, 2017), and southern Spain (e.g., Braga et al., 2009), display poritid-dominated reefs associated with coralline algal dominated fore-reefs. This trend has been already noted in the past.
(Esteban, 1979, 1996; Pomar and Hallock 2007; Perrin and Bosellini 2012, Pomar et al., 2017), but our results provide the first quantitative evidence of it based on the microfacies comparison of spatially-close reefs. Therefore, understanding which processes drove the changes observed in the reefs of Cyprus could be relevant for understanding the Miocene evolution of reefs in the Mediterranean.

In modern reefs an increase in nutrient supply is known to foster an increase of heterotroph suspension feeders (like bryozoans and barnacles), mainly at the expenses of hermatypic corals but also of LBF and calcareous algae (Hallock, 1998; Brasier, 1995a, b; Holmes et al., 1997; Halfar et al., 2004; Reijmer et al., 2012; Jessen et al., 2014; Reymond et al., 2016). This pattern is also observed in Miocene systems, in which phosphate-rich successions comprise skeletal assemblages that are richer in both bryozoans and barnacles, compared to coeval phosphate-poor successions located at the same latitude (Coletti et al., 2017). The Koronia and Terra carbonate systems are consistently dominated by a combination of hermatypic corals, coralline algae and LBF (Table 1). Bryozoans are always a minor component and barnacles are entirely absent. Thus, although nutrient influence cannot be entirely discounted, trophic resources were probably not the main driver of the differences between lower and upper Miocene reefs in Cyprus.

The worldwide distribution of modern symbiont-bearing hermatypic corals is strongly related to temperature. Coral species richness, within a certain threshold (i.e., excessively high temperatures are detrimental to most corals), is positively correlated with temperature (Stehli and Wells, 1971; Veron and Minchin, 1992; Chen, 1999). Similar to corals, modern LBF diversity also correlates with temperature, with warm-temperate assemblages having fewer species and genera than tropical ones (Langer and Hottinger, 2000; Beavington-Penney and Racey, 2004). The reduced biodiversity of both corals and LBF, as observed in the Koronia Member reefs versus the Terra Member reefs, is therefore likely to correspond to a reduction in seawater temperatures from the early Miocene to the late Miocene, always assuming that the comparisons with modern settings are valid. A decline in
both corals and LBF can be observed throughout the Mediterranean basin when comparing early and late Miocene shallow-water carbonate systems (Esteban, 1979, 1996; Bosellini, 2006; Bosellini and Perrin, 2008; Pomar et al., 2017), and can be correlated with late Miocene cooling (Herbert et al., 2016; Miller et al., 2020). However, the evolution of reef environments in Cyprus cannot be solely related to temperature (Cannings et al., 2021). Oceanographic changes represent another important factor. The collision of Europe and Africa during the Miocene changed the Mediterranean from a wide seaway connecting the Indo-Pacific and Atlantic ocean to an isolated basin (Rögl, 1999; Dercourt et al., 2000; Robertson et al., 2004; 2016; Hüsing et al., 2009; Taylforth et al., 2014; Torfstein and Steinberg, 2020).

Water exchange with the Indo-Pacific ocean was reduced during the early Miocene and terminated at about 14 Ma (Bialik et al., 2019). Seawater exchange with the Paratethys declined between the Langhian and the early Tortonian (Cornacchia et al., 2018). Furthermore, Herbert et al. (2016) proposed that late Miocene (post 8 Ma) reduction in CO2 levels, together with a decrease in global temperatures, could have triggered a steepening of the pole-to-equator temperature gradient and an increase in seasonality and aridity. Reduced circulation in the Mediterranean, combined with reduced temperatures, increased latitudinal gradients and aridity (Herbert et al., 2016; Steinhorsdottir et al., 2020), could have resulted in a more seasonal and unstable climate, as recorded by marine and terrestrial proxies (Mosbrugger et al., 2005; Prista et al., 2015). Whereas early Miocene conditions were favourable to many taxa of corals, LBF and coralline algae, late Miocene conditions suited only a few tropical carbonate-producing taxa, thus explaining the overall reduced biodiversity of late Miocene reefs.

Shallow-water carbonate systems may also be significantly influenced by sea-level changes (e.g. Schlager, 1999). Significant sea-level variations (40 - 60 m), related to the waxing and waning of the East Antarctic Ice Sheet, occurred during the early Miocene, following the middle Miocene Climatic Optimum (16.9 - 14.7 Ma) (Miller et al., 2020; Steinhorsdottir et al., 2020), and
possibly during the late Miocene (Ohneiser et al., 2015). Such major changes are likely to have
influenced both the onset and demise of the reefs in Cyprus (Follows et al., 1996; Cannings et al.,
2021). The record of δ¹⁸O also suggests that the amplitude of sea-level changes was generally slightly
larger during the early and middle Miocene than during the late Miocene (Westerhold et al., 2015;
Miller et al., 2020). However, frequency analysis suggests that the late Miocene fluctuations were
much faster (Miller et al., 2020), thus possibly further contributing to the late Miocene instability that
favored the transition towards reefs with reduced biodiversity.

An outstanding problem is the cause (or causes) of the upward depth shift of the Miocene
coral-reef facies. Based on the analysis of the coral-bearing successions of the Balearic Islands, Sicily,
central Italy and Turkey, Pomar and Hallock (2007) proposed that reefs underwent major changes
during the Miocene. Before the late Tortonian, hermatypic corals formed patches and mounds from the
platform top to the base of the slope, well below sea level. During the late Tortonian, hermatypic corals
migrated upwards, building larger and stronger reefs that reached sea level. This shift has been related
to various factors including, evolution of dinoflagellate symbionts and late Miocene cooling which
could have favoured expansion of hermatypic corals into the upper part of the euphotic zone, which
was too warm during the early and middle Miocene. Our research indeed suggests that, on average, in
Cyprus, during the late Miocene, reef development was preferentially occurring in shallower water than
during the early Miocene, but neither our data nor those of Follows (1990, 1992) indicates that during
the late Miocene the reefs became able to build stronger frameworks. Both reefs display sediment-filled
cavities, as well as the presence of adjacent coarse-grained deposits, suggesting a certain degree of
resistance to wave impacts. According to Follows (1990, 1992), lower Miocene reefs displays a more
complex and developed framework than their upper Miocene counterparts which were instead
dominated by encrusting colonies with limited topographic relief relative to the surrounding sediments.
Although, other factors could have been involved which require future research to unravel, a possible
scenario that combines both Cyprus evidence with the Pomar and Hallock (2007) hypothesis, is that the late Miocene cooling could have reduced the temperature-related risk of photo-oxidative stress in the upper euphotic zone (i.e., the bleaching). In the upper euphotic zone, high-irradiance levels would have supported higher photosynthesis rates, promoting a faster growth rate. By growing faster, the few species of corals able to live in the upper euphotic zone would have become able to better keep-up with the rapidly changing sea-level (and the overall less-stable climate).

7. Conclusions

The Neogene succession of Cyprus encompasses two different intervals that are characterised by the development of both coral-reefs and neritic carbonates: the lower Miocene Terra Member and the upper Miocene Koronia Member. Our results, based on microfacies analysis, shed new light on their palaeoenvironmental differences.

1) The frame-reefs of the lower Miocene Terra Member display an high biodiversity including various genera of corals, coralline algae (both Corallinales and Hapalidiales) and large benthic foraminifera (mainly miogypsinids). Based on algal and foraminiferal assemblages, as well as on the morphology of coral colonies, these reefs developed at between 20 and 40 m of water depth (lower euphotic zone). In the shallow shoals landward of the reefs (0 – 30 m; euphotic zone) flourished a carbonate factory characterised by coralline algae and benthic foraminifera (possibly associated with a vegetated substrate). Down-slope (30 - 60 m; upper oligophotic zone), carbonate production was dominated by large benthic foraminifera (mainly lepidocyclinids) and echinoderms.

2) The upper Miocene Koronia Member reefs were characterised by few genera of corals (mainly Porites), coralline algae (solely Corallinales) and encrusting miliolids (mainly nubecularids), together with abundant peloids. Based on coralline algal and foraminiferal assemblages, as well as on the morphology of coral colonies, these reefs developed in < 15 m of water depth (upper euphotic
Back reefs, usually not extensive, were characterised by the presence of green calcareous algae.

Shallow (< 15 - 20 m; upper euphotic zone) high-energy shoals between the reefs were dominated by large miliolids. Down-slope (lower euphotic zone to upper oligophotic zone), reef carbonate production was dominated by coralline algae, and in the lower oligophotic zone (~ 100-120 m of water depth) by heterosteginids.

3) The lower Miocene reefs were characterised by a higher taxonomic biodiversity of coralline algae, large benthic foraminifera and corals, compared to their upper Miocene counterparts. The observed decrease of Hapalidiales coralline algae and of large rotaliids, together with the concurrent increase of miliolids and of Corallinales (coralline algae), suggests that reef growth shallowed from an estimated 20 - 40 m during the early Miocene, to an estimated < 15 m during the late Miocene. Reduced biodiversity can be related to the lower temperatures and the more unstable climate of the late Miocene. Lower temperature could also have reduced the risk of bleaching in the upper euphotic zone, prompting the observed upward shift of the reef environment.

4) Miocene skeletal assemblages nearly identical to those of Cyprus have been observed on the Eratosthenes Seamount, directly to the south. Significant similarities also occur between Cyprus and other reef-bearing Miocene successions elsewhere the Mediterranean, suggesting that the changes in the reef environment observed in Cyprus are likely to have applied elsewhere in the Mediterranean; this particularly prompts the need for additional quantitative investigations of the skeletal assemblages of Miocene carbonate systems.

Acknowledgments

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anonymous reviewers for their helpful comments on the originally submitted manuscript. Special thank also go to Irene Cornacchia for her helpful suggestions and to Yasafumi Iryu and the International Association of Fossil Algae for fruitful discussions and information concerning modern reefs in southern Japan. The first author would also like to thank Milano Bicocca University for funding his post-doctoral grant, the International Ocean Drilling Program, Ratio Oil Exploration Limited Partnership, Aaron Meilijson and Silvia Spezzaferri for supporting his research in the Eastern Mediterranean, and last but not least Curzio Malinverno for his invaluable help in preparing the thin sections. Torin Cannings acknowledges the support of a Natural Environmental Research Council (UK) PhD training award, while Elizabeth Balmer thanks the University of Edinburgh for financial support for her ongoing PhD studies. This research represents a scientific contribution to Project MIUR - Dipartimenti di Eccellenza 2018-2022.

Supplementary material: Supplementary Table 1

References


Renema, W., 2006. Large benthic foraminifera from the deep photic zone of a mixed siliciclastic-carbonate shelf off East Kalimantan, Indonesia. Marine Micropaleontology, 58, 73-82.


Table Captions

**Table 1:** Recognised facies of the Miocene of Cyprus, including the presence of non-skeletal grains (based on thin-section observations), the average composition of the skeletal assemblage (based on point-counting of recognisable bioclasts), the main frame-work builders of reef facies, the most common group of encrusting foraminifera; characteristics of the foraminiferal assemblage (based on thin-section area counting), and the characteristics of the coralline-algal assemblage. A very small amount of Sporolithales (0.5%) was recognised in the lower Miocene coral reef facies but was not included in the table as Sporolithales do not occur in the remaining facies were the surface quantification of the algal assemblage was performed.
**Table 2:** Comparison of Miocene facies of Cyprus and of Eratosthenes Seamount (highlighted in light grey); the microfacies data from the Eratosthenes Seamount are from Coletti et al., 2019, whereas the data of coralline-algal cover are from Coletti and Basso 2020.

**Supplementary table 1:** Unprocessed results of the point-counting and of the analyses of the foraminiferal and algal assemblages.

**Figure 1:** Location of the study area, outline geological map of Cyprus and schematic Cenozoic stratigraphy of the studied areas, modified from Follows et al. (1996) and Cannings et al. (2021). A) World map with the Mediterranean region highlighted in dark grey (B). B) General map of the Mediterranean region with Cyprus highlighted in dark grey (C). C) Simplified geological map of Cyprus showing some of the geological units (main panel); and the main Cenozoic basins (inset). The shallow-water carbonate Terra and Koronia members comprising the Pakhna Formation, are indicated in bright blue and red, respectively (main panel); the investigated outcrops are indicated in bold red and blue in the main panel. D) Cenozoic stratigraphy of southern Cyprus (i.e. the study area); modified from Follows et al. (1996) and Balmer et al. (2019).

**Figure 2:** Schematic tectonic map of the Eastern Mediterranean region showing the main tectonic features. Submarine highs are indicated in grey; BS= Bitlis Suture; DSTF= Dead Sea Transform Fault; ESM= Eratosthenes Seamount; ECB= Eratosthenes Continental Block; IAESZ= İzmir-Ankara-Erzincan Suture Zone; IPS = Intra-Pontide Suture; ITS= Inner Tauride suture; K= Kyrenia Range; M= Mammypia Complex; MAS= Misin-Andırın Suture; T = Troodos massif; modified from Robertson et al., 2013b.
**Figure 3:** Outcrops of the coral domestones of the Terra Member at Cape Greco. A) Panoramic view of the largest of Cape Greco’s lower Miocene reefs showing the locations of outcrops CG2 and CG3; the terraced morphology is related to Quaternary marine erosion. B) Outcrop CG3, detailing the reef framework mainly consisting of domal colonies (red arrowheads). C) Outcrop CG2, colonial coral with platy morphology= red arrowheads. D) Outcrop CG1, coralline algae= red arrowhead. E) Outcrop CG3, massive colonial corals with moulds of endolithic bivalves. F) Outcrop CG1, a pocket of bioclastic limestone (red arrowhead) between coral colonies.

**Figure 4.** Microfacies of the coral domestones of the Terra Member at Cape Greco. A) Outcrop CG1, Coral (Cor) encrusted by coralline algae (red arrowhead) and acervulinids (black arrowhead). B) Outcrop CG2, miogypsinids (red arrowhead) and amphisteginids (black arrowhead) associated with corals (Cor). C) Outcrop CG1, bryozoans (Bry) with miogypsinids (red arrowheads). D) CG3, *Halimeda* (red arrowheads).

**Figure 5:** Large benthic foraminifera of the coral-reef facies of the Terra Member at Cape Greco. A) Outcrop CG1, *Miogypsina* (red arrowhead) and an agglutinated benthic foraminifer (black arrowhead). B) Outcrop CG1, detail of the embryo of a *Miogypsina*; red arrowhead= protoconch. C) Outcrop CG2, large miliolids; red arrowhead= *Borelis*. D) Outcrop CG3, *Sphaerogypsina* (red arrowhead) and *Amphistegina* (black arrowhead).

**Figure 6:** Coralline algae of the coral-reef facies of the Terra Member at Cape Greco. A) Outcrop CG3, thick crust of *Mesophyllum* growing attached to a coral colony (Cor), red arrowhead= coaxial hypothallus, black arrowheads= multiporate conceptacles; B) Outcrop CG2, fragment of a thin crust of *Neogoniolithon* with a well-preserved coaxial hypothallus; red arrowheads= trichocytes. C) Outcrop...
CG3, *Spongites fruticulosus* uniporate conceptacle, red arrowhead= central columella. D) Outcrop CG3, detail of the dome-shaped epithallial cells (black arrowheads) and the non-coaxial hypothallus (red arrowhead) of the specimens of *Spongites fruticulosus* in C. E) Outcrop CG3, thick crusts of *Phymatolithon* attached to a recrystallized coral colony, red arrowheads= multiporate conceptacles, black arrow= non-coaxial hypothallus. F) CG3, detail of the epithallial cells (red arrowheads), of the specimen of *Phymatolithon* in E. G) Outcrop CG1, *Chamberlainium*, dimerous organization (black arrowheads), small uniporate conceptacle covered by a thin roof (red arrowhead). H) Outcrop CG1, *Lithophyllum*, red arrowhead= uniporate conceptacle.

**Figure 7:** Packstones of the Terra Member at Cape Greco, outcrop CG4, LBF and echinoderm facies. A) Overview of the outcrop, red arrowhead= small patch-reef consisting of coral domestones, black arrowhead= LBF and echinoderms packstone. B) Large echinoid specimens in the packstones. C) LBF-echinoderm facies, red arrowheads= coralline algae, white arrowheads= lepidocyclinids. D) LBF-echinoderm facies, red arrowheads= echinoderm fragments, Mol=bivalve fragment, Rca= coralline alga, Rot= large rotaliid. E) Planktic foraminifera (red arrowhead), white arrowheads= echinoderm fragments. F) Axial cut of a *Nephrolepidina* (red arrowhead)

**Figure 8:** Microfacies of the Terra Member packstones at Cape Greco, outcrop CG5, coralline-algal-LBF facies. A) Mio= miogypsinid, Rca= coralline algal specimen of the genus *Sporolithon*, red arrowhead= *Triloculina*, white arrowhead= *Quinqueloculina*. B) Black arrowhead= small mioliolids, red arrowhead= *Borelis*.

**Figure 9:** Kottaphi Hill, Koronia Member, outcrop KH1. A) Panoramic view, the red overlay indicates the uppermost part of the hill consisting of Koronia Member neritic carbonates. B) Benthic...
foraminiferal packstones (red arrowheads), alternating with planktic foraminiferal wackestones. C) Sheetstone clast mainly consisting of Porites colonies (red arrowheads. D) Sheetstone clast with abundant coralline algae (red arrowhead).

**Figure 10:** Microfacies of the benthic foraminiferal packstones at Kottaphi Hill (KH1). A) Overview of the facies; red arrowhead= serpulid worm, possibly Ditrupa. B) Thin and flat heterosteginid specimen (Het); white arrowhead= heterosteginids in axial section displaying the secondary septa which separate the chamber; red arrowhead= planktic foraminifera. C) Elphidium specimens. D) Lenticulina specimen; red arrowhead= planktic foraminifera.

**Figure 11:** Microfacies of the coral-reef facies of the Koronia Member in the Kottaphi Hill area, outcrop KH1. A) Coral colony (Cor) encrusted by coralline algae (Rca). B) Coral (Cor) encrusted by nubecularids (red arrowheads). C) Bivalve shell (Mol) encrusted by nubecularids (red arrowheads). D) Peloids in the material trapped within cavities in the sheetstone. E) Gastropod mould (black arrowhead). F) Homotrema (white arrowhead), encrusted by a coralline alga (Rca), further encrusted by a nubecularid miliolid (red arrowhead). G) Echinoderm fragments (white arrowheads) and Acetabularia (red arrowheads) in a micrite matrix. H) Serpulid tube, red arrowhead= miliolid.

**Figure 12:** Benthic foraminifera of the coral-reef facies of the Koronia Member in the Kottaphi Hill area, outcrop KH1. A) Triloculina. B) Elphidium; red arrowhead= sutural bridges.

**Figure 13:** Coralline algae of the sheetstones of the coral-reef facies of the Koronia Member at Kottaphi Hill, outcrops KH1, KH2. A) KH1, Neogoniolithon; red arrowheads= trichocytes; black arrowhead= coaxial hypothallus. B) KH1, Neogoniolithon; red arrowheads= trichocytes; black
arrowheads = cell fusions. C) KH1, *Neogoniolithon*; red arrowhead = trichocyte; black arrowhead = dome-shaped epithallial cells; D) KH1, *Neogoniolithon*; red arrowhead = uniporate conceptacle; E) KH1, *Titanoderma*; red arrowhead = uniporate conceptacle. F) KH1, thin hooked crust of *Titanoderma*.

G) KH1, *Lithophyllum* sp.; red arrowhead = uniporate conceptacle; H) KH2, *Lithophyllum dentatum*; black arrowhead = uniporate conceptacle; red arrowheads = filaments with well preserved and visible primary pit connections.

**Figure 14:** Koronia Member, outcrop TC, near Tochni Village. A) Red arrowhead = mixed siliciclastic carbonate mass-flow deposits; white arrowhead = conglomerate. B) Microfacies of the mixed siliciclastic carbonate deposits displaying both rock fragments, coralline algal fragments and thin and flat specimens of heterosteginids (red arrowhead). C) Coralline algal packstones/rudstones, *Phymatolithon*; red arrowhead = multiporate conceptacle; white arrowhead = non-coaxial hypothallus. D) Coralline algal packstones/rudstones, *Neoconorbina* (white arrowhead) and a planktic foraminifera (red arrowhead); E) Coralline algal packstones/rudstones, well preserved textularid. F) Large miliolid grainstone displaying a large heterosteginid specimen; black arrowhead = *Borelis melo melo*; red arrowheads = *Dendritina*; blu arrowhead = gastropod mould. G) Large miliolid grainstone, small miliolid (red arrowhead) and a segment of an articulated coralline alga (black arrowhead). H) Large miliolid grainstone, small miliolid, small rotalid (red arrowhead) and clast of basaltic rock (black arrowhead).

**Figure 15:** Microfacies of the Koronia Member, outcrop CP, near Cape Pyla. A) Planktic foraminiferal wackestone with *Orbulina universa*. B) Rhodolith rudstone with abundant coralline algae (Rca) and common bryozoans (Bry); red arrowhead = *Elphidium*. C) Rhodolith rudstone with *Halimeda* (white arrowhead); red arrowhead = small miliolid.
Figure 16: Palaeoenvironmental reconstruction of the lower Miocene Terra Member (modified after Follows et al., 1996) showing the distribution of the facies and the main groups of carbonate producing organisms; the presumed depth of the euphotic zone during the early Miocene in Cyprus is indicated in the lower part of the figure.

Figure 17: Palaeoenvironmental reconstruction of the upper Miocene Koronia Member (modified after Follows et al., 1996) showing the distribution of the facies and the main groups of carbonate producing organisms; the key to the symbols is the same as for Fig. 16; the presumed depth of the euphotic zone during the late Miocene in Cyprus is indicated in the lower part of the figure.
Figure 1
Figure 3
Figure 4
Figure 10
Figure 12
Figure 14
Figure 15

Figure 16
Figure 17
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**Skeletal Assemblage [Point Counting; %]**

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**Main framework builder**

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**Main encrusting foraminifera**

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**Foraminiferal Assemblage [Area Counting; specimen per thin section]**

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<th>Lepidocyclinds; Amphistegina; Operculina</th>
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**Chemical Composition**

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| Domestone | 50 | 20 | 10 | 10 | 5 | 1 | 0.5 | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Packstone | 50 | 20 | 10 | 10 | 5 | 1 | 0.5 | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Sheetstone | 50 | 20 | 10 | 10 | 5 | 1 | 0.5 | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Rudstone | 50 | 20 | 10 | 10 | 5 | 1 | 0.5 | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Packstone/rudstone | 50 | 20 | 10 | 10 | 5 | 1 | 0.5 | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |

**Skeletal Assemblage [Point Counting; %]**

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<td>68</td>
<td>66</td>
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<td>35</td>
<td>45</td>
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<td>14</td>
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</tbody>
</table>

**Chemical Analysis**

<p>| Element | Ca | Mg | Al | Si | Fe | Ti | Mn | Cr | Ni | Cu | Zn | Pb | Co | Cd | Hg | As | Se | Br | Cl |
| Domestone | 50 | 20 | 10 | 10 | 5 | 1 | 0.5 | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Packstone | 50 | 20 | 10 | 10 | 5 | 1 | 0.5 | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Sheetstone | 50 | 20 | 10 | 10 | 5 | 1 | 0.5 | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Rudstone | 50 | 20 | 10 | 10 | 5 | 1 | 0.5 | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Packstone/rudstone | 50 | 20 | 10 | 10 | 5 | 1 | 0.5 | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |</p>
<table>
<thead>
<tr>
<th>Coralline Algal Assemblage [Surface Quantification]</th>
<th>Corallinales</th>
<th>Hapalidiales</th>
<th>Sporolithales</th>
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<tbody>
<tr>
<td>Early Miocene</td>
<td>99.9%</td>
<td>//</td>
<td>//</td>
</tr>
<tr>
<td>Late Miocene</td>
<td>64%</td>
<td>24%</td>
<td>//</td>
</tr>
<tr>
<td>Middle to late Miocene</td>
<td>//</td>
<td>76%</td>
<td>97.0%</td>
</tr>
<tr>
<td>Latest Miocene</td>
<td>//</td>
<td>71%</td>
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<table>
<thead>
<tr>
<th>Skeletal Assemblage [Point Counting]</th>
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<tbody>
<tr>
<td>Coralline algae</td>
</tr>
<tr>
<td>Corals</td>
</tr>
<tr>
<td>Benthic foraminifera</td>
</tr>
<tr>
<td>Planktic foraminifera</td>
</tr>
<tr>
<td>Echinoderms</td>
</tr>
<tr>
<td>Molluscs</td>
</tr>
<tr>
<td>Bryozoans</td>
</tr>
<tr>
<td>Others</td>
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<table>
<thead>
<tr>
<th>Lithology</th>
<th>Packstone</th>
<th>Rudstone/boundstone</th>
<th>Sheetstones</th>
<th>Boundstone</th>
<th>Packstone/rudstone</th>
<th>Wackestone to packstone</th>
<th>Grainstone</th>
<th>Grainstone to wackestone</th>
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</thead>
<tbody>
<tr>
<td>Early Miocene</td>
<td>//</td>
<td>//</td>
<td>//</td>
<td>//</td>
<td>//</td>
<td>//</td>
<td>//</td>
<td>//</td>
</tr>
<tr>
<td>Late Miocene</td>
<td>//</td>
<td>//</td>
<td>//</td>
<td>//</td>
<td>//</td>
<td>//</td>
<td>//</td>
<td>//</td>
</tr>
<tr>
<td>Middle to late Miocene</td>
<td>//</td>
<td>//</td>
<td>//</td>
<td>//</td>
<td>//</td>
<td>//</td>
<td>//</td>
<td>//</td>
</tr>
<tr>
<td>Latest Miocene</td>
<td>//</td>
<td>//</td>
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<table>
<thead>
<tr>
<th>Age, Lithology, and Biofacies</th>
<th>Early Miocene</th>
<th>Late Miocene</th>
<th>Middle to late Miocene</th>
<th>Latest Miocene</th>
<th>Latest Miocene</th>
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<tr>
<td>Facies</td>
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<td>Skeletal and benthic assemblage</td>
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<tr>
<td>Coral-reef flat</td>
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<tr>
<td>Large miliolid mollusc and benthic foraminifera</td>
<td>//</td>
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<tr>
<td>Benthic foraminifera in the lobe and mouth of the coral-reef flat</td>
<td>//</td>
<td>//</td>
<td>//</td>
<td>//</td>
<td>//</td>
</tr>
<tr>
<td>Heterostegina</td>
<td>//</td>
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</tr>
<tr>
<td>Echinoderm</td>
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