

Re-deposited rhodoliths in the Middle Miocene hemipelagic deposits of Vitulano (Southern Apennines, Italy): Coralline assemblage characterization and related trace fossils

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ABSTRACT

An integrated analysis of rhodolith assemblages and associated trace fossils (borings) found in hemipelagic Middle Miocene *Orbulina* marls (Vitulano area, Taburno–Camposauro area, Southern Apennines, Italy) has revealed that both the biodiversity of the constituent components and taphonomic signatures represent important aspects which allow a detailed palaeoecological and palaeoenvironmental interpretation.

On the basis of shape, inner arrangement, growth forms and taxonomic coralline algal composition, two rhodolith growth stages were distinguished: (1) nucleation and growth of the rhodoliths, and (2) a final growth stage before burial. Nucleation is characterized by melobesioids and subordinately mastophoroids, with rare sporelithaceans and lithophylloids. The rhodolith growth (main increase in size) is represented by abundant melobesioids and rare to common mastophoroids; very rare sporelithaceans are also present. The final growth stage is dominated by melobesioids with rare mastophoroids and very rare sporelithaceans. Each rhodolith growth stage is characterized by a distinct suite of inner arrangement and growth form successions.

Well diversified ichnocoenoses (*Gastrochaenolites*, *Trypanites*, *Meandropolydora* and/or *Caulostrepsis*, *Entobia*, *Uniglobites*, micro-borings) related to bivalves, sponges, polychaetes, barnacles, algae, fungi, and bacteria are distinguished in the inner/intermediate rhodolith growth stage, while mainly algal, fungal and bacterial micro-borings are present in the outer final growth stage.

Rhodolith growth stages and associated ichnocoenoses indicate significant change in the depositional setting during the rhodolith growth. In the Vitulano area, the Middle Miocene rhodolith assemblages formed in a shallow-water open-shelf carbonate platform, were susceptible to exportation from their production area and then to sedimentation down to deeper-water hemipelagic settings, where the rhodoliths shortly kept growth and were finally buried. Such re-deposition of unlithified or only weakly lithified (i.e. rhodoliths and intraclasts) shallow-water carbonates into deeper-water settings was likely favoured by storm-generated offshore return currents rather than sediment gravity flows.

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1. Introduction

Crustose coralline red algae (Corallinales, Sporelithales, Rhodophyta) can grow as free-living forms (rhodoliths) constituting extensive beds worldwide over broad latitudinal and depth ranges (e.g. Adey, 1986; Minnery, 1990). Rhodoliths can be very abundant in shallow-water carbonate depositional systems becoming dominant facies components such as in rhodolith beds and crustose coralline algal pavements in different shallow-water (e.g. tidal channels as well as in reefs; Adey and MacIntyre, 1973; Bosence, 1983a; Perrin et al.,

1995; Foster, 2001) and deeper-water (e.g. Minnery, 1990; Iryu et al., 1995) settings. Modern rhodolith beds are diversified benthic communities with a variety of coralline growth forms and their detritus associated with other biotic components, over coarse or fine carbonate soft substrates. In these rhodolith habitats, which constitute one of the Earth's macrophyte dominated benthic communities (Foster, 2001), biodiversity can be very high (Steller et al., 2003). Rhodoliths require water motion (waves and currents) or bioturbation to maintain their unattached and unburied state (e.g. Bosence, 1983b; Braga and Martín, 1988; Littler et al., 1990; Foster et al., 1997; Marrack, 1999; Foster, 2001; Braga et al., 2003).

In the rhodoliths varied physical and biological processes are preserved as taphonomic signatures and are important constraints for rhodoliths' cycles because these processes influence the composition

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and character of coralline material entering the fossil record (e.g. Nebelsick and Bassi, 2000). Destructive processes, which remove or degrade rhodoliths, have been associated thus far with the effects of either physical (water turbulence, currents and storms) disturbance or biological erosion. Biological erosion (termed bioerosion; Neumann, 1966) is associated with both the grazing activities of a range of organisms such as fish and regular echinoids, as well as the activities of an array of borers. These include specific groups of sponges, bivalves and worms (termed macroborers), as well as cyanobacteria, chlorophytes, rhodophytes and fungi (termed microborers; Hutchings, 1986).

The relative importance of each bioerosional process and the rates at which they operate vary spatially across individual carbonate systems (for reef systems see Perry, 1999) and, consequently, they may influence styles and rates of carbonate fabric development (e.g. Scoffin, 1992; Nebelsick, 1999a,b; Nebelsick and Bassi, 2000). In addition, many of these processes leave distinctive signatures on or within the rhodoliths. These signatures represent useful palaeoenvironmental tools, firstly because they have good preservation potential and, secondly, because the range and extent of many of the individual species, groups and processes involved exhibit reasonably well-constrained environment and/or depth-related trends (Speyer and Brett, 1986, 1988, 1991; Zuschin et al., 2000; Taylor and Wilson, 2003). Consequently, a number of studies have shown the potential in using individual groups of taphonomically important organisms (especially calcareous encrusters and macroborers) to delineate bathymetric gradients across environments, as well as in identifying depositional processes (e.g., Martindale, 1992; Basso and Tomaselli, 1994; Perry, 1996, 1998; Nebelsick, 1999a,b; Zuschin et al., 2000; Greenstein and Pandolfi, 2003). Several actualistic analyses have validated its usefulness to study the preservation states of organisms in different present-day shallow-water settings (e.g. Feige and Fürsich, 1991; Staff et al., 2002; Yesares-García and Aguirre, 2004).

There is thus a high palaeoecological potential for an integrated analysis based on rhodolith characteristics and related borings in understanding the palaeoecology of fossil shallow-water carbonate benthic communities, as well as the dynamics of carbonate sedimentary successions. Although borings in present-day and fossil rhodoliths are very abundant (e.g. Steneck, 1985; Rasser and Piller, 1997), little is known about the taphonomic processes of borer activity in rhodolith carbonate deposits and little attention has been paid to the integrated potential use of rhodoliths and borings as palaeoecological and palaeoenvironmental indicators.

This paper contributes with an integrated study of Middle Miocene rhodolith assemblages and related trace fossils (borings) to reconstruct the palaeoecological history of the rhodoliths from their shallow-water original setting to their final burial stage in deeper-water hemipelagic *Orbulina* marls deposited in Southern Apennines (Vitulano area, Italy). This paper thus documents: (1) the rhodolith characteristics including taxonomic composition, shape, inner arrangement and growth forms, (2) the types of fossil ichnocoenoses present in the rhodoliths, and (3) the rhodolith growth history by assessing the palaeoecological scenario.

2. Stratigraphic setting

Temperate-type carbonate open-platform deposits are very common in the Early and Middle Miocene of the Central and Southern Apennines (Italy). These deposits, known as 'Bryozoan and *Lithothamnium* Limestones', Burdigalian–Langhian in age (BLL in Carannante and Simone, 1996 and references therein), are characterised mainly by large rhodoliths and subordinately by bryozoans, bivalves, benthic foraminifera, echinoids, serpulids and barnacles. The BLL deposits pass upward into hemipelagic marly limestone and marls rich in planktonic foraminifera (the *Orbulina* marls, Serravallian in age; Lirer et al., 2005) through a palimpsest interval characterized by

phosphatic and minor glauconitic grains. The BLL deposits witness the inception of rhodalgal/bryo-rhodagal carbonate factories in middle-/outer-shelf areas following a significant Paleogene emersion phase (Carannante et al., 1988). Formerly interpreted as *in situ* skeletal sediments (Barbera et al., 1978), large portions of the Miocene BLL rhodolith successions represent channelized deposits (Carannante, 1982; Carannante and Vigorito, 2001).

In the Taburno–Camposauro Group, Southern Apennines (Fig. 1), BLL deposits are known as Formazione di Cusano and show a very complex geographical distribution and a high facies diversity varies from lower Burdigalian *Miogypsina*-coralline algal ridges (Schiavino, 1985), through pectinid banks to rhodolith floatstone/rudstone. Locally, as in the studied Vitulano area (south-eastern Camposauro area), shallow-water deposits referable to BLL are missing and Middle Miocene hemipelagic marls bearing rhodoliths directly lie on the Cretaceous substrate (Fig. 2). In the Camposauro area, as well as in the adjacent Matese Group, a tectonic-driven mid-Cretaceous structuring phase brought about a complex palaeomorphology whose heritage heavily influenced the following Miocene depositional contexts (Carannante et al., 2009). Channel networks and minor tectonic-controlled incisions characterized the marginal areas of the Miocene rhodolith-bearing open-platforms. Previous studies focused only on the basal unconformity between the BLL and the underlying Cretaceous/Paleogene and described trace fossil assemblages from different Central–Southern Apennines BLL outcrops (e.g. Maiella area, Central Apennines, Catenacci et al., 1982; Pietrarola area, Monti del Matese, Southern Apennines, Galdieri, 1913; Barbera et al., 1978, 1980; Carannante et al., 1981).

In the Vitulano area (Monte Camposauro; Fig. 1) the BLL deposits are completely missing and the *Orbulina* marls lying directly on the Cretaceous substrate are represented by hemipelagic marls with rhodolith floatstone and carbonate intraclasts (Fig. 2). Locally the rhodolith floatstone can be present as sediment infilling sedimentary veins occurring within the underlying Cretaceous carbonates. These sedimentary veins have been interpreted as being formed during pre- and syn-Miocene tectonic activity and successively filled by the Miocene sediments (D'Argenio, 1963, 1967).

The studied outcrop is located in the SE part of Vitulano village where Cretaceous limestones are overlain by not-stratified hemipelagic marls, 2–2.3 m thick, yielding rhodoliths and large carbonate intraclasts (5–20 cm in size). The intraclasts are made up of packstone rich in coralline algae and bryozoan, pectinid, oyster and echinoderm fragments. Rhodoliths and intraclasts are randomly scattered within the marls. The contact between the Cretaceous substrate and the Miocene hemipelagic marls consists in an irregular, partially fractured and dissolved surface. A preliminary analysis of the planktonic foraminiferal association, characteristically occurring in the marly matrix, resulted in the identification of *Globigerinoides primordius* Blow and Banner, *Globigerinoides trilobus* (Reuss), globorotalids referable to the *Globorotalia scitula* (Brady) group, *Orbulina universa* d'Orbigny, *Orbulina bilobata* d'Orbigny, as well as other globorotalids and globigerinids. This association indicates a time interval not older than middle Langhian in age.

3. Material and methods

A single rhodolith horizon (CASV section), c. 2 m in thickness, characterised by a rhodolith floatstone with marly to very fine sandy matrix rich in planktonic foraminifera was sampled in the studied area. This horizon corresponds to a peculiar local deposition of the *Orbulina* marls and is stratigraphically localized directly on the top of the Cretaceous succession (Fig. 2).

Fifty-nine rhodolith samples were collected from the studied horizon. Rounded carbonate intraclasts rich in coralline algae and other bioclasts, and Cretaceous limestone clasts were also sampled.

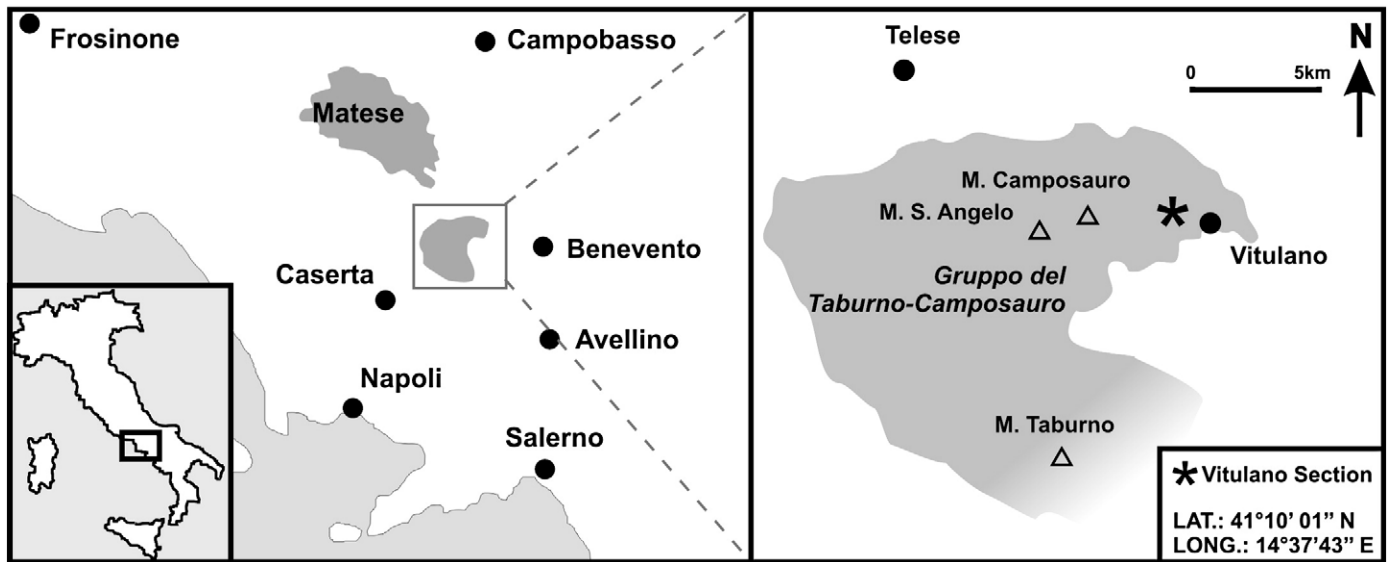


Fig. 1. Geographic location of the studied rhodolith outcrop in the Vitulano area (Monte Camposauro, Southern Apennines, Italy).

Fifty-four of these samples are represented by complete rhodolith specimens easily extracted from the friable marly matrix which is rich in planktonic foraminifera. Several acetate dry-peels and two or more thin sections (7.5×11 cm in size) were prepared from each rhodolith

sample. Thin sections and acetate dry-peels were semi-quantitatively analyzed using the point counter method with the points distanced 1 mm apart (e.g. Bassi, 1998; Nebelsick et al., 2000; Flügel, 2004). This allowed a semi-quantitative estimation of corallines and rhodolith constructional voids. The textural classification follows Embry and Klovan (1972).

The sphericity of the rhodoliths was calculated by measuring the three main diameters (longest L, intermediate I, shortest s; see Sneed and Folk, 1958); these data were plotted in triangular diagrams by using the TRI-PLOT software (Graham and Midgley, 2000).

Coralline family and subfamily ascription follows Woelkerling (1988), Verheij (1993) and Braga et al. (1993). Taxonomic uncertainties concerning fossil coralline taxonomy as discussed by Braga and Aguirre (1995), Rasser and Piller (1999), and Iryu et al. (2009) were avoided by using generic names only. The identification at genus level was based on the circumscriptions proposed by Woelkerling (1988), Braga et al. (1993), Braga and Aguirre (1995), Aguirre and Braga (1998), Braga (2003) and Iryu et al. (2009). Coralline algal growth-form terminology follows Woelkerling et al. (1993). Semi-qualitative analysis of coralline growth-form abundance was estimated both for the entire rhodolith and for each growth stage within a rhodolith (Figs. 5–7, Table 1).

Trace fossil assemblages were studied on polished rhodolith slabs and in thin sections. To reconstruct the three-dimensional development of boring network shapes, a densely spaced sequence of parallel polished slabs (serial sections) was studied. Cross section analysis carried out on polished square surfaces of 1 cm in length-side and on thin section square surfaces of 1 cm in length-side was developed to estimate boring volume. The semi-quantitative estimation of abundance of encrusters (coralline algae, bryozoans, bivalves, foraminifera, and serpulids) and of other organisms enveloped by coralline thalli (mainly echinoderms) was also assessed.

4. Results

4.1. Rhodolith assemblage

The sampled horizon consists of a rhodolith–floatstone with planktonic foraminiferal marly wackestone/packstone matrix. Rhodalgal/foramol packstone intraclasts are also present. The greyish marly matrix contains abundant planktonic foraminifera (97% in abundance of the washed sample) and other rare (3%) skeletal and non-skeletal components (corallines, miliolids, cibicids, amphisteginids, small carbonate

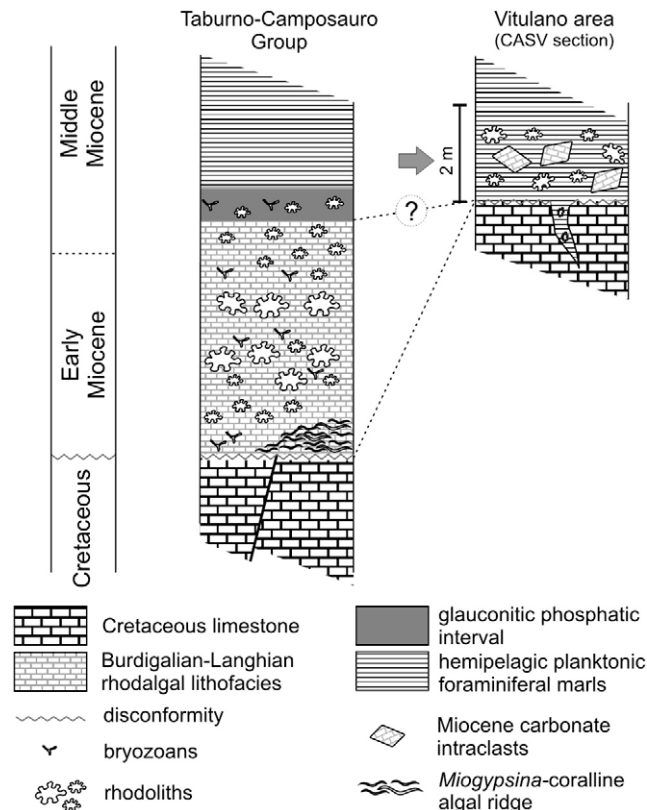


Fig. 2. In the Monte Camposauro area (Taburno–Camposauro Group) the transition between the BLL ('Formazione di Cusano' characterized by rhodoliths and bryozoans) and the *Orbulina* marls can be generally either gradual or corresponding to 10–35 cm thick phosphatic rudstones rich in corallines, bryozoans and bivalves. In the Vitulano area the typical stratigraphic succession is not present and the studied rhodolith horizon represents therefore a rare exception to this succession. The studied rhodolith–floatstone horizon, about 2 m thick, occurs at the base of the *Orbulina* marls which lie directly on the Cretaceous substrate. Locally the rhodolith floatstone can be present as sediment infilling sedimentary veins occurring within the underlying Cretaceous carbonates. Not to scale.

Table 1

Summary table indicating the rhodolith types, rhodolith characters for each distinguished growth stages and the boring types recorded by the studied rhodoliths during the palaeoenvironmental dynamics in the Vitulano area (Camposauo Mountain, Southern Apennines, Italy). sym., symmetric; asym., asymmetric; la, laminar; en, encrusting; wa, warty; lu, lumpy; fr, fruticose; ■ common; □ rare; ● present. G, *Gastrochaenolites*, E, *Entobia*; T, *Trypanites*; M, *Meandropolydora*; A, Ichnotype A; B, Ichnotype B; C, Ichnotype C.

Rhodolith type	Growth stage	Inner accretionary pattern		Dominant growth forms					Boring types							Overturning		
		sym.	asym.	la	en	wa	lu	fr	G	E	T	M	A	B	C	Low	High	
1	1	●	●	●	●	●			■	□	■	■	■	■	■	□	●	●
	2		●	●	●				□		□	□	□	□	□	■	●	●
2	1	●		●	●				■	■	■	■	■	■	■	■	●	●
	2		●	●	●				■		□	□	□	□	■	■	●	●
3	1	●	●	●		●	●	●		■	■	■	■	■	■	■	●	●
	2		●	●							□	□				●	●	

clasts, and fish teeth). In addition to the prevailing coralline algae, other biotic components such as bryozoans, encrusting foraminifera, serpulids, solitary corals and barnacles are present in the studied samples (Fig. 3). Bivalves, echinoderms, *Amphistegina*, textulariids and planktonic foraminifera are rarely present within the rhodoliths. These components are more abundant within the packstone intraclasts.

The rhodolith maximum diameter ranges from 4.0 to 13.1 cm (average $L = 6.7 \pm 2.1$ cm; $n = 54$), the intermediate diameter ranges from 3.3 to 11.9 cm (average $I = 5.7 \pm 2.0$ cm; $n = 54$), and the minimum diameter ranges from 2.0 to 9.6 cm (average $s = 4.6 \pm 1.8$ cm; $n = 54$). Sphericity analysis shows the dominance of the sub-spheroidal shape (Fig. 4).

The coralline algal assemblage is represented by the subfamily Melobesioideae (with the genera *Lithothamnion* and *Mesophyllum*), Mastophoroideae (*Spongites*, *Neogoniolithon*, and *Lithoporella*), Lithophylloideae (*Lithophyllum*) and the family Sporolithaceae (*Sporolithon*). Most of the studied rhodoliths are multigeneric (90%).

The nuclei are characterized by oyster valves, barnacle fragments and infilling matrix sediment.

Although the final rhodolith shape is generally sub-spheroidal, on the basis of taxonomic coralline assemblage succession, inner arrangement and growth forms, three different rhodolith types were distinguished: R1 rhodoliths (representing the 80% of the collected samples), R2 rhodoliths (10%) and R3 rhodoliths (10%). Analysed rhodolith characters such as shape, growth forms, inner arrangement and coralline taxonomic association along with the different ichno-coenoses allow two different growth stages (GS1 and GS2) to be distinguished, each of them identified in each rhodolith type (Table 1).

4.1.1. R1 rhodoliths

These rhodoliths are sub-spheroidal in shape and very heterogeneous in size. The maximum diameter ranges from 4.0 to 11.1 cm (average $L = 6.5 \pm 1.8$ cm; $n = 44$), the intermediate diameter ranges from 3.6 to 10.2 cm (average $I = 5.5 \pm 1.6$ cm; $n = 44$),

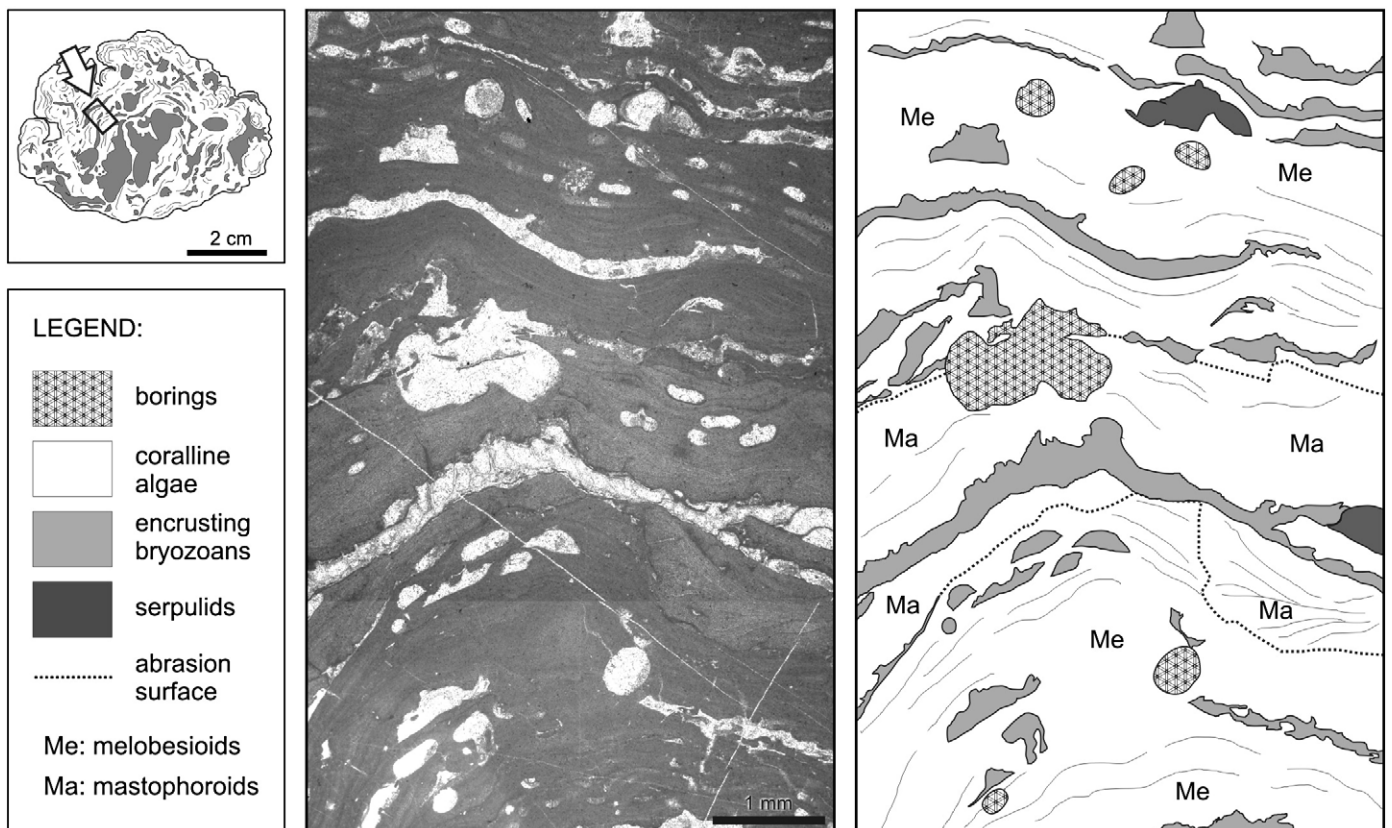


Fig. 3. Detail of performed thin section micro-analysis illustrating the coralline taxonomic succession and the interpreted taphonomic signatures.

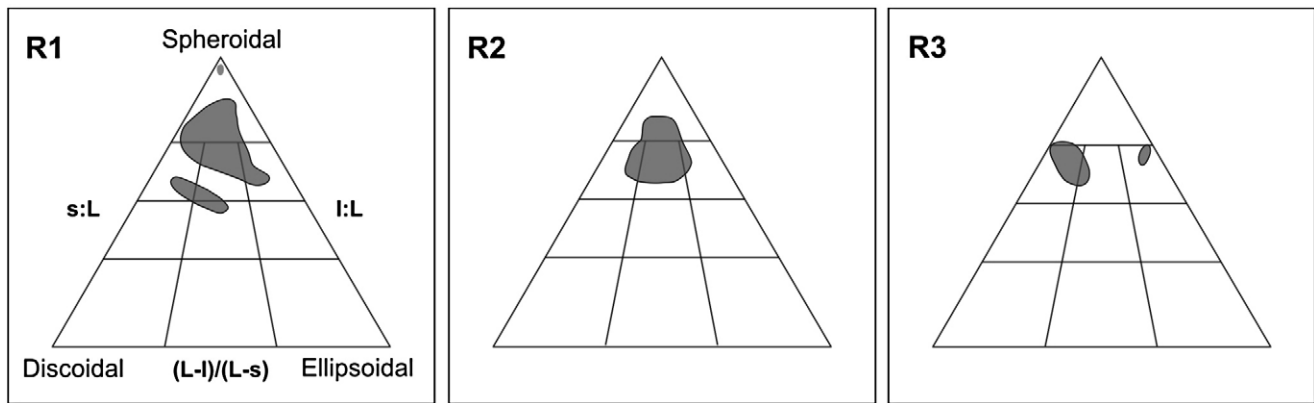


Fig. 4. Shape classification of the rhodoliths from the studied Middle Miocene *Orbulina* marls horizon outcropping in the Vitulano area (Monte Camposauro, Southern Apennines, Italy). Shape classification according to Sneed and Folk (1958). Rhodolith diameters: L, longest; I, intermediate; s, shortest.

and the minimum diameter ranges from 2.4 to 9.0 cm (average $s = 4.4 \pm 1.6$ cm; $n = 44$). The earliest coralline development stage grew as a thin encrusting thalli on oyster shells or on coralline fragments. The inner arrangement consists of the two growth stages, from the core to the outer part: (GS1) encrusting or laminar concentric thalli, enveloping the nucleus, passing to encrusting and warty thalli with symmetric or asymmetric growth; (GS2) asymmetric or symmetric laminar growth (Fig. 5). Rare specimens have the GS1 stage missing. The contact between GS1 and GS2 is characterized by a slightly abraded thallus surface.

Coralline taxonomic assemblage is represented by dominant melobesioids. *Lithothamnion* (cover percentage 48% of the total coralline assemblage) develops laminar, encrusting, warty and secondarily lumpy growth forms; *Mesophyllum* (10%) is present as encrusting thalli. Mastophoroids are represented by encrusting and warty thalli of *Spongites* (30%) and *Neogoniolithon* (3%). Rare encrusting lithophylloids (*Lithophyllum*, 4%) and encrusting and warty sporeolithaceans (*Sporolithon*, 5%) were also identified. GS1 is characterized by melobesioids, mastophoroids or, rarely, by litho-

phylloids and sporeolithaceans. The GS2 is characterized almost exclusively by melobesioids (*Lithothamnion*) with very few mastophoroids.

Constructional voids are from rare to very common in GS1, while they are very rare in GS2. This infilling sediment varies in texture and composition depending on rhodolith growth stage. In GS1 constructional voids are mainly filled with coralline algal, bryozoan and echinoderm wackestones/packstones; in GS2 they are filled with coralline algal, bryozoan, echinoderm and planktonic foraminiferal wackestones/packstones. Planktonic foraminifera occur, therefore, only in GS2.

GS1 is characterized by the presence of *Gastrochaenolites*, *Entobia* (*Uniglobites*), *Trypanites*, *Meandropolydora* (and/or *Caulostrepsis*) and Ichnotype C. In GS2 Ichnotypes A, B and C, rare *Gastrochaenolites*, *Trypanites*, *Meandropolydora* (and/or *Caulostrepsis*) were recorded.

Coralline taxonomic assemblage and growth-form variations from nucleus to the outer part compared with the boring and matrix distribution within rhodoliths suggest an early stage (GS1) development of rhodoliths in a very shallow-water, high-energy environment

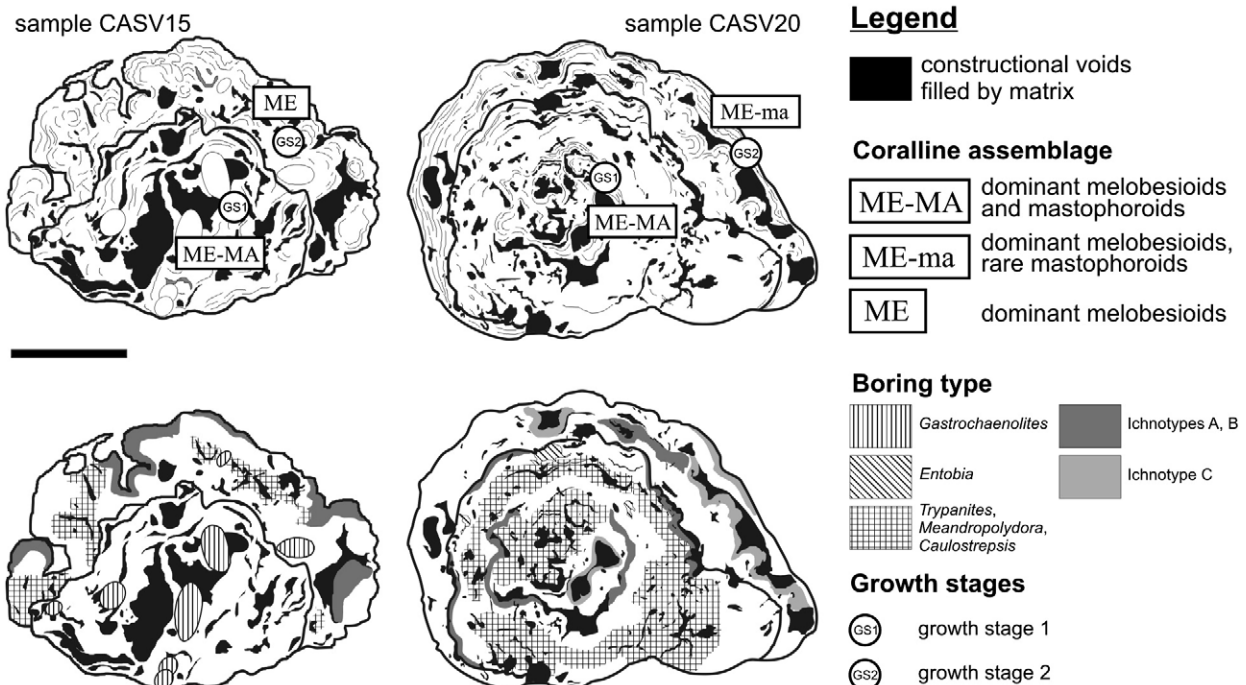


Fig. 5. Polished slabs through R1 rhodoliths showing the interpreted growth stages (GS) which are characterized by different taxonomic coralline assemblages, growth forms, thallial arrangement and borings. See text for details.

with frequent overturning and the latter stage (GS2) in a relatively deeper, more quiet environment with scarce overturning.

4.1.2. R2 rhodoliths

The R2 rhodoliths are sub-spheroidal in shape. Their maximum diameter ranges from 4.3 to 11.5 cm (average $L = 7.1 \pm 3.0$ cm; $n = 5$), the intermediate diameter ranges from 3.7 to 10.2 cm (average $I = 6.2 \pm 2.8$ cm; $n = 5$), and the minimum diameter from 2.9 to 9.6 cm (average $s = 5.1 \pm 2.8$ cm; $n = 5$).

GS1 shows symmetric coralline growth and is dominated by encrusting thalli (up to 1.5 cm thick) which generally grew in a symmetrical arrangement. The last GS2 consists of thin coralline encrusting thalli developing only on one side of the rhodolith creating an asymmetric arrangement (Fig. 6). Constructional voids decrease in abundance from the core to the outer part of the rhodolith, being common to abundant in GS1 and very rare in GS2. The constructional voids are filled by matrix-related sediment. Common encrusting organisms such as bryozoans and rare serpulids and acervulinids are superimposed with the encrusting coralline thalli.

The nucleus composition was rarely identified and consists of oyster shells, barnacle fragments, bored bivalve shells or of fine to medium grained sediment. As in other rhodolith types, the sediment within constructional voids varies in texture and composition within the same rhodolith ranging from coralline, bryozoan and echinoderm packstone/wackestone (generally in the inner part of the rhodolith) to bioclastic wackestone (generally in the outer rhodolith part; Table 1). The contact between GS1 and GS2 is characterized by an abraded rugged surface deeply colonised by macro- (mainly *Entobia*) and micro-borings.

Melobesioids dominate the assemblage with *Lithothamnion* (70% of the total coralline assemblage) being developed principally as encrusting and laminar and rarely as warty and lumpy growth forms. *Spongites* (12%) is the only representative of mastophoroids. Rare sporolithaceans (*Sporolithon*, 4%) and lithophylloids (*Lithophyllum*, 14%) as smooth warty protuberances or encrusting thalli were also identified. GS1 is generally characterized by melobesioids (*Lithotham-*

nion) and subordinately by mastophoroids (*Spongites*), lithophylloids (*Lithophyllum*) or, as recorded in one specimen only, by sporolithaceans (*Sporolithon*). GS2 is constituted only by melobesioids (*Lithothamnion*).

In GS1 *Gastrochaenolites*, *Entobia* (*Uniglobites*), *Trypanites*, *Meandropolydora* (and/or *Caulostrepsis*) and Ichnotype A, B, C dominate the ichnocoenosis. In GS2 Ichnotypes A, B and C and subordinate rare *Trypanites*, *Meandropolydora* (and/or *Caulostrepsis*) and very rare *Gastrochaenolites* and *Entobia* are present. Coralline characteristics and boring and sediment distribution suggest that GS1 developed in a shallow turbulent environment with frequent overturning. The GS2 took place in a low-energy environment where overturning was almost absent and where corallines could hardly develop.

4.1.3. R3 rhodoliths

The R3 rhodoliths are sub-discoidal/sub-ellipsoidal in shape. Their maximum diameter ranges from 4.3 to 13.1 cm (average $L = 7.1 \pm 3.4$ cm; $n = 5$), the intermediate diameter ranges from 3.3 to 11.9 cm (average $I = 6.2 \pm 3.3$ cm; $n = 5$), and the minimum diameter from 2.5 to 7.4 cm (average $s = 4.7 \pm 1.8$ cm; $n = 5$). The loose inner arrangement is characterized by warty, lumpy and fruticose protuberances. Laminar thin crusts dominate the inner and the outer parts of the rhodoliths, while encrusting thalli are only locally present in the inner part. As with the other rhodolith types, two growth stages were generally distinguished: (GS1) symmetric laminar and/or asymmetric branched thalli around the nucleus, and asymmetric thin to thick branched growth stage with lumpy and fruticose protuberances; (GS2) outer laminar asymmetric coralline growth (Fig. 7). The contact between the two growth stages is represented by a well preserved to scarcely abraded surface deeply colonised by micro-borings (Ichnotypes A, B, and C); trace fossils are almost absent in the latter growth stage and this contributes to highlight the transition between GS1 and GS2.

The nuclei consist of oyster shells or infilling matrix sediment. Constructional voids are very abundant in GS1 and they become rare in GS2. The infilling matrix varies from wackestone to coralline algal,

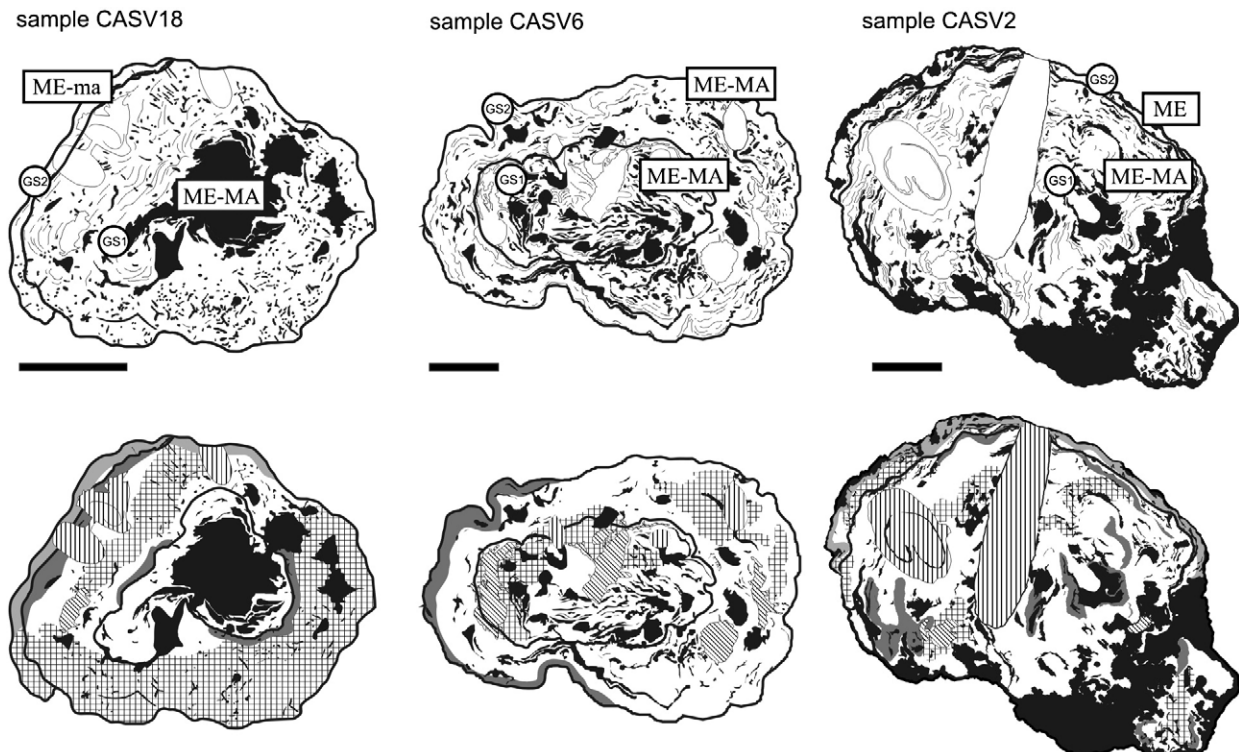


Fig. 6. Polished slabs through R2 rhodoliths surfaces showing the interpreted growth stages (GS). Scale bar represents 2 cm. See Fig. 5 for the legend.

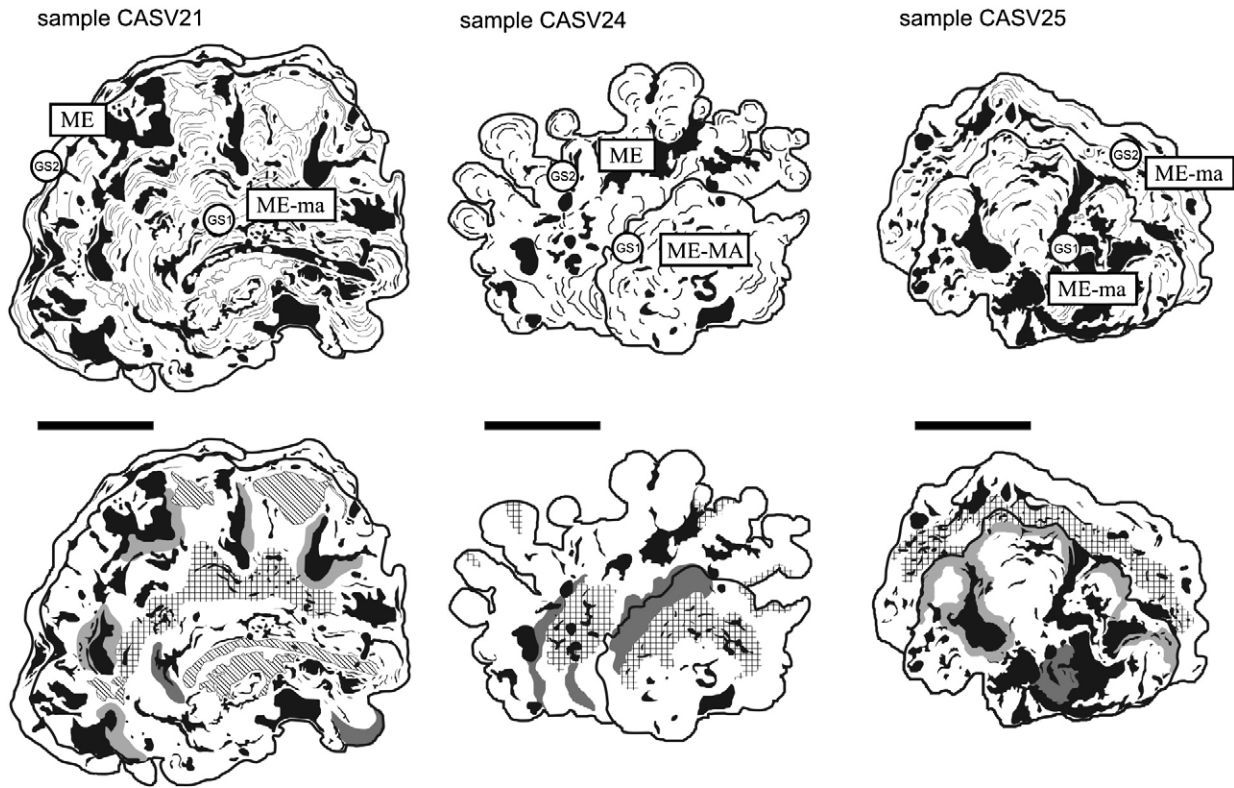


Fig. 7. Polished slabs through R3 rhodoliths showing the interpreted growth stages (GS). Scale bar represents 2 cm. See Fig. 5 for the legend.

bryozoan and echinoderm packstone/wackestone where planktonic foraminifera can also be present (mainly in GS2).

Melobesioids are the most abundant corallines (*Lithothamnion*, 57% of the total coralline assemblage; *Mesophyllum*, 9%). Mastophoroids are present with *Spongites* (20%) and *Neogoniolithon* (6%), whilst the sporolithaceans with *Sporolithon* (8%). *Lithothamnion* develops mainly as laminar, encrusting and warty growth forms and only locally lumpy and fruticose branches. *Mesophyllum* and *Neogoniolithon* are present only as thin encrusting thalli, while *Spongites* and *Sporolithon* grow mainly as encrusting and laminar growth forms and rarely as warty protuberances.

Melobesioids (*Lithothamnion*) and mastophoroids (*Spongites*) contribute to the laminar part of GS1, whilst the branched part is characterized by melobesioids (*Lithothamnion* and rare *Mesophyllum*), mastophoroids (*Spongites* and rare *Neogoniolithon*) and rare lithophylloids (*Lithophyllum*) and sporolithaceans (*Sporolithon*). Melobesioids (*Lithothamnion*) and mastophoroids (*Spongites*) dominate GS2.

GS1 is mainly characterized by the presence of *Trypanites*, *Meandropolydora* (and/or *Caulostrepsis*) and Ichnotype C and secondarily rare *Gastrochaenolites* and *Entobia*. In GS2 trace fossils are rare and represented by *Entobia*, *Trypanites*, *Meandropolydora* (and/or *Caulostrepsis*), Ichnotypes A, B and C. Coralline growth forms, thallial growth and coralline taxonomic assemblage suggest that both growth stages

developed in a relatively deep water within the photic zone where a low turbulence leads to a scarce overturning and consequently to a not significant rhodolith abrasion. However, the variation of sediment composition that was trapped within borings and in constructional-void spaces (e.g. the increase in planktonic foraminiferal abundance) highlights a deepening in the environmental scenario occurred during rhodolith growth.

4.2. Borings

The analysis of the morphological characteristics of traces present within rhodoliths allowed the recognition of seven different ichnotypes (Checconi and Monaco, 2009). These traces comprise one ichnotaxon attributed to the activities of bivalves (*Gastrochaenolites*), one to sponges (*Entobia*), three to polychaetes and barnacles (*Trypanites*, *Meandropolydora* and *Caulostrepsis*) and three micro-traces comparable to that produced by micro-excavations such as fungi, algae, bacteria and/or sponges (Ichnotypes A, B, and C; Table 2).

Recorded borings, ranging in size from a few micrometers up to some centimetres, are often concentrated parallel to the outer rhodolith growth. The sedimentary infilling textures of the boring traces are very heterogeneous ranging from wackestones to packstones. Bioclastic particles include coralline algae, bryozoans, bivalves,

Table 2

Summary table of the main trace fossil characters and related ichnogenera identified in the Middle Miocene studied rhodoliths from the Vitulano area.

	Borings	Boring shape	Associated borers
Macro-boring	<i>Gastrochaenolites</i>	Single chamber, straight, elliptical	Bivalves
	<i>Entobia</i> , (<i>Uniglobites</i>)	Single or multiple rounded, irregular chambers connected with narrow apertures	Sponges
	<i>Trypanites</i>	Cylindrical, straight chamber with constant diameter	Polychaetes, barnacles
	<i>Meandropolydora</i> , <i>Caulostrepsis</i>	Cylindrical bended or helicoidally arranged chamber with constant diameter	Polychaetes, barnacles
Micro-boring	Ichnotype A	Cylindrical, straight chamber with constant diameter perpendicular to surface	Algae, fungi, sponges
	Ichnotype B	Network of very contorted and sinuous, cylindrical micro-galleries	Algae, fungi, bacteria, sponges
	Ichnotype C	Branched network of micro-galleries with irregular diameter	Algae, sponges

echinoderm fragments and planktonic foraminifera. Larger borings are filled with wackestone/packstone matrix, while the smallest are generally filled with calcite cement. Rare non-skeletal components such as glauconitic and phosphatic grains were also identified in the boring traces.

4.2.1. *Gastrochaenolites*

This ichnotype is ellipsoidal in shape with the main axis perpendicular to the hard substrate surface. The main chamber is sub-ellipsoidal with a variable eccentricity in longitudinal sections and circular in cross sections. The apertural region of the boring, which is circular and generally abraded, is narrower than the main chamber. The apertural neck is very rarely present and seems to be circular in cross section (Fig. 8). The largest diameter is located approximately centrally within the chamber and can reach up to 1.4 mm in diameter. Bivalve shells, whose shape reflects their excavation shape, are often preserved in the boring. The type of boring can be referred to the ichnogenus *Gastrochaenolites* Leymerie, which is similar in shape and dimension to the borings produced by the bivalve *Lithopaga* (e.g. Miocene shallow-water coral carbonate platforms in the Egidir area, Turkey, Kleemann, 1994; modern Bermuda reefs, Bromley, 1978).

4.2.2. *Entobia* (*Uniglobites*)

These borings show single or multiple, wide (2.1–8.9 mm in width) chambers with an irregular rounded-oval or polygonal shape. Narrow apertures showing two size ranges (0.3–0.5 mm and 0.8–2.1 mm in average diameters) are frequent and are either connected to other chambers or to the outer surface of the rhodoliths. Small and short apertural canals were very rarely identified. Multiple, short and fine (0.015–0.035 mm in diameter) apophyses, characterized by sinuous and twisted axes, arise from the chamber walls. The recorded morphological and size parameters, when the boring pattern is multi-chambered, correspond to those reported in the emended diagnosis of the ichnogenus *Entobia* Bronn (Bromley and D'Alessandro, 1984). In the studied material, taxonomic identification at species level is hampered by the fact that only a bi-dimensional analysis (thin section or polished surface) could be carried out (Fig. 8). However, most of the recorded borings shows similar morphology and size to *Entobia geometrica* Bromley and D'Alessandro. Whereas single-chambered specimens can be referred to *Uniglobites* Pleydell and Jones. Sometimes the bi-dimensional analysis does not allow one or more chambers to be distinguished. For this reason, in the studied specimens the ichnogenus *Entobia* and *Uniglobites* have not been distinguished. The development of similar networks has been extensively described in the literature as the product of boring sponges (e.g. Pleydell and Jones, 1988; Perry, 1996).

4.2.3. *Trypanites*

This trace fossil is represented by a simple boring with a single aperture consisting in a cylindrical tube, generally perpendicular to the substrate surface, an almost constant diameter and a rounded termination. Diameter ranges from 0.6 to 1.7 mm while the maximum recorded length is 11 mm. As measurements were carried out on polished rhodolith slabs, a greater length is probable (Fig. 8). These borings, which can often be randomly concentrated within the rhodoliths, are similar to the ichnogenus *Trypanites* Mägdefrau. In particular some specimens correspond to *Trypanites solitarius* (Hagenow). *Trypanites*-type borings may be produced generally by polychaetes, even if sipunculacean worms and acrothoracican barnacles can also produced similar borings (Ekdale et al., 1984).

4.2.4. *Meandropolydora* and *Caulostrepsis*

This fossil trace group consists of cylindrical galleries, irregularly convoluted, sometimes looping round and coming into contact with itself or intercepting other similar borings; diameter ranges from 0.3

to 1.8 mm and length from 1.8 to 13.4 mm. This growth often produces fusion between boring walls. In correspondence to lobes produced by chamber bending, the diameter may remain constant in size or enlarge creating a sack-like chamber (Fig. 8). Two circular apertures have sometimes been observed. The trace network is developed freely in all directions within the thick coralline algal thalli, while the network is parallel and superficial within thin coralline algal thalli where the thalli often alternate with other encrusting organisms (mainly bryozoans). These borings can be ascribed to the ichnogenus *Meandropolydora* Voigt and *Caulostrepsis* Clarke. Most specimens represent *Meandropolydora sulcans* Voigt. Rare specimens of *Meandropolydora elegans* Bromley and D'Alessandro and *Meandropolydora* cf. *barocca* Bromley and D'Alessandro were also identified. They may be produced by polychaetes and barnacles.

4.2.5. *Ichnotype A*

Ichnotype A shows a simple, single apertural micro-tubular boring with a straight axis (always perpendicular to the substrate surface), a circular transverse section, an almost constant diameter (10–40 µm in average) and a rounded termination (Fig. 9). It reaches a maximum length of 500 µm and it can be attributed to the action of boring sponges, endolithic algae and/or fungi (e.g. Rooney and Perkins, 1972; May et al., 1982; Ghirardelli 2002).

4.2.6. *Ichnotype B*

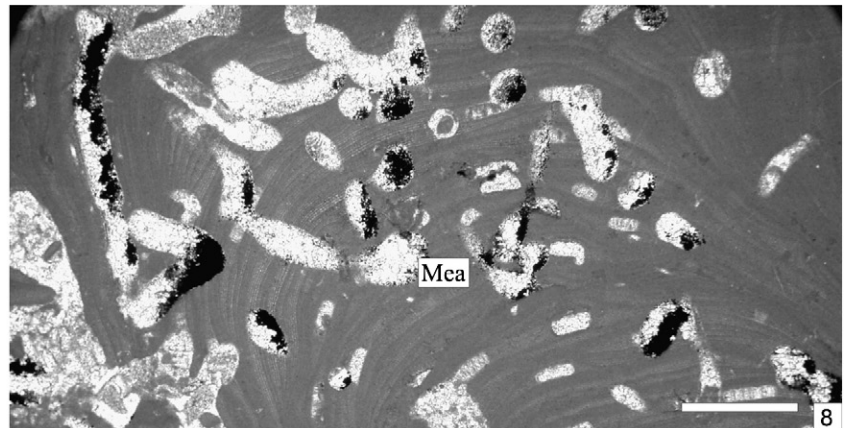
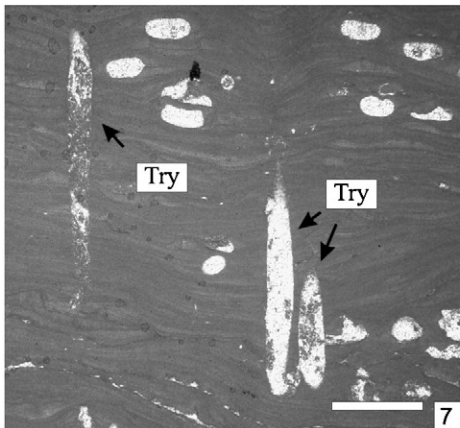
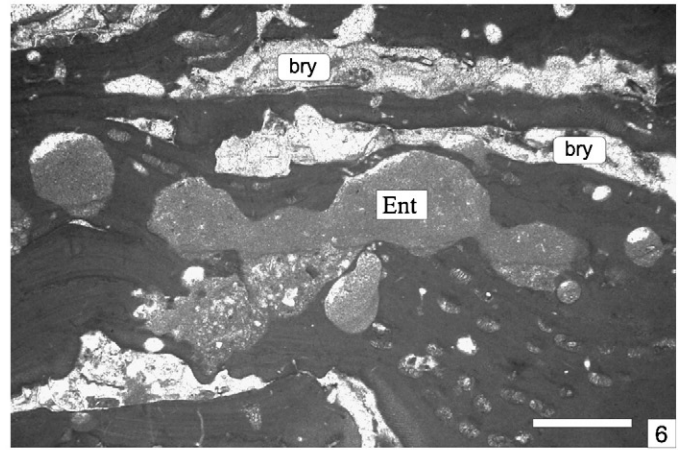
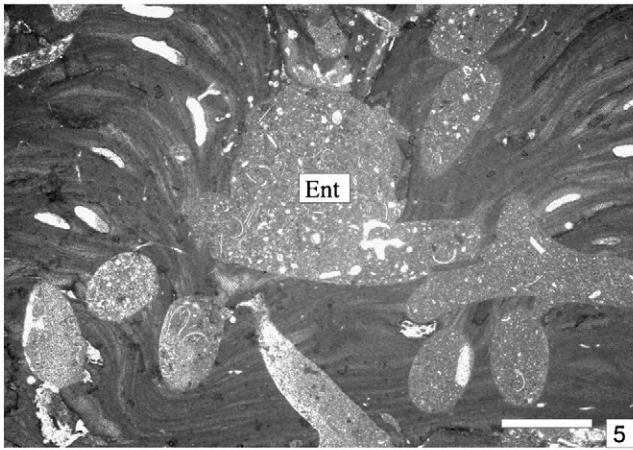
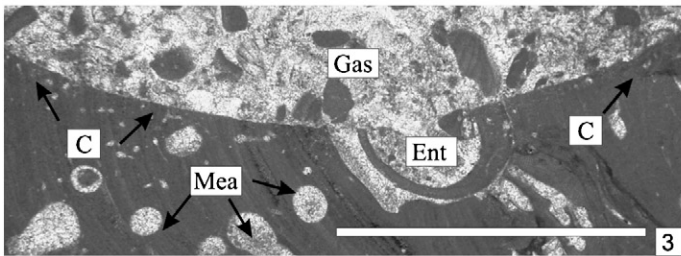
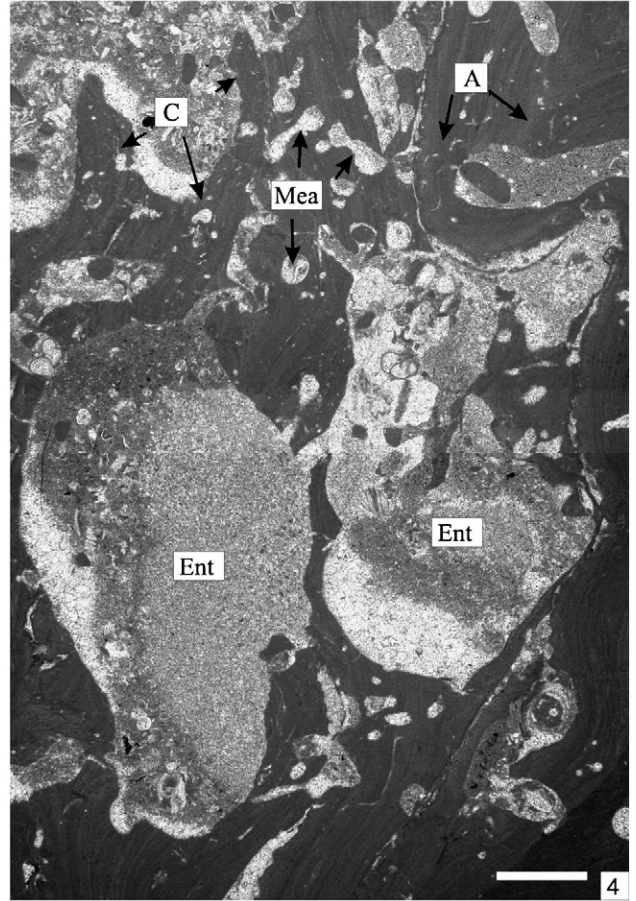
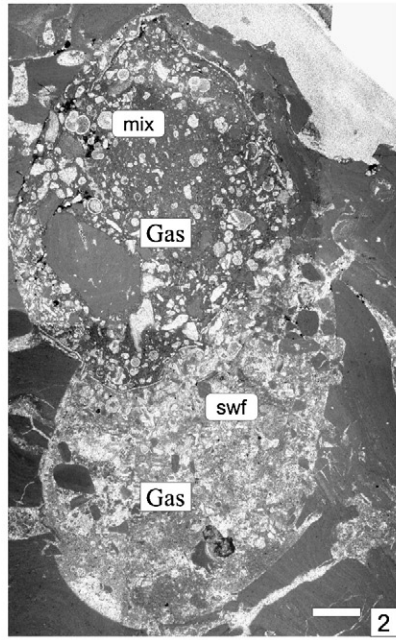
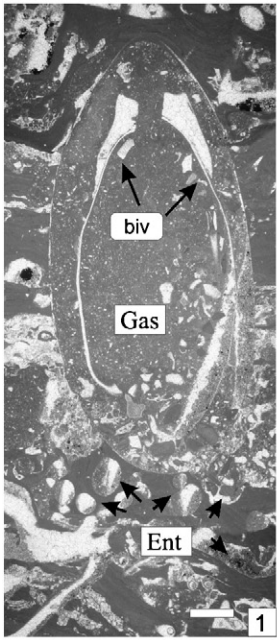
Ichnotype B consists of a network of branched micro-galleries which irregularly change in diameter from 5 to 25 µm. The main axes of branches are generally sub-perpendicular to the substrate surface. Sometimes two galleries may converge forming a “Y” pattern (Fig. 9). Boring size increases up to 30 µm at branch junctions. Secondary branches, perpendicular to slightly oblique to the main axis, may be present and develop a dendritic network pattern. These borings usually develop within the surface layers of coralline thalli down to 550 µm in depth from the rhodolith surface and are filled with calcite cement. Comparison with borings described in literature (e.g. Rooney and Perkins, 1972; Edwards and Perkins, 1974; Golubic et al., 1975; Tudhope and Risk, 1985) suggests that these micro-excavations could be produced by fungi, algae, bacteria and/or sponges.

4.2.7. *Ichnotype C*

The traces designated as Ichnotype C are characterized by a shallow complex network of sinuous and contorted micro-galleries with a rounded chamber (Fig. 9). The average diameter of the galleries ranges from 5 to 20 µm. The boring shape and distribution suggest that boring sponges or algae might be the producers of these meandering micro-patterns (e.g. Rooney and Perkins, 1972; Tudhope and Risk, 1985).

4.3. Other biotic components

All rhodoliths, independently of size or inner arrangement, are characterized by epibionts (Figs. 8 and 9). The most frequent epibionts are represented by cyclostome and cheilostome bryozoans and encrusting foraminifera (mainly acervulinids and subordinate *Miniacina*), while solitary corals and barnacles are rare. Bioclasts such as bivalve and echinoderm fragments, *Amphistegina*, textulariids and planktonic foraminifera commonly occur within the rhodoliths. Pectinid, gastropod and *Operculina* fragments, *Sphaerogypsina*, *Gypsina* and *Elphidium*, rotaliids, miliolids and cibicides are also subordinately present within the rhodoliths. All these components occur as envelope-builders and infilling-sediment constituents. Planktonic foraminifera are present in the infilling sediment.



4.4. Boring abundance, preservation and distribution

Gastrochaenolites, *Entobia* (*Uniglobites*), *Meandropolydora* (and/or *Caulostrepsis*), Ichnotype C and micro-tunnels made by boring sponges dominate the boring ichnocoenosis. *Trypanites* and other micro-patterns are common but less abundant (Tables 2 and 3).

The quantitative analysis shows that the boring volume ranges from 12% to 89% with an average of 26%. Higher values (65%–89%) derive from surfaces comprising large *Gastrochaenolites* or *Entobia*. However, high boring volume was also obtained for micro-borings, reaching a maximum for Ichnotype C (58%–62%).

Inner borings are generally filled by coarse-grained packstone/wackestone matrix with coralline algal, bryozoan and echinoderm fragments. Moving from the rhodolith core to the outer part, coralline algae, bryozoans and echinoderm fragments decrease gradually in abundance while planktonic foraminifera become dominant and the matrix fine grained. Geopetal structures, locally present within macro-borings, generally are iso-oriented within the same rhodolith specimen. Mudstones occur locally, generally within medium-sized boring chambers (*Trypanites*, *Meandropolydora* and *Caulostrepsis*). Calcite cement always characterizes micro-borings and is also frequently present within *Trypanites*, *Meandropolydora* and *Caulostrepsis*.

Generally, boring distribution is equally distributed within the rhodoliths but, frequently and mainly in correspondence to the outer part, only one side of a rhodolith is characterized by a well developed boring network made up by a single ichnotype (Table 2; Figs. 8 and 9).

The distribution of *Gastrochaenolites* is present from the early inner GS1 to the latest outer GS2 stages and its distribution is strictly dependent on coralline growth-forms and on rhodolith inner arrangement. Indeed these borings are mainly present within encrusting, laminar or warty thalli, where the coralline algal thalli are thicker. These borings are rare in correspondence to branches or lumpy protuberances. For this reason, *Gastrochaenolites* is common in R1 and R2 rhodoliths, but rare in R3 where the constructional voids are very frequent. Furthermore, *Gastrochaenolites* size is directly proportional to rhodolith size: larger borings were found within larger rhodoliths, while small forms are the only ones present in the early rhodolith growth stage.

Entobia has a similar occurrence if compared with *Gastrochaenolites*, being mainly present in massive coralline thallial arrangements. They occur only in the GS1 and have never having been recorded in GS2.

Trypanites, *Meandropolydora* and *Caulostrepsis* are very frequent within R1, R2 and R3 rhodoliths. These borings are the most widespread trace fossils being present from the core to nearly the outer part of the rhodoliths, within branched, laminar or thick encrusting thalli. A massive inner arrangement favours the development of a larger and more complex boring pattern. They never occur within the outer rhodolith growth stage.

Ichnotypes A and B (micro-borings) occur mainly within encrusting thalli and are generally related with abraded surfaces. These borings are rare in R3 rhodoliths which are characterized by frequent coralline branches. They are present on the outermost rhodolith parts.

Ichnotype C is generally distributed only in the outer part of coralline branches (GS1 for R3; Table 1) and in the outer laminar part of the rhodoliths (GS2).

5. Discussion

The integrated analysis of coralline algal characteristics along with the associated ichnocoenoses occurring in the studied rhodoliths reflect palaeoenvironmental dynamics and provide valuable information on the depositional environmental conditions. Moreover, the taphonomic features (Tables 1 and 2), the matrix texture present inside the rhodolith and composition of the boring infilling as well as the remains of borers (generally bivalves within *Gastrochaenolites*) trapped within their traces are interpreted in terms of water turbulence and relative water depth changed during rhodolith growth history (Table 3).

Studied rhodoliths testify a gradual water deepening during their growth history. The two distinguished rhodolith growth stages (GS1 and GS2) along with the coralline taxonomic assemblages recorded rhodolith growth history until their final burial (Fig. 10). The rhodoliths started the nucleation from the GS1 in high water-turbulence conditions. Subsequently, they were subjected to lower light-intensity and turning frequency (GS2). In the final step, the rhodoliths were transported down to deeper marly environments on soft muddy substrates where the rhodoliths were buried.

The thickness of each distinguished growth stage within the studied rhodoliths is not correlated to the coralline growth rate as such, but rather to the duration of the rhodolith growth in that particular stage. Physical or biological disturbances permanently reduce the living coralline biomass of rhodolith deposits. These deposits can be disturbed by natural events such as storms, drastic changes in temperatures, and increased turbidity and sedimentation. The recovery of rhodolith growth after natural events may be very slow (Frantz et al., 2000; Halfar et al., 2000; Rivera et al., 2004). The late GS1 phase lasted longer than GS2 phase as is shown by the more complex patterns in rhodolith growth-form successions. The GS2 was lasted shorter because of the physical constraints (e.g. rhodolith size and soft muddy substrate) under which the rhodoliths grew.

A consistent growth-form succession inside rhodoliths is usually interpreted as being due to changing environmental conditions (Bosence, 1983a,b; Braga and Martín, 1988). This is also the case shown by the changed rhodolith growth forms from GS1 to GS2 (Tables 1 and 3). The GS1 took place in a shallow-water setting (Fig. 10). At this stage, in all the three distinguished rhodolith types, the early rhodolith shape is sub-spheroidal or sub-discoidal, made up of encrusting thalli with symmetrical and asymmetrical inner patterns of accretion. The sub-spheroidal shape suggests a multiple-directional growth of the coralline thalli and, together with the sub-discoidal shape, points to a frequent overturning and a remarkable instability (e.g. Reid and Macintyre, 1988; Bassi, 1995; Ballantine et al., 2000; Rasser and Piller, 2004; Bassi, 2005). In this stage, no indication of water deepening by the coralline taxonomic assemblages was recognized. During the rhodolith growth (increase in size), the rhodoliths developed mainly sub-spheroidal shapes with

Fig. 8. 1. *Gastrochaenolites* (Gas) preserving a bivalve (biv); the elliptical bioerosion clearly reflects the bivalve shape (sample CASV5); *Gastrochaenolites* (Gas) cuts the *Entobia* (Ent) specimens present in this portion of the rhodolith suggesting that bivalve activity succeeded the sponge-related bioerosions. 2. Superimposition of bivalve-related borings (*Gastrochaenolites*) (Gas); the formation of these two borings is not synchronous as evidenced by two different filling sediments characterized respectively by a packstone rich in coralline, echinoderm and bryozoan fragments and by a floatstone/packstone with planktonic foraminifera, carbonate clasts and coralline fragments (sample CASV15); swf, floatstone rich in fragments of shallow-water taxa skeletal fragments; mix, wackestone rich both in fragments of shallow-water taxa skeletal fragments and planktonic foraminifera. 3. Portion of a large *Gastrochaenolites* (Gas) boring filled by coralline and echinoderm packstone (upper part of the photo); boring wall was successively subjected to micro-bioerosion as shown by the concentration of Ichnotype C borings (C); *Entobia* (Ent) and *Meandropolydora*–*Caulostrepsis* (Mea) borings are also present (sample CASV5); 4. Sponge-related borings developed within coralline thalli; rhodoliths were deeply bioeroded during their growth history by several borers which produced a rich and diversified ichnocoenosis characterized by *Entobia* (Ent), *Meandropolydora*–*Caulostrepsis* (Mea), Ichnotype A (A) and Ichnotype C (C) borings (sample CASV10); 5. Sponge-related borings attributed to *Entobia* (Ent); larger chambers are connected with others through narrow channels (sample CASV22); 6. *Entobia* (Ent) bioerosion made by boring sponges (sample CASV1); bry, bryozoans); 7. *Trypanites* (Try) borings developed perpendicularly to the coralline thallial surface (sample CASV18); 8. Complex network of gently curved and sinuous tubular chambers referable to *Meandropolydora*–*Caulostrepsis* (Mea) (sample CASV30). Scale bars represent 1.0 mm.

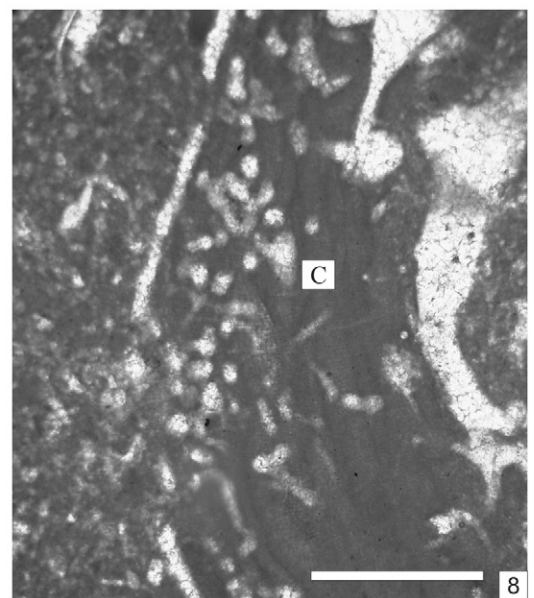
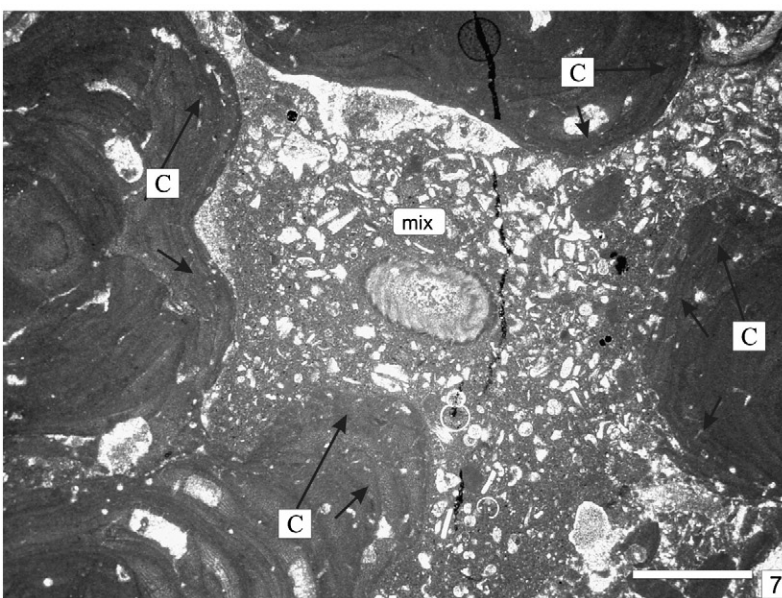
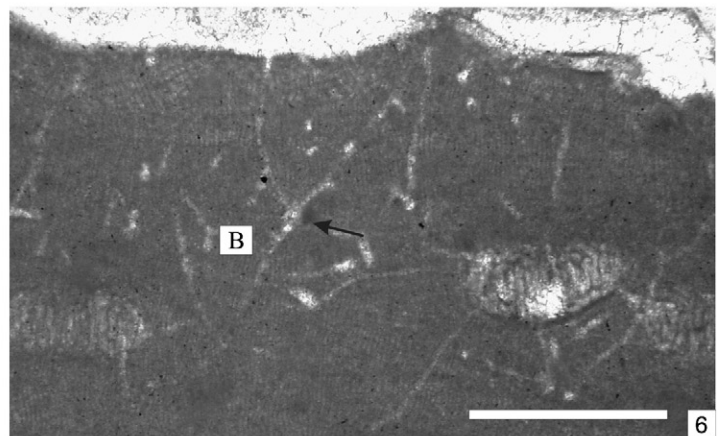
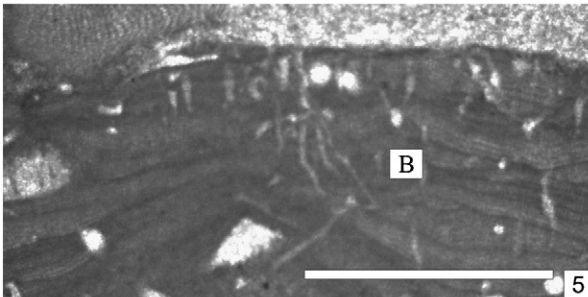
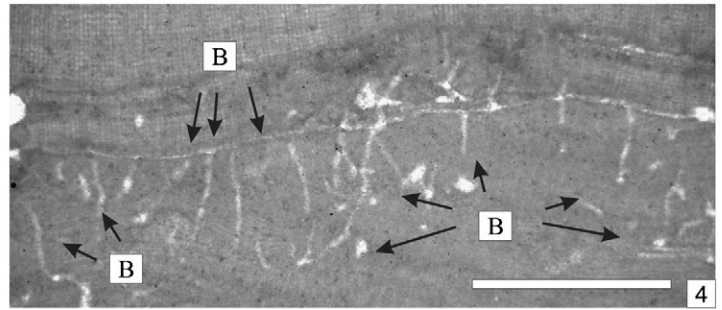
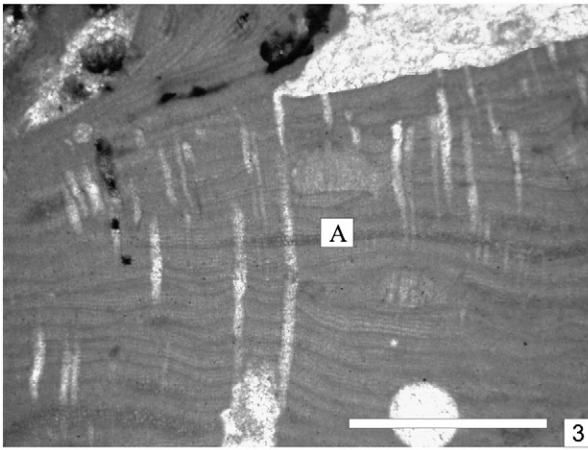
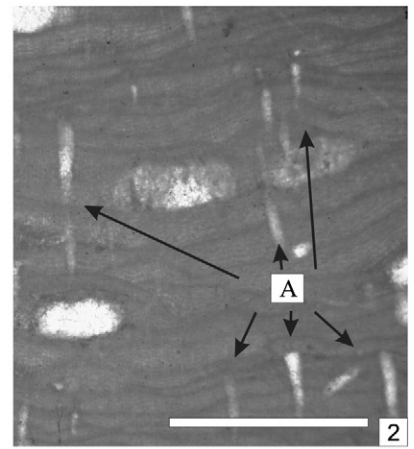
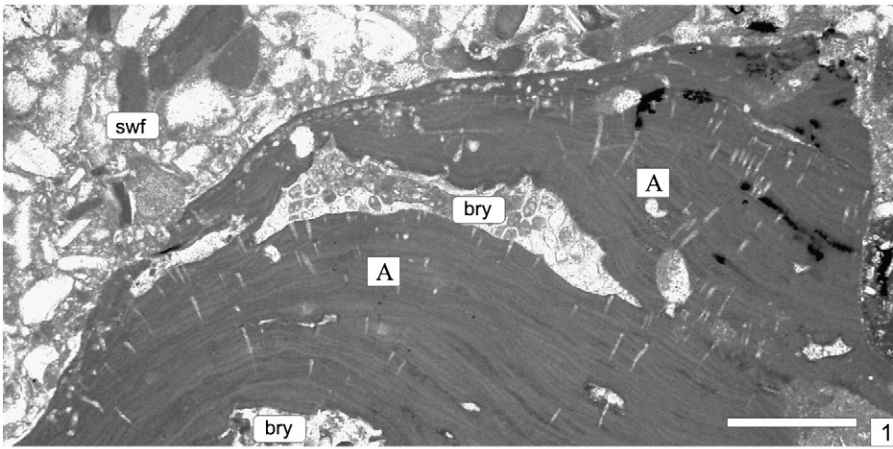


Table 3

Distinctive characteristics of the studied rhodolith assemblage during the two distinguished growth stages (GS1 and GS2). Family and subfamily names in brackets indicate subordinate occurrence. mel, melobesioids; mas, mastophoroids; lit, lithophylloids; spo, sporolithaceans. ■ common; □ scarce to rare.

	GS1	GS2/hemipelagic marls
Rhodoliths		
Growth forms	Encrusting, protuberances	Thin encrusting
Taxonomic assemblage	mel, mas, (lit, spo)	mel, (mas)
Inner arrangement	Symmetrical	Asymmetrical
Ichnocoenoses		
<i>Gastrochaenolites</i>	■	□
<i>Entobia (Uniglobites)</i>	■	
<i>Trypanites</i>	■	□
<i>Meandropolydora/Caulostrepsis</i>	■	□
Ichnotype A	■	■
Ichnotype B	■	■
Ichnotype C	□	■
Dominant bioeroders	Bivalves, sponges, polychaetes, barnacles, algae, fungi, bacteria	Algae, fungi, bacteria, small bivalves, polychaetes
Overturning frequency	Frequent	Occasional/buried
Substrate	Coarse, sandy, mobile	Fine, muddy, mobile
Water turbulence	High, frequent	Low, very low, occasional

symmetrical and asymmetrical inner arrangement pointing out to movement allowing growth in all directions. In GS1, the rhodoliths were not only overturned by water turbulence, movement from the activities of various benthic organisms such as sea urchins, crabs or fishes, appears to be more probable (e.g. Piller and Rasser, 1996; Marrack, 1999). In fact, three-dimensional rhodolith growth is generally assumed to be a consequence of regular overturning (e.g. Bosellini and Ginsburg, 1971; Bosence, 1983a). Non-spheroidal rhodoliths are indicative of a lack of turning, more stable conditions or occasional unidirectional overturning (e.g. Bosence, 1983a; Reid and Macintyre, 1988; Rasser, 2001; Bassi, 2005; Bassi et al., 2006; Nalin et al., 2006, 2007; Bassi et al., 2008). Nonetheless, although coralline algal rhodoliths off Fraser Island (eastern Australia) show that their size and shape are highly dependent on the size and shape of their nuclei, no variation in nodule shape has been recorded at all studied depths (Lund et al., 2000). The dominance of sub-spheroidal shapes at GS1 in the studied rhodolith assemblage (mainly in R1 and R2), therefore, suggests continuous multi-directional overturning, leading to a complete enveloping of coralline plants. In the late GS1, R1 and R2 rhodoliths are generally characterized by massive encrusting thalli with thin laminar crusts. This growth form suggests permanently high-energy conditions during the rhodolith growth history. The R3 rhodoliths are characterized by an asymmetrical development and well developed protuberances that can be referred to lower-water turbulent conditions and, therefore, to a sudden change (deepening) in environmental conditions after the nucleation phase (Fig. 10). In late GS1, dominant coralline growth forms are encrusting (R1 and R2), warty (R1 and R3) and lumpy-fruticose (R3), indicating occasional overturnings. Well-preserved thin coralline crusts in the rhodolith outer part alternating with encrusting bryozoan colonies suggest a low coralline growth rate along with relative stabilisation and scarce rhodolith overturning. The late GS1, therefore, evidences a lower-water turbulence for R1, R2 and R3 rhodoliths, confirming a deepening of the depositional setting.

The GS2, which took place in very low-turbulence conditions, represents the final growth stage for all three rhodolith types (Fig. 10). The rhodoliths grew with an asymmetrical laminar thallial arrangement before being buried. In R1 rhodoliths (Fig. 10), GS2 starts

with the development of protuberances on rhodolith surfaces facing upward and, successively, with laminar crusts developing on these previous protuberances. In R2 and R3 rhodoliths (Fig. 10), GS2 corresponds to the development of laminar encrusting thalli on rhodolith surfaces facing upward. During this stage, no change in water depth of the rhodolith assemblages has been recognized. The asymmetrical final growth of all the studied rhodoliths indicates that they were rarely overturned (i.e. R1 and R2 with encrusting outer growth forms) or were trapped/partially buried in soft muddy substrates (i.e. R3, unidirectional upward growth of protuberances). Asymmetric algal growth suggests a long stable position of rhodoliths, and columnar protuberances and laminar thalli characterize calm water environments (Bosence and Pedley, 1982; Braga and Martín, 1988; Zuschin and Piller, 1997; Perry, 2005).

The soft substrate represented by the *Orbulina* marls in which the rhodolith growth stage terminated (GS2) may have limited the sub-spheroidal rhodoliths beyond a certain size, since the larger rhodoliths would tend to sink into the soft muddy sediment (e.g. Rasser and Piller, 1997; Ballantine et al., 2000; Bassi, 2005). The studied rhodoliths show a homogeneous large size (ca. 13 cm in mean diameter) which represents their final growth size as constrained by the physical characteristics of their terminal depositional setting.

The occurrence of thin laminar thalli and bryozoan crusts on upward facing R1 rhodolith surfaces reflects an increase in rhodolith stabilisation and only occasional movement in calm water prior to burial (e.g. Pissera and Studencki, 1989; Aguirre et al., 1993).

The appearance of protuberances in the GS2 for R3 rhodoliths is indicative of a reduction in turning and, therefore, in water turbulence with respect to the GS1. These growth forms are covered with thin encrusting thalli which testify frequent calm periods. Irregularly shaped rhodoliths with low branch densities, such as those described for rhodolith type R3, are more abundant in deeper-water areas where transport by water motion is infrequent (Marrack, 1999). Complete envelopes of living coralline thalli can, in fact, be maintained on rhodoliths which remain static for several months, but which rest on mobile (shifting) coarse substrates as these rhodoliths require only slight repositioning rather than complete turning in order to maintain their coralline thallial formation (e.g. Scoffin et al., 1985; Reid and

Fig. 9. 1. Ichnotype A (A) micro-galleries generally characterize the outer coralline thallial portion (sample CASV14; scale bar represents 0.5 mm), straight tubular chambers are always perpendicular to coralline thalli with a parallel pattern; 2, 3. Scattered Ichnotype A (A) micro-borings within a coralline thallus; some tunnels show a wedge-shape (2, sample CASV31, scale bar represents 1.0 mm; 3, sample CASV37; scale bar represents 0.5 mm); bry, bryozoans; 4. Extremely slender Ichnotype B (B) micro-borings possibly related to the action of fungi, algae and/or sponges (sample CASV3; scale bar represents 0.5 mm); 5. Ichnotype B (B) micro-tunnels generally develop slightly perpendicular to the coralline thallus but they can also be weakly angled with the normal axis (sample CASV12; scale bar represents 0.5 mm); 6. Ichnotype B (B) micro-tunnels generating a Y-shaped pattern (arrow; sample CASV9; scale bar represents 0.5 mm); 7. Coralline algal branches belonging to a rhodolith R3 showing the typical heavily micro-bored outer surface (Ichnotype C) (C); sample CASV24; scale bar represents 1.0 mm; mix, wackestone rich both in fragments of shallow-water taxa skeletal fragments and planktonic foraminifers; 8. Ichnotype C (C) micro-borings concentrated on the outer rhodolith part (sample CASV21; scale bar represents 0.15 mm).

Macintyre, 1988; Ballantine et al., 2000). Moreover, coralline red algae usually develop thick thalli in shallower environments and are around three times smaller in deeper-water settings (Lund et al., 2000).

The increasing depth of deposition from GS1 to GS2 is also inferred from the coralline taxonomic assemblages (Table 3). The taxonomic trend can be summarised as follows: GS1, nucleation characterized by melobesioids (*Lithothamnion*) and subordinately mastophoroids (rare to common *Spongites*) and very rare sporolithaceans; GS2, dominated by melobesioids (mainly *Lithothamnion*) with rare mastophoroids (Table 1). In the studied rhodoliths, an evident increase in the abundance of melobesioids from GS1 to GS2 was identified. A similar increase in melobesioids with depth together with a relative decrease in lithophylloids/mastophoroids has been widely documented in modern settings (e.g. Adey, 1979; Adey et al., 1982; Minnery et al., 1985; Minnery, 1990; Iryu et al., 1995; Lund et al., 2000) and fossil palaeoenvironments (Braga and Martín, 1988; Aguirre et al., 1993; Martín and Braga, 1993; Martín et al., 1993; Perrin et al., 1995; Bassi, 1995, 1998, 2005; Bassi et al., 2006; Barattolo et al., 2007; Checconi et al., 2007). The drastic increase in abundance of melobesioids and

the decrease of mastophoroids in GS2 fit with the deepening of rhodoliths through time suggested by growth form and thallus characteristics.

The present-day geographical distribution of coralline red algal sub-families and families reflects a clear pattern (Aguirre et al., 2000). Lithophylloids and mastophoroids are common in low- to mid-latitude shallow-water settings, but mastophoroid-dominated assemblages thrive in the tropics while lithophylloids are more frequent in subtropical and warm-temperate environments. Melobesioids do not show a latitudinal restriction, however, in low- and mid-latitudes they have the tendency to live in deeper-water settings. Sporolithaceans are principally confined to low latitudes, where they generally colonise deep-water and cryptic reef habitats (e.g. Adey and MacIntyre 1973; Adey et al., 1982; Aguirre et al., 2000). The studied coralline assemblages are, therefore, likely indicative of transitional tropical-temperate settings.

The taphonomic analyses of the rhodolith confirm the deepening of the depositional environment during their growth history. In GS1 the early fillings of the studied rhodoliths are characterized by

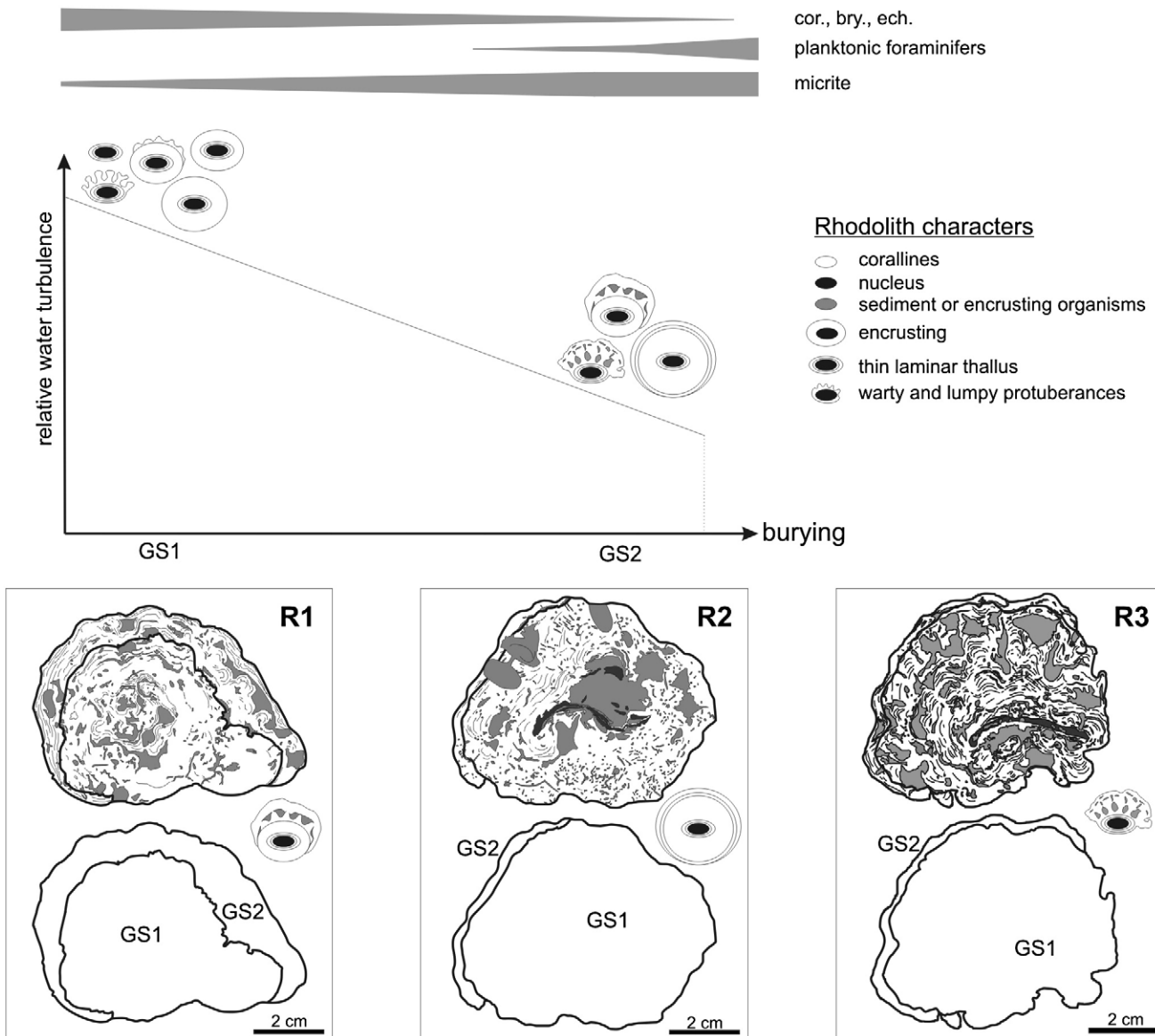


Fig. 10. Growth-stage succession (GS1 and GS2) in the three distinguished types of rhodoliths (R1, R2, and R3). During the growth stages the rhodoliths recorded the relative water-depth increase by change in shape, coralline growth forms and inner accretionary patterns (further detail in the text). For each type of rhodolith, a detailed schematic drawing of polished slabs along with the interpretation of the rhodolith growth stages is shown. Relative abundances of biotic component (cor., coralline fragments; bry., bryozoans; ech., echinoids), planktonic foraminifera and micrite content associated with the studied rhodoliths are also shown.

bioclastic packstones/wackestones with fragments of shallow-water benthic invertebrates, whilst the boreholes of the outer part (GS2) of the rhodoliths preserve planktonic foraminiferal packstones. This lithological pattern recorded by the rhodoliths clearly reflects a gradual change in substrate composition from shallow-water coarse bioclastic to fine hemipelagic deposits (Table 3).

Borings are frequently randomly scattered within studied rhodoliths. In some cases, however, borings occur only at one side of the rhodoliths (e.g. *Trypanites*, *Meandropolydora*, *Caulostrepsis*, and Ichnotypes A and B). This aspect, characterizing the outer rhodolith part in GS1, highlights episodes of coralline growth stasis together with a temporary stabilisation increased, as boring abundance and concentration. This is a function of surface residence time on the sea floor (e.g. Piserà and Studencki, 1989; Gischler and Ginsburg, 1996; Greenstein and Pandolfi, 2003).

Boring preservation reflects both the intensity of abrasion and the rhodolith overturning frequency. The frequent occurrence of borings truncated by abrasion at different depths within the rhodoliths along with the presence of younger borings cutting older ones indicates the succession of several taphonomic events during rhodolith growth. Each rhodolith growth stage (especially GS2) is characterised by two taphonomic phases: (a) colonisation of boring organisms and (b) abrasion. The lack of preserved boring organisms and the highly abraded surfaces in GS1 rhodoliths point to a short exposition time for those rhodolith surfaces which were frequently overturned. The comparable abundance of both borings and abrasion in late GS1 suggests frequent alternations from low to high water-turbulence events. The dominance of both large-boring and the occurrence of micro-boring signatures in GS2 confirm a low water-turbulence setting. In high-turbulence setting micro-borings and shallowest traces can, in fact, be easily obliterated by abrasion (e.g. Radwanski 1965, 1970; Babić and Zupanić, 2000).

In the studied rhodoliths, a change in boring abundance and ichnocoenoses from the rhodolith core to the outer part was recognised (Table 3). In GS1, where coralline are generally more massive and encrusting and where mastophoroids commonly occur, the ichnocoenosis is diversified and is generally represented by common *Gastrochaenolites*, *Trypanites*, *Meandropolydora*, *Caulostrepsis*, and Ichnotypes A and B. Ichnotype C borings are rare in R1 rhodoliths, common in R2 rhodoliths, and absent in R3.

In GS2, the trace fossil assemblages become less diversified. *Trypanites*, *Meandropolydora* and *Caulostrepsis* are present in R1, R2 and R3 rhodoliths. In addition, R1 rhodoliths are also characterized by the presence of common Ichnotypes A, B and C; rare Ichnotypes A and B were also recorded within R2 rhodolith in association with common *Gastrochaenolites* and Ichnotype C.

An active biotic and/or physical abrasion of the rhodolith surface, in which bivalve borings developed, commonly removed the surface portion of borings such as the apertural narrower portion. The poor preservation of the boring necks is in contrast with the occurrence of well-preserved bivalve shells within some *Gastrochaenolites* specimens. These taphonomic evidences suggest high abrasion on the rhodolith surfaces scarce overturning. Rhodolith overturning was necessarily occasional since boring bivalves need occasional overturning periods to colonise within hard substrates.

In the studied inner rhodolith portions (GS1), bivalve shells are generally absent within *Gastrochaenolites*, whilst well-preserved articulated shells were commonly recorded within *Gastrochaenolites* developed in GS2. This suggests faster and more frequent rhodolith overturning during the GS1 and subsequent occasional to rare overturning during the last rhodolith growth stage (GS2) in which valves were preserved within the boring.

Rhodolith abrasion is evident in GS1 for R1 and R2 rhodoliths and only in early GS1 for R3 rhodoliths. The smaller and shallower the traces are, more prone to abrasion and scarcely preserved they are (Radwanski, 1965, 1970; Bromley, 1975; Babić and Zupanić, 2000).

This could explain the common high preservation state of the deepest borings (i.e. *Gastrochaenolites*, *Entobia*, *Trypanites*, *Meandropolydora* and *Caulostrepsis*) in the rhodoliths both within high- (GS1) and low-turbulence (GS2) rhodolith growth stages.

Ichnotypes A and B were mainly observed in rhodoliths developed in a low-turbulence environmental setting (GS2 for R1 and R2 rhodoliths; GS1 and GS2 for R3 rhodoliths). Micro-borings were also possibly produced in other stages (GS1 for R1 and R2 rhodoliths), but the relatively frequent abrasion of the rhodolith surfaces may have obliterated them all. These micro-borings are also well preserved within massive thick thalli in correspondence of some abrasion surfaces (GS1 for R1 and R2 rhodoliths). This micro-boring location evidences that sometimes, though remaining in high-turbulence settings, rhodoliths were subjected to temporary stabilisation or to longer residence time which allowed the colonisation of their outer surface by borers to take place. During this provisional stabilisation, an early covering of this micro-bored rhodolith surface by corallines or other encrusters took place, preserving these shallow borings from the successive abrasion phase. This conclusion is in good accordance with that assessed by the rhodolith characteristics.

Micro-borings (Ichnotypes A and B) could occasionally develop and consequently be preserved also within high-energy growth stage. Ichnotype C borings were only recorded in the outer part of the coralline branches or outer laminar thalli (GS2 for R1 and R2 rhodoliths; GS1 for R3 rhodoliths), all developed in low-energy conditions. Consequently, the distribution of Ichnotype C borer organism was effectively reliant on hydrodynamic energy.

In GS2 for R1 and R2 rhodoliths, and in GS1 and GS2 for R3 rhodoliths, upward facing rhodolith surfaces are generally colonised by borers, the opposite rhodolith surface being buried in the muddy bottom. Sometimes, however, a symmetric distribution of boring all around the rhodolith was recorded. Assuming that water turbulence was too low to cause the overturning of larger rhodoliths and consequently exposing all rhodolith sides to borer action, grazing and other borer activity have to be considered as overturning causes (e.g. Adey and MacIntyre, 1973; Bosence and Pedley, 1982; Marrack, 1999; Steller et al., 2003). Intense borer action, as shown by the highly diversified ichnocoenosis on the studied rhodolith outer parts may explain the local symmetrical bioerosion during rhodolith growth in deeper-water settings (growth-stage GS2).

In shallow-water environments ichnofaunal assemblages are generally highly diverse (with no dominant borers), whereas in deeper-water settings the assemblages decrease in ichnospecies diversity (Bromley and D'Alessandro, 1990; Bromley, 1994). In Pliocene to Recent marine sediments from the Mediterranean area, the association of *Gastrochaenolites*, abundant *Entobia*, *Meandropolydora* (and/or *Caulostrepsis*) and *Trypanites* is indicative of a very shallow, clear marine environment (Bromley and D'Alessandro, 1990; Bromley and Asgaard, 1993). This association has close similarity with those recorded in GS1 for R1 and R2 rhodoliths, and in GS1 for R3 rhodoliths, all related to a high-turbulence shallow-water setting. Furthermore, the decrease in ichnocoenosis diversity in the last GS2 confirms its deeper-water setting with respect to GS1.

6. Concluding remarks

The biodiversity of constituent components, the features related to their developed growth forms and the taphonomic signatures considered altogether represent important aspects that constitute the base for the shallow-water carbonate fabric description, facies analysis and for the palaeoecological and palaeoenvironmental interpretation of biogenic carbonate sediments (e.g. Nebelsick and Bassi, 2000). The integration of these parameters has turned out to be a significant tool for interpreting the palaeoecology of the rhodolith assemblages present within the hemipelagic Middle Miocene *Orbulina* marls in the Vitulano area, allowing rhodolith growth stages from

their first nucleation to their burial to be assessed from the comparative analysis of rhodoliths and trace fossil assemblages (borings).

On the basis of shape, inner arrangement, growth forms and taxonomic coralline algal composition, two rhodolith growth stages were distinguished: (GS1) nucleation of the rhodoliths and intermediate growth stage; (GS2) final growth stage before burial. GS1 took place in a high-energy setting where the rhodoliths developed an early laminar symmetrical and then a thick, massive inner arrangement. In the late GS1, rhodoliths permanently grew in high-energy conditions where they generally developed encrusting and warty morphologies on sub-spheroidal or sub-discoidal rhodolith shapes. The symmetrical and asymmetrical patterns of accretion along with massive encrusting thalli with thin laminar crusts suggest mostly multi-directional overturning and remarkable instability. The rhodoliths were not only overturned by water energy, even during moderate storms. Movement generated by the activity of various benthic organisms such as sea urchins, crabs or fishes, cannot be excluded. The change in the rhodoliths turning direction and frequency coincides with their transport into deeper settings. The final rhodolith growth (GS2) mainly developed in a low-energy, outer platform, soft muddy substrate environment where scarce turning allowed the development of coralline branches and protuberances together with an asymmetrical pattern of accretion. Such a change in depositional environmental depth, testified by shape, size and inner rhodolith arrangement, is also mirrored by the coralline taxonomic assemblages. GS1 is characterized by melobesoids and scarce to common mastophoroids, with rare sporolithaceans and rare lithophylloids. GS2 is dominated by melobesoids with rare mastophoroids and very rare sporolithaceans.

Boring-infilling sediment texture and trace fossil assemblages within the rhodoliths confirm such a deepening trend. The inner/intermediate rhodolith part (GS1) is characterized by a well diversified ichnocoenosis (*Gastrochaenolites*, *Trypanites*, *Meandropolydora* and/or *Caulostrepsis*, *Entobia* (*Uniglobites*)) and other microborings (related to fungi, algae, sponges and/or bacteria), while the outer rhodolith part (GS2) shows only micro-organisms-related and rare bivalve-related borings (*Gastrochaenolites*). In the inner portions of the rhodoliths, the borings are filled mainly by abraded coralline, bryozoan, and echinoderm fragments while, towards the outer rhodolith part, the trapped sediment becomes gradually richer in planktonic foraminifera and muddy matrix.

In the Vitulano area, the studied rhodoliths were (a) removed and transported basin-wards into deeper settings down to the hemipelagic *Orbulina* marls, in which (b) they kept growth and were finally buried. Erosive events associated with storm-generated offshore return currents (e.g. Rubin and McCulloch, 1979; Bassi, 2005) can most likely have transported some still living rhodoliths or only weakly lithified rhodolith intraclasts into deeper-water settings. On the steep flanks of the shallow-water carbonate open shelves in the Taburno–Camposauro area, re-sedimentary episodes and flows have been identified during the TB2 supercycle (Haq et al., 1987) when tectonic controls interacted with sea level fluctuations (D'Argenio, 1963, 1964, 1967; Carannante et al., 1988). However, sediment gravity flows or a transgressive phase can be excluded as main circumstances affecting the studied rhodoliths. Gravitational transport mechanisms have been described from the eastern Matese Mountains where Middle Miocene broad channelized shelf margin is characterized by several sub-marine channels (Carannante and Vigorito, 2001). However, a rapid burial of the studied rhodoliths due to sediment gravity mass flows would not have allowed a successive rhodolith growth to take place as it is evidenced and testified by the last growth-stage GS2. The sediments infilling the rhodolith constructional voids pass gradually from fine skeletal packstone (GS1) to wackestone and planktonic foraminiferal marls (GS2) pointing out a gradual change in substrate characteristics. The studied rhodoliths

occur a few tens of centimetres above the Cretaceous/Middle Miocene boundary, in the lowermost part of the *Orbulina* marls. An *in situ* deepening trend of the rhodoliths is therefore excluded because it would imply in GS1 the absence of shallower-water evidences such as packstone sediment inside the rhodoliths and a well diversified ichnocoenosis. The studied peculiar outcrop represents so far the only example of shallow-water BLL rhodoliths and intraclasts re-sedimented into deeper-water marls. The discovery of further outcrops recording such events would allow a better and exhaustive analysis of the possible transport mechanisms which affected the Lower Miocene open-platforms in the Camposauro area.

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