



ORIGINAL ARTICLE

Coralgal buildups associated with the Bolca *Fossil-Lagerstätten*: new evidence from the Ypresian of Monte Postale (NE Italy)

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Abstract The Monte Postale and Pesciara di Bolca sites are well-known Eocene *Fossil-Lagerstätten*. The origin of these deposits has been previously related to a lagoon environment, protected from the open sea by a barrier formed by some kind of reef. However, no detailed description of a bioconstructed system has ever been reported in the area. This study provides the first detailed characterization of the upper Ypresian Monte Postale reef, made of in situ corals, calcareous algae, and encrusting foraminifera. Three main facies associations have been recognized: (1) a coralgal rim, roughly E/W oriented, (2) lagoon deposits in the south and (3) fore-reef sediments towards the north. The coralgal rim is represented by a wave-resistant framework made of heavily calcified organisms associated to *Alveolina* accumulations; the adaptation of most of these organisms to the euphotic zone promoted their growth in proximity to the sea level, allowing this structure to act as an effective barrier. In particular, during relative sea-level lowstands or highstands, the coralgal rim could have limited the water exchange between the lagoon and the open sea, reducing

the oxygenation in the lagoon and allowing the formation of the *Fossil-Lagerstätten*. During relative sea-level transgressions, the water could have risen well above the margin, establishing normal oxygenation and hampering the fossils' preservation. The Monte Postale succession represents one of the few examples of lower Eocene bioconstructions. The description of this biotic assemblage provides new data for the characterization of reef communities during a crucial climatic phase, near the end of the early Eocene climatic optimum global warming.

Keywords Coralgal reef · Late Ypresian · Bolca *Fossil-Lagerstätten* · Northern Italy · Paleoenvironment · Reef evolution

Introduction

The lower Eocene Monte Postale succession is located in the eastern part of the Lessini Mountains (NE Italy), close to the Pesciara di Bolca, a worldwide famous Eocene *Fossil-Lagerstätte* (Fig. 1). Starting from the 16 century (Roghi et al. 2014), the Pesciara and Monte Postale localities provided a great amount of exquisitely preserved fossils. This includes mainly fishes, along with seagrass and terrestrial plant remains, reptiles, bird feathers, insects, molluscs, jellyfishes, crustaceans, worms, foraminifers, and insects (Sorbini 1972, 1999; Papazzoni et al. 2014). The ichthyofauna, extraordinarily well diversified, is represented by about 240 different taxa, and documents the earliest clearly defined coral reef fish assemblage (Bellwood 1996; Bellwood et al. 2014; Carnevale et al. 2014).

The Pesciara succession has been interpreted since a long time as deposited in a carbonate platform setting, within an intra-platform depression or lagoon, protected

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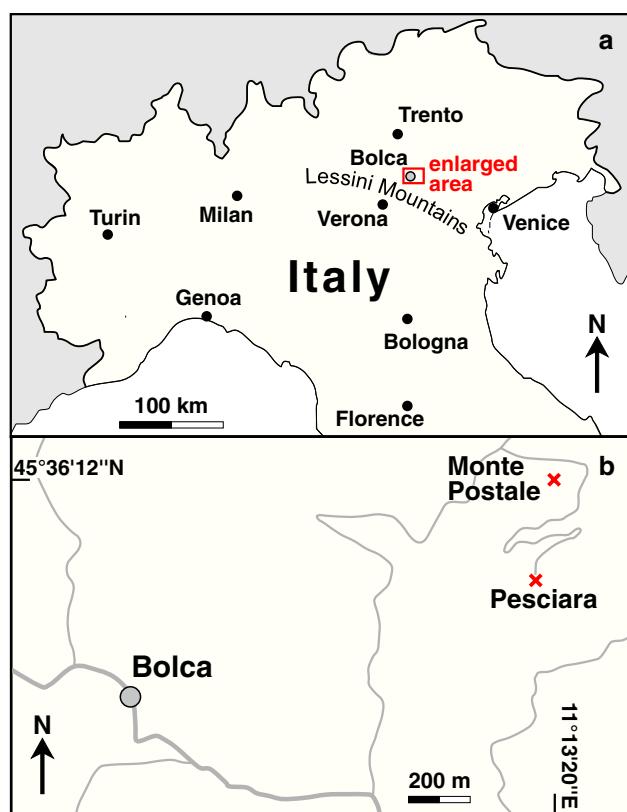


Fig. 1 **a** Location map of the study area. **b** Close-up of the Bolca area and location of the Monte Postale and Pesciara outcrops

from the open sea by some kind of threshold (Sorbini 1972; Papazzoni and Trevisani 2006; Schwark et al. 2009; Trevisani 2015). Both the reef-related fish assemblage and the common occurrence of coral fragments in the Pesciara deposits suggest that this threshold may be formed by some kind of bioconstructed margin. The presence of isolated blocks of reef limestones has been briefly reported by Barbieri and Medizza (1969) from a few localities some kilometers north of the Pesciara di Bolca. In addition, a recent survey of the Monte Postale (Trevisani 2015) mentioned the presence of large benthic foraminifera–calcareous algal buildups that acted as a margin separating the Postale–Pesciara lagoon from the open sea. However, despite this evidence, no detailed description of a reef-building association, or facies analysis of reef-related sediments, have been previously reported in the Bolca surroundings.

Monte Postale represents the most complete stratigraphic record of this area (Munier-Chalmas 1891; Fabiani 1914, 1915; Dal Degan and Barbieri 2005; Trevisani 2015) and, although a valley, volcanic deposits and possibly a fault separate this succession from the nearby Pesciara (Fig. 4a), strong similarities between lithological features and fossil associations suggest that the two sites were part of the same depositional system. In order to improve and

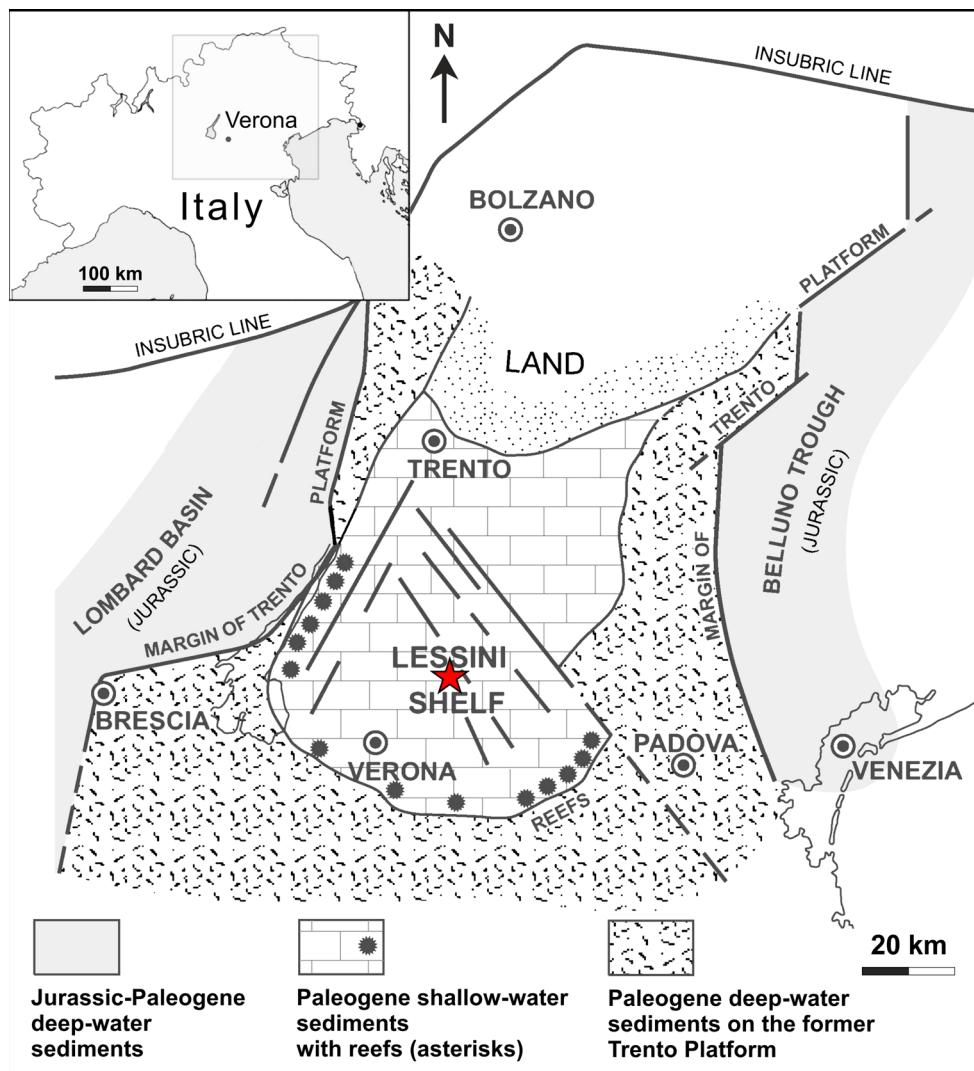
update both stratigraphical and paleontological data sets, a new geological survey of this area has been carried out. During the fieldwork, several massive to weakly stratified limestones were observed along the northern side of the Monte Postale, and their in situ position within the stratigraphic succession was ascertained. They are composed mainly of corals and calcareous algae, in growth position or preserved as broken rubble, associated to *Alveolina* accumulations. These sediments form a narrow, discontinuous belt, several meters thick and arranged along an E/W-directed alignment.

The main goal of this study is to provide, for the first time and within a sound biostratigraphic framework, a detailed description of the reef system associated to one of the most important Eocene *Fossil-Lagerstätten* in the world, and to reconstruct the environmental conditions that controlled the development of this structure. The results of this study will thus contribute to clarify the complex early Eocene paleoenvironmental setting of the Bolca area, providing the base for a more detailed paleoecological interpretation of the entire *Fossil-Lagerstätten* biota. Moreover, as the Monte Postale site represents one of the few examples of lower Eocene bioconstructions, the detailed analysis of the reef-building assemblage provides new information on the structure of Paleogene reefs in a time-window when these associations are poorly known (Scheibner and Speijer 2008; Zamagni et al. 2012), and during a critical climatic phase, when Cenozoic Earth surface temperatures attained their warmest state (Zachos et al. 2001; Payros et al. 2015).

Geological setting

The Lessini Mountains are located within the Southern Alps area, a structural element corresponding to the northernmost corner of the Adriatic plate (Schmid et al. 2004; Márton et al. 2011; Carminati et al. 2012; Handy et al. 2015). During the Early Jurassic, this area was occupied by a carbonate platform (the Trento Platform), confined to the West by the Lombard Basin and to the East by the Belluno Trough (Bosellini et al. 1981; Winterer and Bosellini 1981) (Fig. 2). This platform, starting from the Middle Jurassic, drowned, and became a pelagic plateau (Trento Plateau), until the Alpine collision produced a gradual uplift, with the segmentation of the plateau into several blocks. This phase was accompanied by extensive volcanic activity, possibly as a consequence of a mantle plume, with eruptive products (mainly basalts) contributing to raise parts of the sea bottom (Piccoli 1966; Barbieri et al. 1991; Zampieri 1995; Macera et al. 2008; Cannatelli 2012). Barbieri et al. (1991) recognized six volcanic stages between the late Paleocene and the middle Eocene. Some of the uplifted blocks reached the photic zone during the early Eocene and

Fig. 2 Paleogeographic reconstruction of the Lessini Shelf during the Paleogene (modified from Bosellini 1989). The star indicates the position of the study area



started to act as centers of initiation of shallow-water carbonates, eventually coalescing together to form a vast platform called Lessini Shelf (Fig. 2) (Doglioni and Bosellini 1987; Bosellini 1989; Luciani 1989; Bassi et al. 2008).

The old geological literature attributed all the lower Eocene deposits in the Lessini Mountains to an informal unit named “Calcaro di Spilecco” (e.g., Malaroda in Bosellini et al. 1967; Ungaro 2001). However, in the Spilecco area, only a very short time interval is represented, namely latest Paleocene to earliest Eocene (NP9–10; Papazzoni et al. 2014). Therefore, it seems more advisable to refer most of the lower Eocene sediments in the Lessini Mountains to the Chiusole Formation (*sensu* Luciani 1989), made of carbonates deposited in basinal to slope settings. These deposits also contain resedimented shallow-water carbonates, whose presence gradually increases toward the raised areas of the Lessini Shelf. These shallow-water sediments have been informally indicated as “Calcaro Nummulitico” (nummulitic limestones) (Bosellini

et al. 1967; Carraro et al. 1969; De Zanche et al. 1977; Sarti 1980; Ungaro 2001) and in the middle Eocene they overlaid the deeper sediments of the Chiusole Formation. The Calcaro Nummulitico unit, to which the Monte Postale limestones belong, is characterized by a complex geological setting. This is related to local tectonics, with a complex system of faults displacing the sedimentary successions, and to several volcanic intercalations, associated to the magmatic events that occurred during and after the carbonate deposition (Fig. 3) (Barbieri et al. 1991; Barbieri and Zampieri 1992; Zampieri 1995). Different types of lithologies have been assigned to the Calcaro Nummulitico complex: limestones rich in larger foraminifera, corals and molluses; coralline algal breccias; marly limestones and clays with freshwater and terrestrial fossils (Bosellini et al. 1967). This lithological heterogeneity and the complexity of the geological setting are the causes of a long debate on the precise definition of the Calcaro Nummulitico (see for example Bosellini et al. 1967; Antonelli et al. 1990;

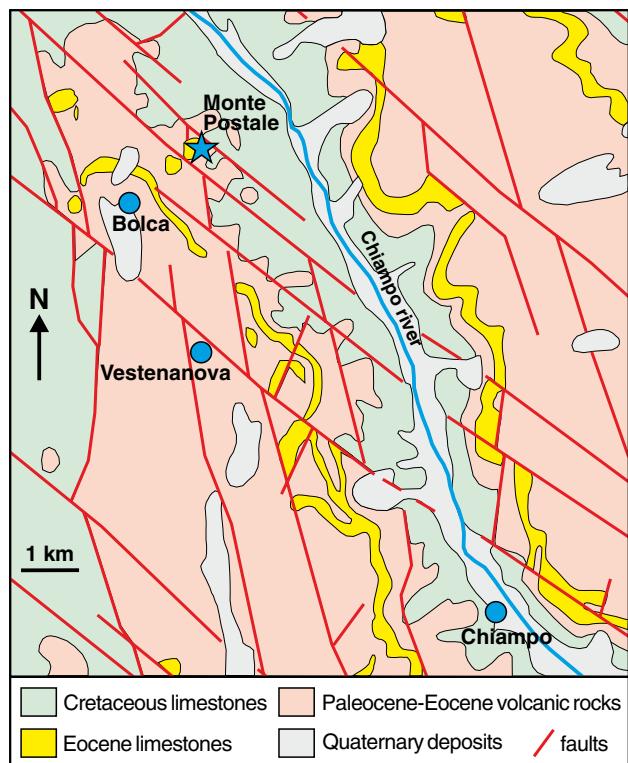


Fig. 3 Simplified geological map of the Monte Postale area; modified from Muscio and Tintori (2005)

Muscio and Tintori 2005), that still needs a thorough revision (Papazzoni et al. 2014).

The volcanic activity ceased during the late Eocene, a phase underlined by the deposition of deep-platform, marly sediments (Barbieri et al. 1980; Mietto 1992; Trevisani 1997). During the early Oligocene, the Lessini Shelf became a rimmed platform, as testified by a reef margin still preserved toward the eastern boundary of this area (Frost 1981; Bosellini and Trevisani 1992; Mietto 1992). During the late Oligocene, sandstones and limestones (Arenarie e Calcaro di S. Urbano Formation) deposited only in the easternmost part of the Lessini Mountains (Bassi et al. 2007). The lower Miocene Marne Argillose del Monte Costi Formation constitutes the last marine deposits in the Lessini Mountains (Bosellini et al. 1967; Bassi et al. 2007, 2008; Bassi and Nebelsick 2010).

Materials and methods

The present study has been based on an extensive fieldwork, including a detailed geological survey, stratigraphic logging and sampling, together with facies analysis. Fieldwork was challenging due to the presence of a dense

vegetation cover, the occurrence of minor tectonic displacements and a generally poor preservation of the outcrops.

The vegetation cover, present all over the year, considerably reduced the number and the extension of suitable outcrops. Even though, seven different sections have been measured and sampled (Fig. 4). The maximum thickness is displayed in the log E , measured on the southeastern side of the Monte Postale, facing the Pesciara outcrop (Fig. 4). Logs A1, A, B, C, D, and D1 are reduced in thickness and are related to small outcrops, maximum 15 m long and 10 m wide, arranged along the northern side of the Monte Postale (Fig. 4a). There, an alignment (approximately 180 m long and 25 m wide) of massive limestones rich in corals and calcareous algae has been identified (Fig. 4b). These coralgal limestones have been specifically selected for the study of the Monte Postale reef depositional system.

Although no major faults were recognized during fieldwork, several minor tectonic disturbances have been observed, related to the widespread occurrence of volcanic intrusions. Therefore, we considered the current bedding orientations and dippings of the studied outcrops as not completely reliable for the reconstruction of the original architecture of the depositional system.

Finally, the poor preservation of the outcrops greatly hampered the field observations and, in many cases, biotic components and sedimentary features have been recognized only by hammering the rock surface. To overcome this limitation, a large number of samples have been collected. From 108 samples, 16 polished sections have been prepared to integrate macroscopic field observations, whereas 132 thin-sections (6×4.5 cm) have been prepared for microfacies analysis.

In order to further improve the description of the reef depositional system, quantitative analyses have been applied for different purposes. To document facies distribution, not directly recognizable in the field, an average of 18 samples has been considered within each of the studied outcrops and the percentage of samples belonging to the different facies has been calculated.

Moreover, in order to document the composition of the reef-builders, relative abundances of corals were obtained considering the number of fragments or individual colonies recognized in thin-section on 64 samples. Corals have been identified at the genus level. Counts also included the selenoporacean alga *Parachaetetes*, which constitutes a dominant component of the reef-building biota.

In addition, to establish the diversity of the encrusting association, the percentage of each taxon has been calculated through point counting on 16 thin-sections. For each section, an average of 170 points has been considered as adequate for a reliable quantitative characterization, due to the relatively large size of most of the encrusting organisms.

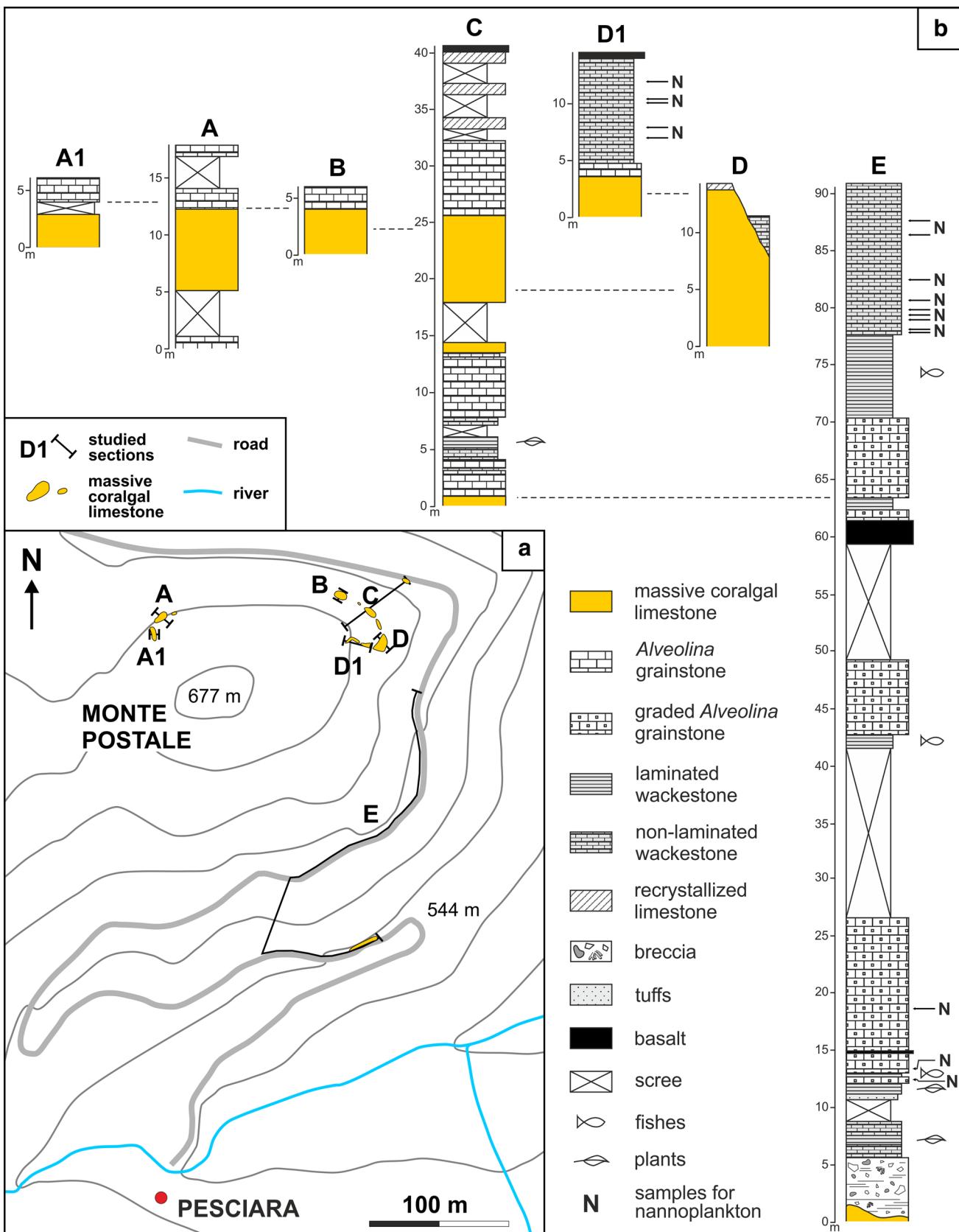


Fig. 4 **a** Positions of the measured stratigraphic sections. **b** Measured logs with stratigraphic correlations

Carbonate textures have been named following Dunham (1962) and Embry and Klovan (1971), whereas coral growth fabrics have been described using the terminology by Insalaco (1998). The nomenclature by Woelkerling et al. (1993), originally established for the description of coralline algae growth forms, has been here extended to characterize polygenetic crusts made of various encrusting organisms.

Stratigraphic setting and age determination

Stratigraphic setting

The Monte Postale corallal limestone can be easily identified in the field by its massive to weakly stratified appearance and by the remarkable abundance of coral colonies, calcareous algae, and encrusting organisms, preserved in growth position or as reworked fragments. Along the stratigraphic horizon represented in logs A1, A, B, C, D and D1, the corallal limestones show a maximum thickness of 13.7 m and are frequently superimposed or interspersed by some dm thick strata of *Alveolina* grainstone (Figs. 4b, 5a). This massive to thick-stratified organization differs from the thinner, more marked stratification of the sediments in log E, in the upper part of log D1 and in the lower part of log C (Figs. 4b, 5b). There, *Alveolina* deposits can also be found, but less abundant and associated to well-stratified accumulations of fine-grained, marly wackestones. These stratified deposits are sometimes interrupted by the presence of large slumps.

In Trevisani (2015, Fig. 2), and previously in Munier-Chalmas (1891), the boundary between the massive carbonates and the stratified deposits is considered to be of tectonic origin, related to the presence of a NW/SE oriented, sub-vertical fault across the Monte Postale. In particular, this fault is supposed to separate D and D1 outcrops from the top of the E section (Fig. 4a, b). During our survey, no evidence of this structure has been observed. On the contrary, along the contact between the two lithologies any tectonic breccias have been observed and in two of the best exposed outcrops (southeast side of the D outcrop, Figs. 4a, 5c; upper part of the D1 section, Fig. 4b) the stratified deposits onlap the massive corallal limestone. In particular, while the sharp contact on the side of the D outcrop (Fig. 5c) could be interpreted as a sequence boundary, the transition between massive and stratified carbonates along the D1 section shows stratigraphic continuity, with no evidence of erosion surfaces. For these reasons, the massive corallal limestone and the stratified deposits are here considered as heteropic.

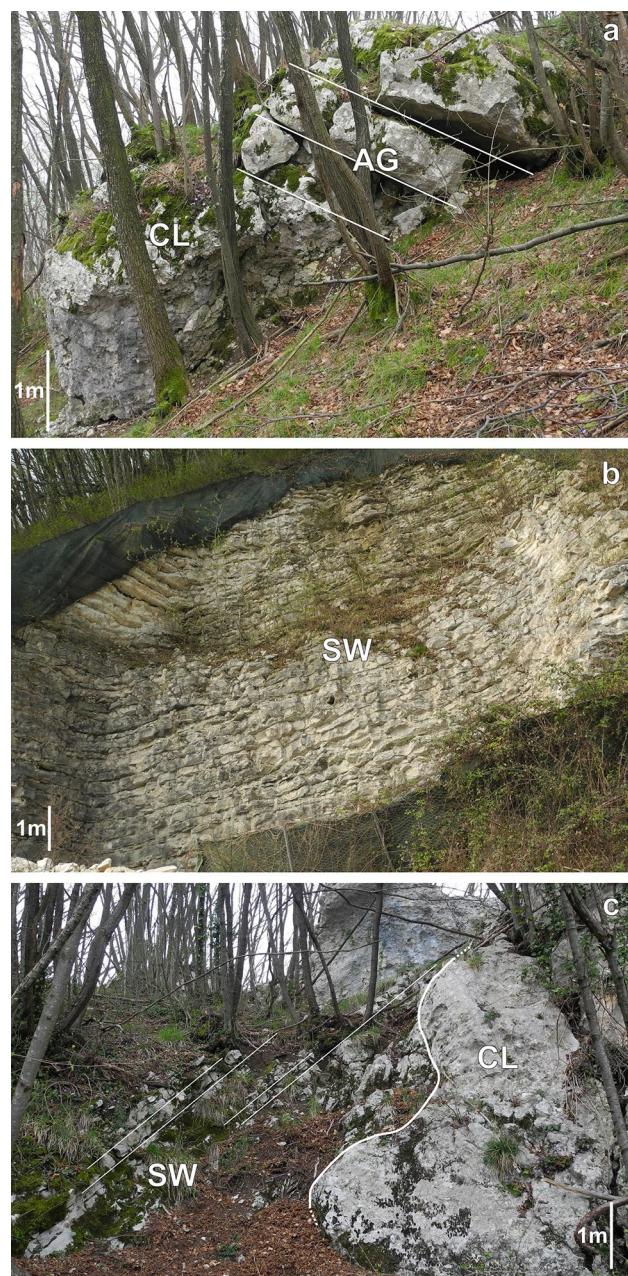


Fig. 5 **a** Massive corallal limestone (CL) superimposed by thick strata of *Alveolina* grainstone (AG), side of log B facing NW. **b** Stratified succession of fine-grained, marly wackestones (SW), top of log E, outcrop facing SE. **c** Contact between the stratified, fine-grained wackestones (SW) and the massive corallal limestone (CL), side of log D facing SE

Dating the Monte Postale succession

The abundance of the larger foraminifer *Alveolina* in the Monte Postale succession allowed a reliable biostratigraphic assignment. The limestones below and above the bioconstructions contain among others *Alveolina cremaeae*

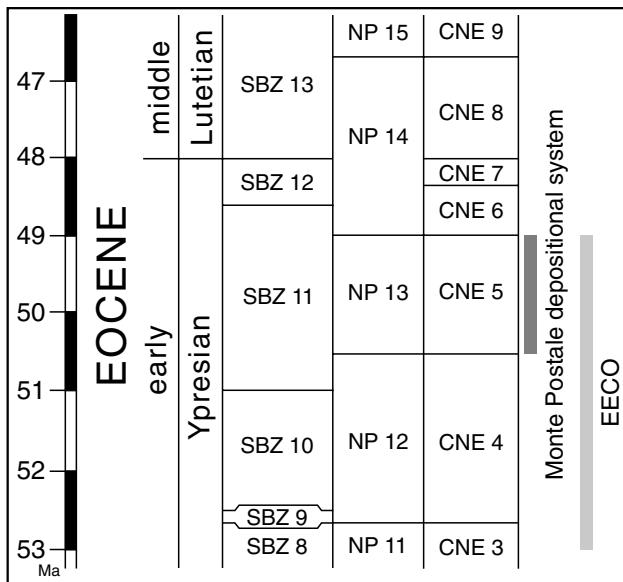


Fig. 6 Age of the Monte Postale depositional system (dark gray bar) and time interval corresponding to the early Eocene climatic optimum (EECO sensu Luciani et al. 2016; light grey bar) refer to the shallow benthic (SBZ) (Serra-Kiel et al. 1998), calcareous nannofossils (NP) (Martini 1971) and Eocene calcareous nannofossils (CNE) (Agnini et al. 2014) biozones

and *A. decastroi*, markers of the SBZ 11 according to Serra-Kiel et al. (1998).

Calcareous nannofossil analysis of several marly layers sampled along the studied sections (Fig. 4) documents the Biozone CNE 5 of Agnini et al. (2014), corresponding to Zone NP13 of Martini (1971). In particular, the presence of two specimens of *Discoaster cf. sublodoensis* in a sample 8 m ca. above the massive coralgal limestones, according to Agnini et al. (2014) suggests to assign this portion of Monte Postale succession to the uppermost part of calcareous nannofossil Zone CNE5 (Fig. 6).

Hence, based on integration of larger foraminifera and calcareous nannofossil zonations, the age of the Monte Postale depositional system is late Ypresian, spanning the interval between ~50.5 and 48.96 Ma (Vandenbergh et al. 2012; Agnini et al. 2014; Fig. 6).

Facies description

Analyses of carbonate textures and fossil associations of the Monte Postale depositional system indicate the presence of eight different facies (Table 1): coralgal boundstone, polygenic bindstone, coralgal rudstone, *Alveolina*-*Nummulites* packstone, *Alveolina* grainstone, laminated wackestone, non-laminated wackestone, and graded *Alveolina* grainstone.

Table 1 Summary of the facies types recognized within the Monte Postale depositional system. Their diagnostic features, together with the main components and related facies associations, are also reported

Facies	Diagnostic features	Main components	Facies association
Coralgal boundstone	Massive limestone rich in corals and calcareous algae in life position	Scleractinian corals, solenoporacean, peysonniacean and coralline red algae, encrusting foraminifera, dasycladacean algae, <i>Alveolina</i> , mioloids	Coralgal rim
Polygenic bindstone	Compact superimpositions of millimetric, sub-horizontal crusts made of calcareous algae and foraminifera	Peysonniacean, solenoporacean and coralline red algae, encrusting foraminifera	Coralgal rim
<i>Alveolina</i> grainstone	Thick strata of coarse <i>Alveolina</i> limestone	<i>Alveolina</i> , fragments of scleractinian corals, mioloids	Coralgal rim
Coralgal rudstone	Massive to weakly stratified limestone rich in poorly sorted fragments of corals and calcareous algae	Scleractinian corals, solenoporacean, peysonniacean and coralline red algae, encrusting foraminifera, dasycladacean algae, <i>Alveolina</i> , mioloids	Coralgal rim/fore-reef
<i>Alveolina</i> - <i>Nummulites</i> packstone	Weakly stratified limestone rich in <i>Alveolina</i> and <i>Nummulites</i>	<i>Alveolina</i> , <i>Nummulites</i> , orthophragminids, fragments of scleractinian corals and encrusting foraminifera	Fore-reef
Laminated wackestone	Thin strata of fine-grained, sometimes-marlly laminated limestone	Micrite, possible presence of fishes and plants remains	Lagoon deposits
Non-laminated wackstone	Thin strata of fine-grained, sometimes marly, homogeneous limestone	Micrite	Lagoon deposits
Graded <i>Alveolina</i> grainstone	Graded strata of <i>Alveolina</i> limestone with erosional base	<i>Alveolina</i> , fragments of scleractinian corals, mioloids	Lagoon deposits

Coralgal boundstone

This facies is represented by massive limestones, up to 4 m in thickness, made of scleractinian coral colonies in growth position together with a consistent component of solenoporacean algae. The coral association displays three main types of growth forms: common are massive colonies (1), up to 30 cm in size (Fig. 7a), but most frequent are platy, encrusting morphologies (2), few centimeters thick (Fig. 7b, c), whose superimposition generate a sheetstone growth fabric that constitutes large part of the coral framework. In places, small branching colonies (ramose and phaceloid) (3) are also present, with sticks rarely exceeding 0.8 cm in diameter (Fig. 7d). These different growth-forms can be frequently found at close distance within the same outcrop, showing no evident distribution pattern or zonation. A quantitative characterization of the reef-building biota is given in Fig. 7e. Even considering biases deriving from limitations in outcrop observations, the bioconstruction is dominated by the coral *Actinacis* (*A. cognata*, Fig. 7g) and solenoporacean algae of the genus *Parachaetetes* (Fig. 7f), representing together 40 % of the reef-building skeletal components. The growth form of *Actinacis* is mostly massive, but fragments of branching colonies are common in thin-sections. *Parachaetetes* is characterized instead by rounded or thick-branching growth forms. Other relatively common genera are represented mainly by branching colonies (ramose and phaceloid) that include *Stylophora*, *Astrocoenia* (Fig. 7h), *Astreopora* (Fig. 7i), *Goniopora*, *Cladocora*, and *Pachygyra*, although their abundance is probably overestimated, as branching corals are more easily fragmented compared to massive corals. *Astreopora* and *Goniopora* also occur as massive (globose) colonies, together with the new genus *Paraleptoria* (Budd and Bosellini 2015) and *Siderofungia*. Platy colonies are mainly represented by *Actinacis* and some agariciid unidentified corals. Subordinate genera are *Acropora*, *Dendratis*, *Caulastrea*, *Euphyllia*, *Favia*, *Montastraea*, and *Siderastrea*.

Corals and solenoporaceans are usually coated by layered polygenic crusts up to 0.5 cm in thickness and sometimes-adjacent coral colonies are connected by the lateral growth of the encrusting organisms. The biotic composition of these crusts is the same of the polygenic bindstone described in the following paragraph. Both corals and polygenic crusts show extensive evidence of bioperforation. In places, the reef-building association also exhibits traces of abrasion, with the truncation of corals and solenoporaceans and the subsequent recolonization of the eroded surface.

Intra-reef sediment shows a wide range of textures: from a fine-grained mudstone/wackestone to a coarser, often poorly sorted packstone/grainstone. Among bioclasts,

most common are fragments of corals and encrusting organisms, dasycladacean green algae, larger foraminifera (mainly *Alveolina*), miliolids, echinoderms, and molluscs fragments.

Polygenic bindstone

This facies is characterized by massive limestones made of sub-horizontal to irregularly arranged polygenic crusts (Fig. 8a). The superimposition of sub-millimetric to millimetric crusts generated an extremely compact, layered bindstone that can reach 80 cm in thickness. The encrusting biota is represented by a well-diversified assemblage (Fig. 9a–f), a quantitative estimation of which is reported in Fig. 8b. Most abundant are calcareous algae, mainly represented by peyssonneliaceans (*Polystrata*, *Peyssonnelia*), by a minor amount of coralline red algae (*Sporolithon*, *Lithoporella*, *Lithothamnion*, some unidentified Mastophoroideae) and solenoporaceans (*Parachaetetes*). Extremely common are also encrusting foraminifera, mainly represented by *Solenomeris* and by a lesser quantity of *Minicinna*, *Acervulina*, *Victoriella*, *Placopsisilina*, *Carpenteria*, *Haddonia* and *Planorbulina*. Less common are encrusting coral colonies, 2–3 cm in thickness (*Actinacis*, *Siderofungia* and some unidentified agariciid corals), bryozoans, serpulids, vermetids and thin micritic crusts of microbial origin.

As in the coralgal boundstone facies, abundant traces of bioerosion, together with sparse signs of abrasion occur. Small cavities among the bindstone are filled by mudstone to packstone deposits with fragments of encrusting organisms, larger foraminifera (mainly *Alveolina*), echinoderms, molluscs and rare dasycladacean algae.

Coralgal rudstone

Massive to weakly stratified carbonate deposits, up to some meters thick, and rich in poorly sorted skeletal fragments of the same reef-building organisms observed in the coralgal boundstone. Abundant are also dasycladacean algae and fragments of encrusting organisms (Fig. 10a); among the latter, frequent are thin *Lithoporella* crusts characterized by foliose, hooked and tubular growth forms (sensu Beavington-Penney et al. 2004) (Fig. 10c, d). Fragments of molluscs, larger foraminifera (mainly *Alveolina*, less frequently orthophragminids and *Nummulites*), miliolids and echinoderms are also present. Sparse in situ polygenic crusts, similar to those of the polygenic bindstone, have also been observed. These reach 1–2 cm in thickness and extend sub-horizontally among the bioclastic rudstone, binding together the skeletal fragments (Fig. 10b).

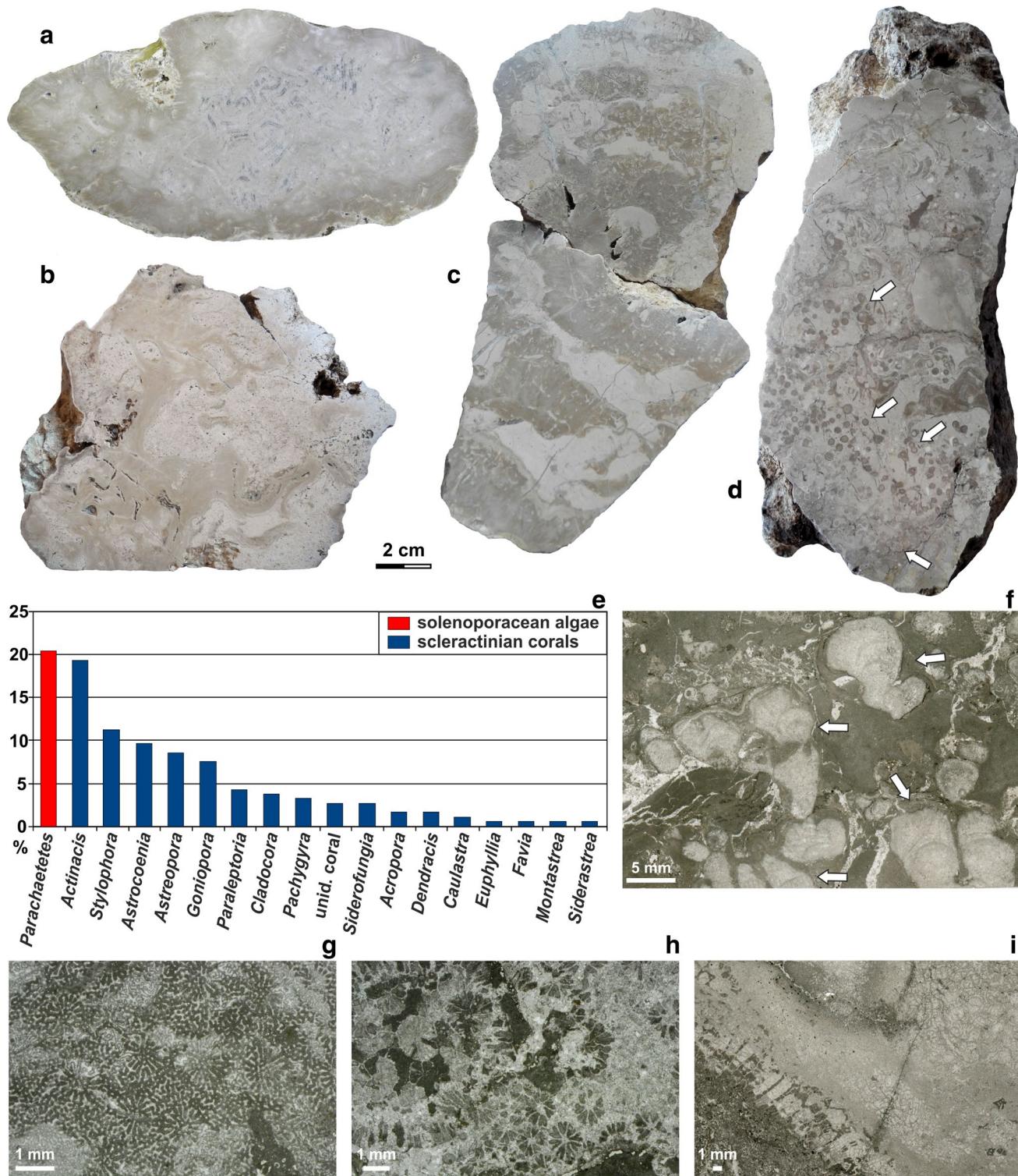
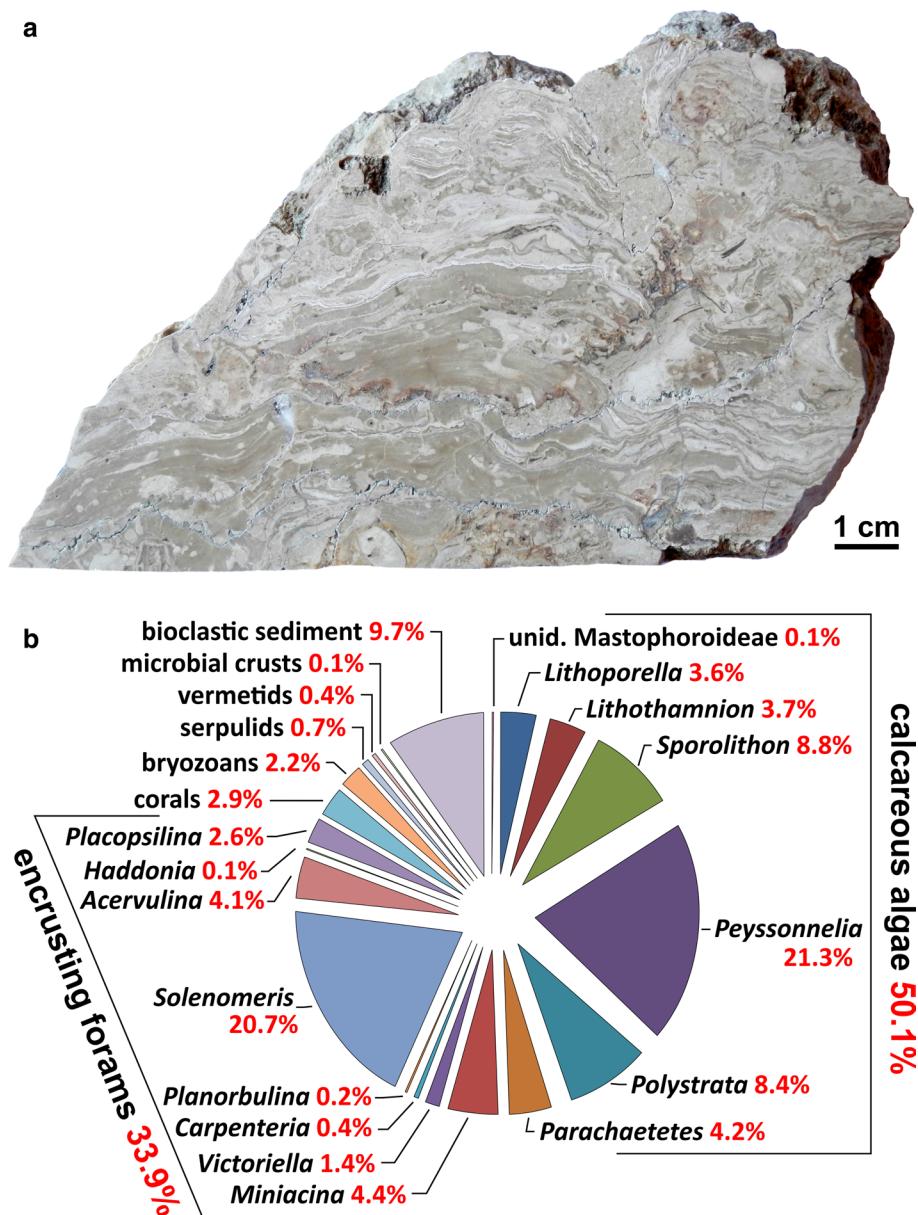


Fig. 7 Coralgal boundstone facies. **a** Massive colony of *Paraleptoria flexuosissima*, polished section. **b** Platy, encrusting colony of *Actinacis cognata*, polished section. **c** Platy, tabular colony of *Siderofungia* sp., polished section. **d** Thin sticks of a branching colony of *Cladocora* sp. (arrows), polished section. **e** Relative abundance of scleractinian corals and solenoporacean algae genera. **f** *Paracheetetes* sp. plants (arrows), thin-section. **g** *Actinacis cognata*, thin-section. **h** *Astrocoenia* sp., thin-section. **i** *Astreopora tecta*, thin-section

cora sp. (arrows), polished section. **e** Relative abundance of scleractinian corals and solenoporacean algae genera. **f** *Paracheetetes* sp. plants (arrows), thin-section. **g** *Actinacis cognata*, thin-section. **h** *Astrocoenia* sp., thin-section. **i** *Astreopora tecta*, thin-section

Fig. 8 Polygenic bindstone facies. **a** Polished section showing the compact, subhorizontal superimposition of the polygenic crusts. **b** Relative abundance of encrusting organisms and bioclastic sediment



Alveolina–Nummulites packstone

Weakly stratified biocalcareite deposits, cropping out for a maximum thickness of 8 m and organized in decimetric layers. The prevalent texture is a packstone, rich in *Alveolina*, *Nummulites* and orthophragminids, all characterized by a moderate to good degree of preservation, together with fragments of corals, encrusting organisms and molluscs. Miliolids and rare dasycladacean algae are also present (Fig. 11a).

Alveolina grainstone

Stratified grainstone to packstone deposits, up to 7 m in thickness and organized in decimetric layers. This facies

is characterized by coarse, highly abraded skeletal grains among which abundant are *Alveolina*, coral fragments and miliolids, associated to orthophragminids, fragments of molluscs and echinoderms. Rare are *Nummulites*, fragments of encrusting foraminifera and of calcareous algae (Fig. 11b).

Laminated wackestone

Extremely fine grained, sometimes marly, wackestone deposits arranged in thin, centimetric strata, with a maximum overall thickness of 7–8 m. A distinctive feature of these sediments is the occurrence of a planar lamination, more rarely undulated, with the alternation of light and darker laminae, millimetric to sub-millimetric in thickness,

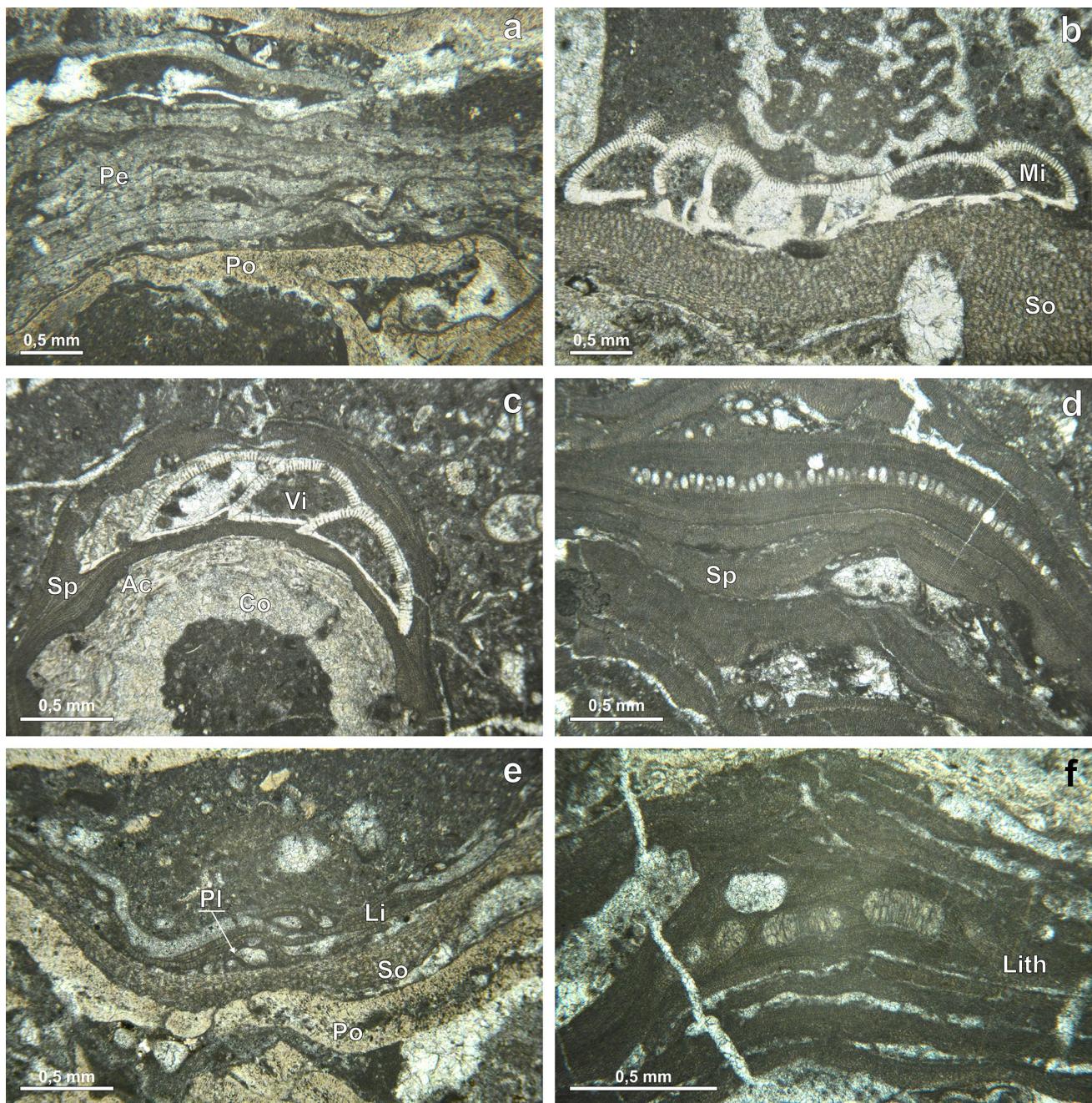


Fig. 9 Polygenic bindstone facies. **a–f** Thin-sections showing some of the main encrusting organisms. *Peyssonnelia* (Pe), *Polystrata* (Po), *Acervulina* (Ac), *Miniacina* (Mi), *Placopsis* (Pl), *Solenomeris* (So), *Victoriella* (Vi), *Lithothamnion* (Lith), *Lithoporella* (Li), *Sporolithon* (Sp), scleractinian coral (Co)

and related to variations in the amount of micrite. Some of these strata show the presence of slightly thicker laminae, white in color and undulated. Concerning the bioclastic grains, even if scattered macroscopic fragments of *Alveolina*, miliolids, corals and calcareous algae have been recognized, their extremely small size usually prevents their precise identification (Fig. 11c). Well-preserved fishes and plants remains can be found inside these strata.

Non-laminated wackestone

This facies is very similar to the laminated wackestone: centimetric layers made of extremely fine grained, sometimes marly wackestone characterized by a maximum overall thickness of 13 m. The main difference is related to the complete lack of lamination, sometimes replaced by irregularly distributed concentrations of micrite and bioclasts that

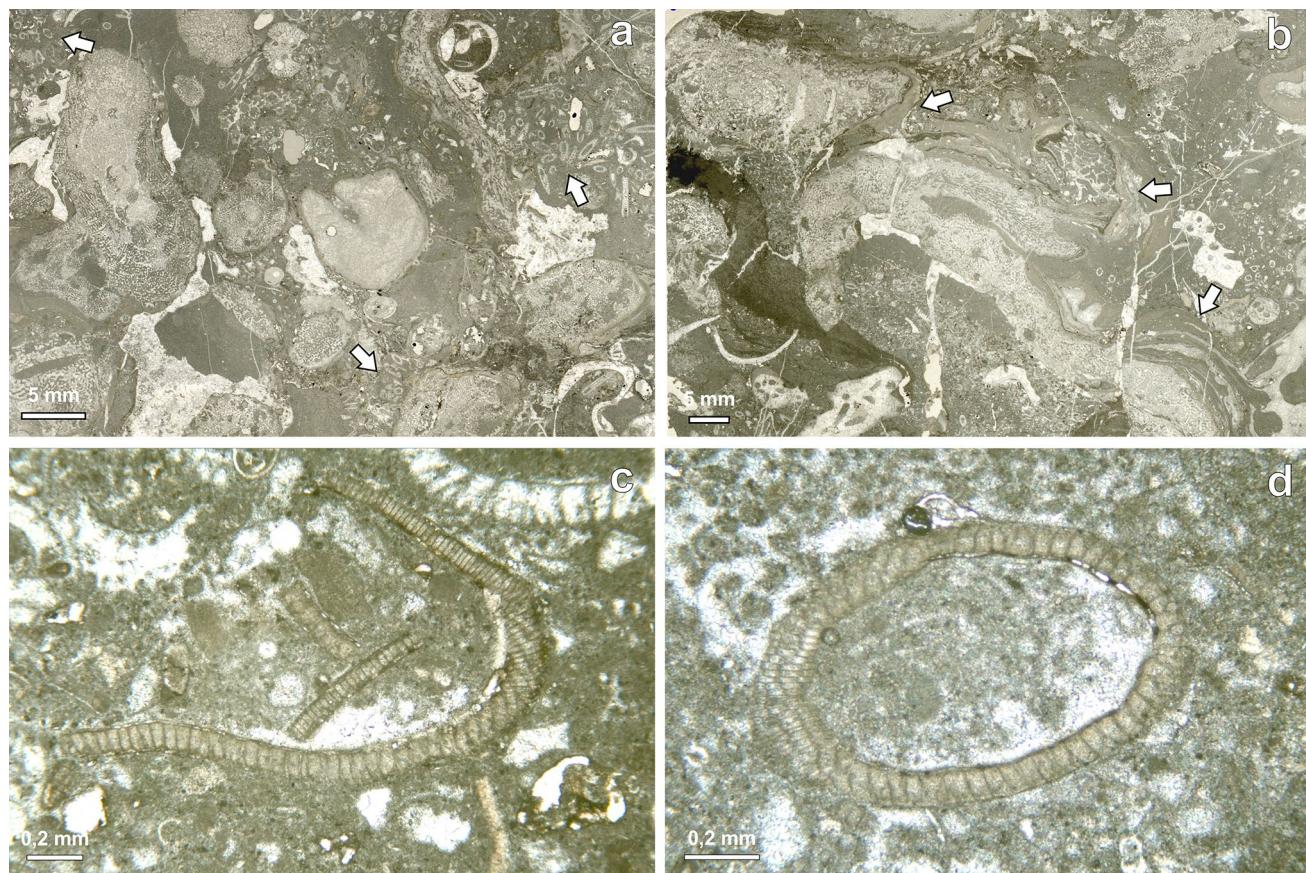


Fig. 10 Coralgal rudstone facies. **a** Bioclastic deposit with abundant dasycladacean algae (arrows), thin-section. **b** Polygenic crusts (arrows) binding the bioclastic fragments, thin-section. **c** Fragment of

Lithoporella crust with hooked morphology, thin-section. **d** Fragment of *Lithoporella* crust with hollow morphology, thin-section

suggest the occurrence of bioturbation (Fig. 11d). No macrofossils have been found within these deposits.

Graded *Alveolina* grainstone

Alveolina grainstone to packstone deposits are organized in 20–50 cm thick strata, characterized by the presence of an erosional base and normal graded bedding; the coarser bioclasts rarely exceed 1 cm in size. The superimposition of these levels forms deposits up to 12 m in thickness. The skeletal composition of these sediments is the same recognized in the *Alveolina* grainstone facies.

The Monte Postale reef system

Facies associations

Spatial distribution and stratigraphic setting of the different Monte Postale facies (Figs. 4b, 12) allow to identify three main facies associations and to interpret their depositional

paleoenvironments: (1) coralgal rim; (2) fore-reef accumulations; and (3) lagoon deposits.

Coralgal rim: description

Coralgal boundstone and polygenic bindstone facies represent the bioconstructed portion of the Monte Postale depositional system. Field observations and quantitative analyses place these two facies in the proximal, internal part of the E/W alignment outlined by the arrangement of the studied outcrops (Fig. 12). This distribution identifies the “backbone” of the coralgal rim structure, in which the percentage of the skeletal framework varies from a maximum of 66 % of the overall lithology, in both A and A1 outcrops, to a minimum of 14 % in outcrop C. Among these bioconstructions, bioclastic deposits are also abundant and represented by the coralgal rudstone facies, largely derived from the breakage and reworking of the main reef-building organisms. The amount of this facies varies from 63 % (outcrop D1) to 22 % (outcrop A). Also the *Alveolina* grainstone deposits belong to the coralgal rim facies association.

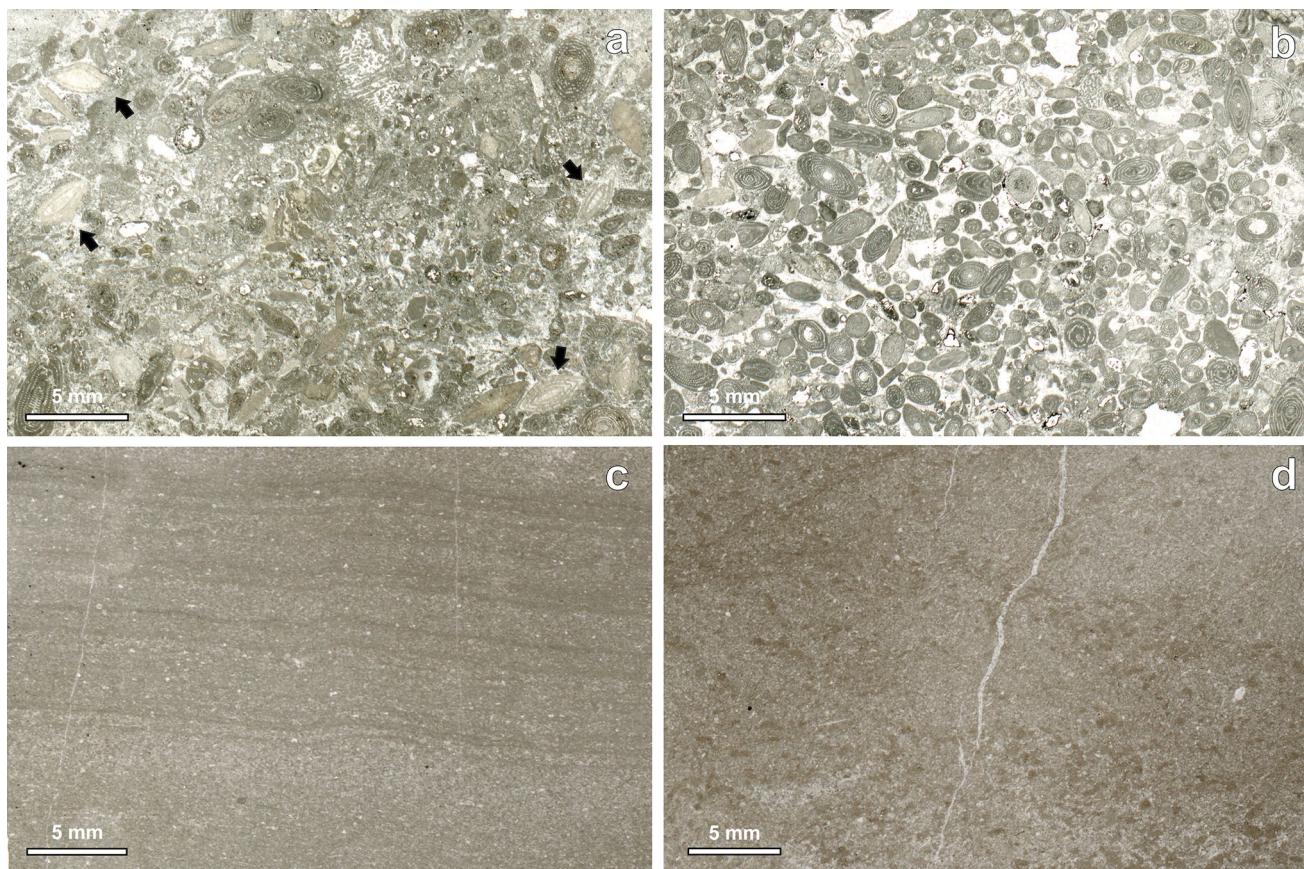


Fig. 11 **a** Alveolina–Nummulites packstone facies, bioclastic deposit with *Nummulites* tests (arrows), thin-section. **b** Alveolina grainstone facies, bioclastic deposit with abraded skeletal grains, thin-section. **c** Laminated wackestone facies, alternation of millimetric to sub-mil-

limetric laminae, thin-section. **d** Non-laminated wackestone facies, concentrations of micrite and small bioclasts suggesting the occurrence of bioturbation, thin-section

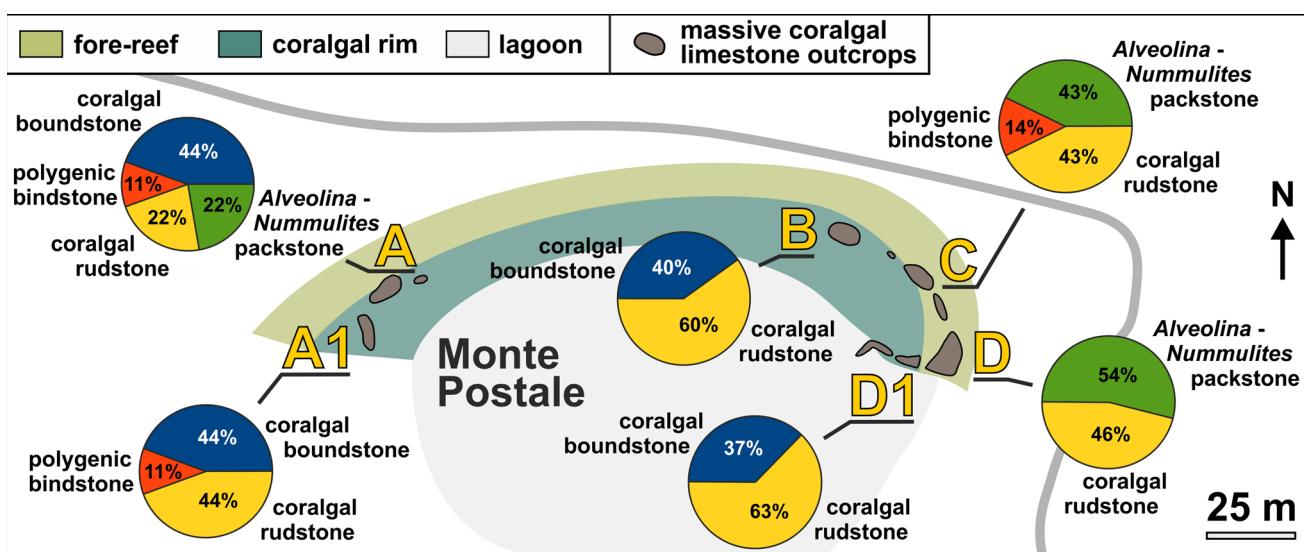


Fig. 12 Spatial distribution of the Monte Postale facies associations. The reconstruction is based on the stratigraphic setting and relative abundance of the different facies within each studied outcrop

Stratigraphical setting of Monte Postale indicates these accumulations precede and overlie the massive coral limestone, but *Alveolina* grainstones can also be found laterally to the bioconstructions (see for example Fig. 4b, logs C and D1), forming bioclastic sand bodies that accumulated beside the skeletal frame.

Coralgal rim: paleoecological setting

A number of components of the coralgal rim biotic assemblage suggest deposition within extremely shallow-water conditions. The remarkable amount of *Alveolina*, sometimes associated to abundant miliolids, indicates a depositional depth above 40 m (Hottinger 1997). Within the calcareous algae association, the occurrence of peyssonneliaceans (*Peyssonnelia* and *Polystrata*), that represent the most important taxa within the polygenic bindstone (Fig. 8b), supports a paleodepth limited to the euphotic zone (Flügel 1979; Fagerstrom 1987). The presence of in situ solenoporacean plants (*Parachaetetes*) in the coralgal boundstone and polygenic bindstone, and of dasycladacean green algae, particularly concentrated within the coralgal rudstone facies, suggests a bathymetric setting restricted to the shallowest part of the euphotic zone (Flügel 1979, 2004; Fagerstrom 1987; De Castro 1997). Coralline red algae (Corallinales, Sporolithales, Hapalidiales) are generally characterized by a wider bathymetric range, that reaches the lower limit of the photic zone (Littler et al. 1985). However, within the coralgal rim assemblage, specific coralline algae growth forms have been identified, which may be indicative of a more restricted bathymetric setting. Fragments of foliose, hooked and tubular crusts, related to the genus *Lithoporella*, have been detected, especially concentrated within the coralgal rudstone facies (Fig. 10c, d). These morphologies, indicative of the presence of seagrass beds, are related to the development of coralline algae as epiphytic organisms on macrophytes, adapting their shape to the morphology of leaves, stems and other portions of the plants (Beavington-Penney et al. 2004; Perry and Beavington-Penney 2005; Sola et al. 2013). Preserved fragments of seagrasses have been also found within the laminated deposits of both Monte Postale and Pesciara sites (Wilde et al. 2014). In present-day tropical and temperate marine environments, seagrass meadows are typical of the shallow-water, euphotic zone (e.g., Fornos and Ahr 1997; Hemminga and Duarte 2000; Larkum et al. 2006; Mateu-Vicens et al. 2010).

Despite the evidence of extremely shallow-water setting, growth morphologies of the coralgal rim biota, as well as considerable variations in the sediment textures, indicate the presence of areas characterized by different hydrodynamic conditions. The extremely compact, layered arrangement of the polygenic bindstone (Fig. 8a), where

thin, bioclastic accumulations constitute <10 % of the overall lithology (Fig. 8b), suggests that this facies developed within a high hydrodynamic setting, under the continuous effect of waves and tides. This interpretation is supported by the dominance, among coral colonies, of encrusting and massive growth forms, which are both well adapted to high-energy environments (Chappell 1980). However, within the same outcrops, coral colonies with completely different morphologies, indicative of lower hydrodynamic conditions, can also be found. This is the case, for example, of outcrop A1, where close to encrusting coral colonies and polygenic bindstone crusts there are in situ branching corals with extremely thin, delicate sticks (Fig. 7d), the latter usually adapted to very low energy settings. This can be explained by the occurrence, within the coralgal rim structure, of protected areas, sheltered from the action of waves and currents. This hypothesis is also supported by the evidence of mud-supported bioclastic accumulations and by the abundance of dasycladacean algae, whose presence is usually associated to lagoon environmental conditions (Génot 1991; Flügel 2004).

Fore-reef: description

Coralgal rudstone deposits, which are widespread within the coralgal rim, also accumulated northward from the bioconstructed margin (Fig. 12). These sediments are mixed with the *Alveolina–Nummulites* packstone facies (for example in outcrops A and C, Fig. 12) that gradually increases towards the more distal areas of the depositional system (up to 54 %, in outcrop D, Fig. 12). The association of coralgal rudstone and *Alveolina–Nummulites* packstone identifies a fore-reef tract, made of accumulations of bioclastic fragments mainly deriving from the dismantling of the coralgal rim by the action of waves and tides. These deposits may have acted as a connection between the coralgal rim and more distal, open-marine environments.

Fore-reef: paleoecological setting

The prevalent packstone texture of the fore-reef deposits suggests a depositional setting with moderate hydrodynamic conditions. The skeletal components of these deposits are quite similar to those of the coralgal rim, except for the common occurrence of *Nummulites*. *Nummulites* distribution is generally limited to the euphotic zone, but in comparison to the coralgal rim facies, they indicate a deeper, open-marine depositional setting (Hottinger 1997).

Lagoon deposits: description

The lagoon facies association crops out southward of the coralgal rim (Fig. 12) and is well exposed along the

southeastern side of the Monte Postale (Figs. 4a, 5b). These deposits are characterized by the occurrence of three main facies: laminated wackestone, non-laminated wackestone and graded *Alveolina* grainstone. These lithologies superimpose to each other, forming alternations characterized by sharp contact surfaces (log E, Fig. 4b). Slump deposits sometimes interrupt this succession and in these cases sediments related to the three facies can be found reworked and mixed together.

Lagoon deposits: paleoecological setting

Paleoecological interpretation of this facies association follows the one proposed by Papazzoni and Trevisani (2006) for the sedimentary succession of the Pesciara di Bolca. Texture, composition, and stratigraphic arrangement of the three Monte Postale Lagoon facies show strong similarities with those described for the nearby Pesciara. In particular, the laminated wackestone can be compared with M1 and M2 microfacies of Papazzoni and Trevisani (2006) (respectively, defined as micritic, evenly laminated limestone with black laminae, and micritic, irregularly laminated limestone with white laminae); the non-laminated wackestone is similar to M3 microfacies (micritic, non-laminated limestone), while the graded *Alveolina* grainstone shows the same features as their F microfacies (biocalcarene–biocalciranite with abundant benthic fossils). Based on this comparison, the paleoecological setting of the lagoon facies association can be reconstructed as follows: quiet, low hydrodynamic conditions characterized this protected environment that allowed the deposition of very fine grained, marly wackestones. The proximity to emerged lands is suggested by the presence of terrestrial plants remains, as part of the *Fossil-Lagerstätte* biota whose occurrence in the Monte Postale is limited to the laminated wackestone facies. The exceptional preservation of this fossil assemblage, as well as the undisturbed, thin lamination, suggest a depositional environment with extremely reduced oxygenation. The presence of anoxic conditions at the bottom of the lagoon has been also indicated by Schwark et al. (2009) on the basis of organic geochemical analyses on the sediments of the Pesciara succession. In addition, the presence of white, undulated laminae, can be interpreted as related to algal mats of cyanobacterial origin, which is as well consistent with the occurrence of anoxic conditions (Papazzoni and Trevisani 2006). To the contrary, the non-laminated wackestone facies, with no evidence of macrofossil preservation, the lack of lamination and the frequent traces of bioturbation, suggests phases characterized by higher oxygenation levels that periodically alternated with the anoxic events. The alternation of these two facies was often interrupted by the deposition of the graded *Alveolina* grainstone. The erosive base and the normal graded bedding clearly indicate

the latter deposits as the product of resedimentation processes, most probably related to storm events. On the basis of the skeletal composition, closely resembling the one of the *Alveolina* grainstone facies, it is possible to recognize these sediments as transported from the coralgal rim facies association.

Discussion

Depositional model

The coralgal rim facies association represents the core of the Monte Postale depositional system, where the growth of the reef-building organisms (mainly corals, calcareous algae, and encrusting foraminifera) and the accumulation of large benthic foraminifera (mainly *Alveolina*) actively contributed to the formation of a narrow, elevated structure (Fig. 13) that developed within a maximum paleodepth of a few meters. This margin was approximately oriented in a E/W direction, facing the open sea toward the north, most probably representing the border of a paleo-embayment or intrashelf seaway within the Lessini Shelf. Although the poor preservation of the studied outcrops does not allow reconstructing in detail the spatial distribution of the coralgal rim facies, there is evidence of a coexistence of areas characterized by high and by low to moderate hydrodynamic conditions. This suggests the occurrence of a complex structure, with compact, wave-resistant buildups directly facing the open sea, interconnected by more protected zones. These sheltered environments were inhabited by reef-building organisms with delicate growth forms, associated to bioclastic deposits with variable textures, filling the cavities among the reef-building organisms and contributing to strengthen the skeletal frame. The same accumulations of loose bioclastic sediments may have acted as substrate for the colonization of seagrass patches and dasycladacean green algae. The coralgal rim structure was probably crossed by channels, connecting the open sea with the rear lagoon. This was the environment in which the *Alveolina* grainstone facies developed, with the high degree of abrasion of its skeletal components most likely related to the continuous action of tides and waves. These accumulations played an important role in strengthening the coralgal rim, contributing to fill the gaps in the bioconstructed portion of the structure.

The role of this margin as an effective barrier, and thus the establishment of a protected lagoon, largely derives from the nature of the Monte Postale biotic association. The large amount of bioclastic sediments removed from the coralgal rim (*Alveolina* grainstone facies) and accumulated within the Lagoon succession (graded *Alveolina* grainstone facies) suggests the occurrence of high-energy

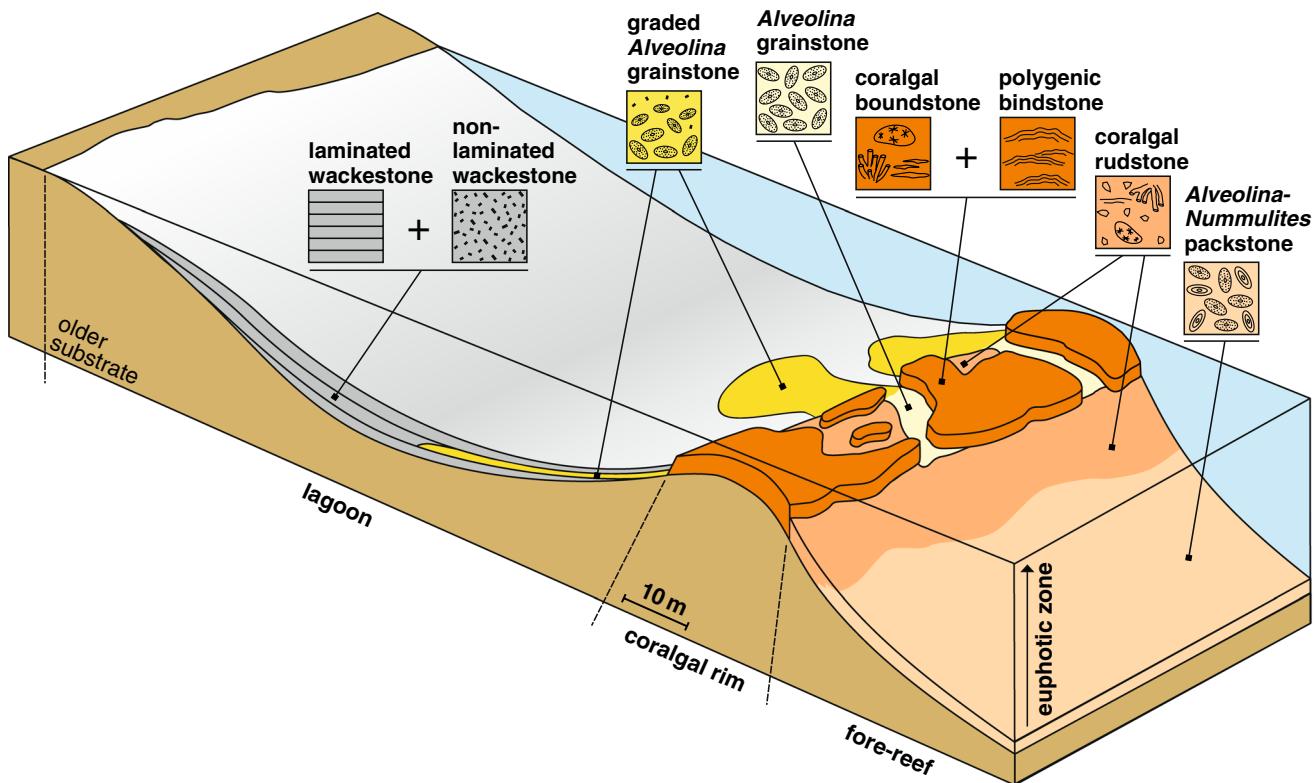


Fig. 13 Reconstruction of the lower Eocene Monte Postale depositional system; the width and depth of the lagoon are not in scale

conditions, most probably related to relatively frequent storms. The width of the Monte Postale sill probably did not exceed 20–30 m across (Figs. 12, 13), even though a larger size could be concealed by the reduced extension of the available outcrops. Such a narrow structure would not have endured extreme hydrodynamic conditions, if not for the contribution of a robust, skeletal framework created by heavily calcified organisms. In addition, the prevalence among the coralgal rim biota of taxa adapted to the euphotic zone (corals, calcareous algae, *Alveolina*), promoted the preferential growth of the reef assemblage within an extremely shallow-water setting. This contributed to the maintenance of the coralgal rim close to the sea level, limiting the water exchange between the lagoon and the open sea.

The reef system here described represents a single phase in the evolution of the Monte Postale succession, whose reconstruction is mainly based on the coralgal limestone alignment of the logs A1, A, B, C, D and D1 (Fig. 4b). However, considering the whole stratigraphic setting of the area, a more complex situation emerges, with evidence of at least two older reef events (base of the logs E and C; Fig. 4), and of two superimpositions of fine-grained, lagoon wackestones on the top of massive coralgal limestones (base of the log C, log D1; Fig. 4). This setting suggests a complex depositional history, characterized by several

changes, with time, in the position of the reef facies associations. These shifts represent different phases in the evolution of the Monte Postale depositional system, most probably as a response to relative sea-level fluctuations. Due to the difficult outcrop situation the following reconstruction of the depositional pattern is partially speculative.

The common presence of fragments of the reef-building association throughout the lagoon sedimentary succession suggests a more or less continuous presence of the coralgal rim. Within this context, three different depositional phases of the Monte Postale margin, associated to relative sea-level fluctuations, are proposed (Fig. 14): (1) during sea-level lowstands, the coralgal rim, even if partially dismantled, could have represented an effective barrier, with the reduction or complete closure of the connections to the sea, the establishment of very low oxygen levels in the lagoon and the prevalent deposition of the laminated wackestone facies (Fig. 14a). This hypothesis agrees with the model proposed by Papazzoni and Trevisani (2006). (2) During rapid transgressions seawater could have risen well above the coralgal rim, increasing the water exchange, improving the lagoon oxygenation and promoting the deposition of the non-laminated wackestone facies (Fig. 14b). (3) During sea-level highstands, the lagoon was progressively isolated, with the gradual re-establishment of anoxic conditions (Fig. 14c). This could have been mainly related to

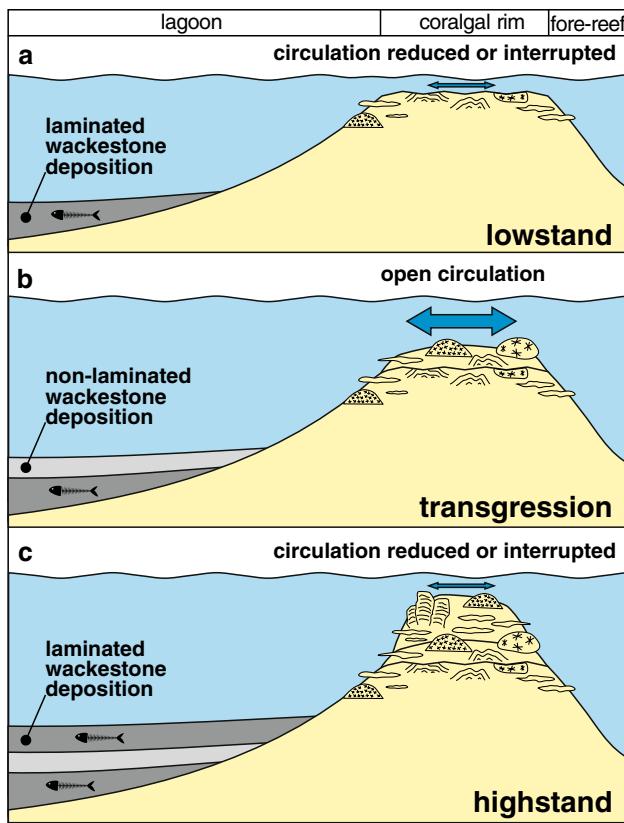


Fig. 14 Hypothetical evolution of the Monte Postale margin and its control over the lagoon depositional environment, explanation in the text

the euphotic adaptation of most of the coralgal rim biotic assemblage, that could have likely promoted the progressive aggradational of the reef structure towards the shallower depths.

Early Eocene coral assemblages and reef habitats

The early Paleogene (Paleocene and early Eocene) is usually considered as a transitional period for the evolution of coral reefs, placed between a time of rapid recovery and reorganization of reef ecosystems after the K/Pg crisis and a definitive flourishing phase represented by the Oligocene–Miocene (Perrin 2002; Kiessling and Baron-Szabo 2004). The early Paleogene warming trend culminated in the early Eocene climatic optimum (EECO, ~49–53 Ma; Luciani et al. 2016), the interval in which Cenozoic global temperatures reached their maximum under high atmospheric $p\text{CO}_2$ concentrations (e.g., Zachos et al. 2001, 2008; Payros et al. 2015; Slotnick et al. 2015). Recent studies were thus concentrated on the pressure that high temperature and other stressors exerted on coral assemblages and associated bioconstructions during the late Paleocene–early Eocene greenhouse (Scheibner and Speijer 2007, 2008; Zamagni et al. 2012).

Whereas the middle–late Paleocene is characterized by a peak of the global preserved volume of coral reefs, the earliest Eocene shows a marked decline (Kiessling and Baron-Szabo 2004). This coral reef gap has been interpreted as related to rising temperatures and extreme environmental conditions that greatly affected zooxanthellate-coral development and probably favored the expansion of marginal settings where corals evolved with a limited frame-building capacity (Scheibner and Speijer 2007; Zamagni et al. 2012).

The upper Ypresian coralgal bioconstructions of Monte Postale developed near the end of the EECO interval (sensu Slotnick et al. 2015; Luciani et al. 2016). The composition of the reef-building biota reveals strong similarities with the middle Paleocene counterparts: a moderate diversity (up to 16 genera), the dominance of massive *Actinacis* together with a strong contribution of the solenoporacean alga *Parachaetetes* and the occurrence of ramosae and phaceloid growth forms. This biotic association was able to form small reef structures within shallow-water and high hydrodynamic conditions when global sea temperatures just started to cool but were still high (Zachos et al. 2001). The Monte Postale coralgal reef system highlights that z -coral communities were able to adapt, and colonize shallow-water environments, during the early Eocene global warming phase, thus preserving the potential to flourish and increase their frame-building capacity from the middle–late Eocene, with more favorable climatic conditions.

Conclusions

This study provides a reconstruction of the stratigraphic architecture of the Monte Postale area, combined with new integrated biostratigraphic data and detailed facies analysis. These data allow the first detailed reconstruction of the coralgal-dominated depositional system associated to the formation of one of the most important Eocene *Fossil-Lagerstätte* in the world. In particular:

1. On the basis of the *Alveolina* assemblages and calcareous nannofossils associations, the Monte Postale succession is firmly ascribed to the upper Ypresian.
2. Three facies associations have been recognized: a narrow coralgal rim (1), roughly oriented E/W, separating lagoon deposits (2) in the south from fore-reef sediments (3) in the north, the latter representing a transition towards the open-marine environment. In particular, the coralgal rim reveals the occurrence of a complex environment, where scleractinian corals, calcareous algae and encrusting foraminifera, together with *Alveolina* accumulations, contributed to the formation of a wave-resistant, shallow-water structure interspersed by channels and protected areas.

3. A close correlation has been recognized between the nature of the biotic assemblage and the possibility, by the corallal rim, to act as an effective barrier. The abundance of heavily calcified organisms was essential in the formation of a robust, wave-resistant threshold, while the euphotic adaptation of most of the reef-related taxa contributed to keep the growth of this structure within an extremely shallow-water setting.
4. Although our data do not allow a precise reconstruction of how the evolution of the corallal rim influenced the water exchange between the lagoon and the open sea, it is possible to speculate three different depositional phases, associated to relative sea-level fluctuations. Sea-level lowstands or highstands may have limited or interrupted the water connections, supporting the deposition of laminated wackestones and the preservation of vertebrate and terrestrial plants remains. On the contrary, transgressions may have established a more open circulation, with the sedimentation of non-laminated wackestones barren in macrofossils.
5. The Monte Postale succession represents one of the very few examples of lower Eocene reef depositional system. Even if further studies are necessary, the detailed description of the biotic assemblage provides new information on the structure of reef communities during a crucial climatic phase, near the end of the EECO global warming.

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