Solid Earth Discuss., 3, 901–942, 2011
www.solid-earth-discuss.net/3/901/2011/
doi:10.5194/sed-3-901-2011

Solid Earth Discussions

Shallow water carbonate platforms (Late Aptian, Southern Apennines) in the context of supraregional to global changes

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Received: 10 October 2011 – Accepted: 18 October 2011 – Published: 21 October 2011

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

A preliminary study based on the comparison of recently published $\delta^{13}C$ record of the Late Aptian Monte Tobenna and Monte Faito sections (Southern Italy) with reference carbon isotope curves reveals how sea-level fluctuations played a fundamental role in regolating the carbonate sedimentation in the inner lagoonal environments of the Apenninic platform and the occurrence of some peculiar facies during a time of increasing volcano-tectonic activity and trophic levels of the water.

During the lowering of the sea level, microbial carbonates were a common product of the shallow marine ecosystem in a general context of deterioration of the inner lagoon environmental conditions. When trophic levels were too high, due to the decisive contribution of a supraregional dictator (e.g. increase of the precipitation rate), and the environmental conditions were unsuitable for the main carbonate producers of the inner lagoonal settings, the Orbitolina (*Mesorbitolina parva* and *Mesorbitolina texana*) level formed, just before the minimum accommodation space on the platform was reached and fresh/brackish water environments spread. In deposits underlying the orbitolinid-rich facies of the carbonates studied, *Salpingoporella dinarica* alga is widespread, possibly due to the seawater's chemical composition that could have encouraged the development of its low-Mg calcite skeleton.

On the contrary, during periods of sea level rise (and early highstand) no or minor microbial carbonates formed in the shallow lagoonal settings that were not influenced by the paleoenvironmental changes mostly induced by the mid-Cretaceous volcanism, and therefore easily remained in a healthy state.

1 Introduction

The shallow-marine carbonate platforms are complex depositional settings whose biota essentially represents the source of most of the sediment. They are highly sensitive to short-term climatic and oceanographic changes and sea level oscillations, since carbonate-precipitating organisms only thrive under specific ecological conditions (Schlager et al., 1988; Jones and Desrochers, 1992; Demicco and Hardie, 1994; Philip, 2003; Schlager, 2003; Hallock, 2005; Stanley, 2006). Therefore, changes in the sedimentary pattern, characterized by different biotic communities now forming laterally-wide isochronous strata, may reflect physico-chemical changes in the seawater (temperature, salinity, light, nutrients) induced by regional-to-global paleoenvironmental perturbations. This could be the case, for example, of the so-called "Orbitolina level", a biostratigraphic marker encased in the Late Aptian (Gargasian) shallow water carbonate strata cropping out in the Central-Southern Apennines and, possibly, coeval with other similar strata deposited around the western Tethys (e.g. Ruiz-Ortiz and Castro, 1998; Pittet et al., 2002; Castro et al., 2008; Vincent et al., 2010). This level is known in literature for a long time (Costa, 1866; Guiscardi, 1866), is usually well visible in the field – being often green-to-grey coloured – and shows skeletals almost exclusively represented by flat conical orbitolinids in association with calcareous algae, rare pelecypod shells and echinoderms (De Castro, 1963; Cherchi et al., 1978; Raspini, 1998).

Although the lithological and paleontological features of the "Orbitolina level" of the Southern Apennines have been accurately described (e.g. De Castro, 1963; Cherchi et al., 1978), no documentation exists on a number of fundamental questions such as the striking concentration of orbitolinids in just a few beds and the relative paleoenvironmental significance. In other sections of the western Tethys and the North Atlantic, orbitolinid-rich facies formed at different stratigraphic intervals and deposited, even contemporaneously, from very shallow-marine environments (in the Vercors platform, France, the eastern Arabian and northeastern African plates including offshore Abu Dhabi, Ethiopia, southwest Iran, Oman, Somalia, Yemen, the eastern Levant Basin and in the Lusitanian Basin, Portugal; Arnaud-Vanneau and Arnaud, 1990; Pittet et al., 2002; Bachmann and Hirsch, 2006; Burla et al., 2008; Schroeder et al., 2010; Vincent et al., 2010) to deeper, sand-dominated settings (in SE Spain; Vilas et al., 1995; Castro et al., 2008). This implies that orbitolinid-rich facies cannot be directly related to

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a specific paleoenvironmental setting on carbonate platforms and may correlate over hundreds-to-thousands of kilometres, suggesting a possible link to regional or supraregional events (Pittet et al., 2002; Burla et al., 2008).

According to several authors, clayey-to-marly strata rich in flat-conical orbitolinids indicate an important deterioration of the paleoenvironmental conditions, reflecting increased nutrient supply and high-trophic levels of the waters that influenced the evolution of shallow carbonate platforms (e.g. Vilas et al., 1995; Bachmann and Hirsch, 2006; Burla et al., 2008; Schroeder et al., 2010). This change in sedimentation pattern may represent the reaction of the shallow carbonate ecosystem to paleoenvironmental perturbations that occurred during the mid-Cretaceous, when the global warming – induced by increased geodynamic activity and massive injection of carbon dioxide in the ocean-atmosphere system (e.g. Larson and Erba, 1999; Jahren, 2002; Hu et al., 2005; Najarro et al., 2011) – accelerated the water cycling and increased weathering rates, resulting in high nutrient transfer from continents to oceans (e.g. Wissler et al., 2003; Weissert and Erba, 2004; Wortmann et al., 2004). An elevated supply of nutrients reduces water transparency and destabilizes oxygen levels and pH, leading to changes in platform communities (Hallock and Schlager, 1986; Mutti and Hallock, 2003; Heldt et al., 2010) and to the blooming of mesotrophic to eutrophic fossil assemblages (Bachmann and Hirsch, 2006; Föllmi et al., 2006; Burla et al., 2008).

By integrating an accurate sedimentological analysis of the Aptian shallow water carbonates of the Southern Apennines with the related carbon-isotope stratigraphy – framed within global trends – it may be possible to shed light on the paleoenvironmental meaning of the "Orbitolina level" and other peculiar facies showing an opportunistic faunal content (microbial carbonates and *Salpingoporella dinarica*-rich facies) that deposited during a time punctuated by faunal, tectonic and environmental events that also resulted in Tethyan carbonate platform drownings (Föllmi et al., 1994; Pittet et al., 2002; Takashima et al., 2007) and concomitant changes in calcareous nannoplankton assemblages (e.g. Herrle and Mutterlose, 2003).

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With this aim, the formerly identified facies evolution along the Monte Tobenna and the Monte Faito shallow-marine carbonate sections (Southern Apennines, Italy; Raspini, 1998, 2001; D'Argenio et al., 1999) is compared with the related trends of δ^{13}C values derived from recently published data (D'Argenio et al., 2004).

Although D'Argenio et al. (2004) evidenced relationships between positive shifts in δ^{13}C recorded in four coeval sections and oceanic perturbations of the carbon cycle, they never discussed if and how the Aptian paleoenvironmental and palaeoceanographic changes (e.g. Weissert and Lini, 1991; Mutterlose, 1998; Friedrich et al., 2003; Takashima et al., 2007; Heldt et al., 2010) influenced the shallow-water carbonate factory of the platform which developed on the southern Tethyan margin and now forms the backbone of Southern Apennines as large ($\leq 10^4$ km^2), thick (even >3–4×10^3 m) and well stratified sedimentary bodies.

2 Geological setting

The carbonate successions discussed in this study consist of well-bedded and laterally continuous beds deposited on the southern margin of the Mesozoic Tethys (Fig. 1). This margin was characterized by the development of a broad, intraoceanic carbonate domain (Apenninic Carbonate Platform; Mostardini and Merlini, 1986) that was part of a larger and articulated carbonate platform-basin system (e.g. Patacca and Scandone, 2007). The tectonic evolution of this area included a phase of continental rifting at the northern edge of the African craton during the Triassic – Early Jurassic, an Early Jurassic (Middle Liassic) – Late Cretaceous/Eocene oceanic rifting accompanied by passive margin formation, and a continental collision (with Eurasia) in the Late Cretaceous/Eocene to Holocene (Zappaterra, 1994; Korbar, 2009; Vezzani et al., 2010). This latter originated a pile of thrust sheets composed by the Apennine carbonate platform and encasing basinal sediments (Casero et al., 1988; Mazzoli et al., 2001). Following the opening of the Tyrrhenian back-arc basin during the Miocene, the pile of thrust sheets rotated counterclockwise (Scheepers and Langereis, 1994; Gattacceca

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and Speranza, 2002) and was ultimately thrust onto the Apulian Carbonate Platform whose undeformed part currently represents the foreland of the Southern Apennines fold-and-thrust belt (Argnani, 2005).

3 The studied sections

The stratigraphically lower section crops out at Monte Tobenna, near the village of S. Mango Piemonte (Picentini Mountains, Campania Apennines; Fig. 1), and is part of a succession composed of Mesozoic-Tertiary rocks, the most ancient of which are Triassic in age. The section is 30 m thick and encloses the "Orbitolina level", a well known upper Aptian (middle Gargasian) litho and biostratigraphic marker in the carbonate platform successions of the Southern Apennines, rich in *Mesorbitolina parva* and *M. texana* (De Castro, 1963, 1991; Cherchi et al., 1978; see also Chihaoui et al., 2010; Schroeder et al., 2010).

The second section crops out along the panoramic road from Vico Equense to Monte Faito (Lattari Mountains, Sorrento Peninsula; Fig. 1) and is located more than 30 km west the Monte Tobenna outcropping. The section (54 m thick) is part of a 400 m-thick succession spanning the upper Hauterivian to the Albian (Robson, 1987) and starts at about 8 m above the "Orbitolina level". The upper part reaches the Aptian/Albian boundary as testified by the first occurrence of *Ovalveolina reicheli* (De Castro, 1991; Chiocchini et al., 1994; Bravi and De Castro, 1995; Husinec et al., 2000, 2009) approximately 50 m above the orbitolinid-rich biostratigraphic marker. Also, high conical orbitolinids have also been found at 48 m from the base of the section. The interval proposed here overlaps the Monte Tobenna section for approximately 6 m and makes it possible to obtain the "Tobenna-Faito composite section" with a total thickness of approximately 78 m.

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4 Facies analysis

Field observations and microfacies analysis performed on 267 thin sections allowed the identification of eight lithofacies, grouped in the following lithofacies associations that, on the whole, represent products of deposition in inner lagoonal settings with a discontinuous belt of submerged shoals (Raspini, 1998; D'Argenio et al., 1999; Raspini, 2001): A – Bio-peloidal limestones; B – Mili-ostracod limestones; C – Char-ostracod limestones. Table 1 lists the lithofacies and lithofacies associations recognized in the Tobenna-Faito composite setion and their environmental interpretation (see also Figs. 2 and 3).

Graded intra-bio-peloidal deposits forming cm-thick intercalations between the lithofacies, with basal erosional contact and normal gradation, are interpreted as the product of storm events that affected the depositional settings in which the lithofacies formed.

Green clayey layers have been found between most beds. These layers can include small carbonate lenses, composed of charophyte wackestone, or contain intraclasts of cryptalgal bindstone or charophyte wackestone reworked from underlying beds. Generally, the lenses and intraclasts show features related to emersion. The top of some charophyte-bearing beds may show cm-thick microbreccia-layers formed of a few mm-sized clasts set in a downward-percolated, unfossiliferous green clayey matrix occurring with a geopetal arrangement.

Emersion-related features are represented by scattered dissolution cavities of irregular shape and less than 1 mm in size with geopetal infills and/or, more rarely, by pervasive silt related to dissolution phenomena. At 22 m along the section, a characteristic microbrecciation consisting of mm-size intraclasts formed of char-ostracod limestones set in a downward-percolated green clayey matrix occurs (Fig. 2g). The microbreccia is very similar to the examples described by Riding and Wright (1981) in the palaeosols of the Lower Carboniferous in southern Britain, and has been interpreted as related to wetting and drying processes producing mm-size intraclasts which give rise to an in

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situ breccia. Calcitic structures comparable to *Microcodium* (cf. Košir et al., 2004) have only been found at 76 m of the composite section (Fig. 2h).

4.1 Peculiar facies of the Tobenna-Faito section

Particular attention has been paid to the analysis of some facies showing peculiar field appearance and/or fossil content: the "Orbitolina level", the lithofacies B4 and B3 and the *Salpingoporella dinarica*-rich strata.

4.1.1 The "Orbitolina level"

The "Orbitolina level" crops out about 17 m from its base. The marker lies above a green clayey level, 25 to 45 cm thick, containing carbonate lenses with ostracods and charophytes (Fig. 3a, b). The level is composed of two beds. The lower bed ranges from about 105–160 cm, features a clayey content that gradually diminishes upward, and shows a wavy base and a typical nodular appearance due to differential compaction, cementation and stylolitization. It can not be excluded, therefore, that this bed originally consisted of several thin layers which are now amalgamated. The upper portion is 10–15 cm thick, shows an erosional base and represents the type-level of the codiacean alga *Boueina hochstetteri moncharmontiae* (De Castro, 1963; Barattolo and De Castro, 1991).

Normally the texture of the "Orbitolina level" is a floatstone with a packstone matrix, but a grainstone matrix occurs in the upper bed. Furthermore, at the base of the upper bed, fossils are mostly arranged horizontally above an erosive surface. Bioeroded pelecypod shell fragments showing a micritic envelope, echinoderm fragments, and dark muddy intraclasts or others composed of cryptalgal bindstone, have been recognized in thin section together with various species of Orbitolina, mostly *Mesorbitolina texana* and subordinately *Mesorbitolina parva* (Cherchi et al., 1978; Barattolo and De Castro, 1991; Bravi and De Castro, 1995), often showing framboidal pyrite on their shell. *Salpingoporella dinarica* (sometimes broken), *Thaumatoporella* sp., *Boueina hochstetteri*

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moncharmontiae, peloids and benthic foraminifers may also be found. Orbitolina floatstone with a marly matrix penetrates downward to about 150 cm into the carbonate strata, filling the underlying complex network of *Thalassinoides*-like burrows that feature lagoonal and fresh/brackish water deposits (Fig. 4c). In thin section, evidence of emersion-related features have been found only in characean facies on which the orbitolinid-rich bed lies.

Based on the observations above and on interpretation of the underlying sediments, the "Orbitolina level" of the Monte Tobenna sequence represents transgressive deposits (Raspini, 1998).

4.1.2 Microbial carbonates

In the field, lithofacies B4 is dark brown in colour and characterized by wavy (sometimes slightly crinkled) laminae, locally forming low-amplitude hemispheroids (Fig. 3d and e). It crops out in thicknesses ranging from 1–25 cm, generally at the top of beds but underlying green clayey levels. In thin section, irregular and frequently discontinuous mm-thick micritic laminae, probably cryptalgal in origin (Riding, 2000), occur, generally containing rare ostracods. The laminae alternate with mm-thick packstone and/or packstone/wackestone layers with peloids, and frequently contain small "subrounded grains" showing chamber-like partitions (Fig. 3f), *Thaumatoporella* sp. and rare ostracods.

Lithofacies B3 is a tanned limestone with numerous dark-orange, mm-sized patches, *Thaumatoporella* sp. and rare small ostracods (Raspini, 1998). Occasionally, small benthic foraminifers (especially miliolids) may also occur in this lithofacies, which crops out in thicknesses ranging from 7–50 cm. In thin section, mm-sized patches appear as microsparitic clots that are frequently associated with the small "subrounded grains" found in cryptalgal bindstones (Fig. 3f), and/or with "filamentous elements" showing several partitions and a final circular aperture (Fig. 3g).

Both lithofacies frequently show a clotted microfabric, consisting of irregular micritic peloidal aggregates surrounded and traversed by microspar (clast in Fig. 3b; cf. Riding,

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2000), or display a microspar groundmass, and are rich in *Thaumatoporella* sp. Both the "subrounded grains" and the "filamentous elements" frequently show an orange-brown isopachous microsparitic rim and are locally concentrated in small groups. Their general morphology and internal structure resemble those of some microbes (Brock et al., 1994; Kaźmierczak and Iryu, 1999; Whalen et al., 2002; Golubic et al., 2006; Herrero and Flores, 2008), to which the thaumatoporellaceans have also recently been ascribed (Cherchi and Schroeder, 2005).

Based on the above observations, the lithofacies B4 and B3 are interpreted as deposits mainly produced by microbial growth and metabolism in restricted lagoonal environments. If this is the case, the clotted microfabric of these deposits could represent calcification of extracellular polymeric substances widely produced by microbes (Riding, 2000).

4.1.3 *Salpingoporella dinarica*-rich deposits

Salpingoporella dinarica is a calcareous alga that was isochronous in the central-southern Tethyan Domain (including the Southern Caribbean Province) with its acme occurring in the Aptian (e.g. Vlahović et al., 2003; Carras et al., 2006). At Tobenna-Faito this calcareous algae is distributed in the first 30 m of the composite section, in both restricted and more open lagoonal deposits; rarely, broken tests have been also found in the char-ostracod limestones. *S. dinarica* shows its maximum abundance below the orbitolinid-rich strata (at 7.5–13.7 m from the base; Figs. 3h and 4), although a mm-thick storm layer formed only of this green alga and peloids has been found in the bed immediately above the biostratigraphic marker.

5 Cyclic stratigraphy

The study and interpretation of lithofacies and lithofacies associations and related early diagenetic overprint formed the basis for the identification of bed-scale cycles that are hierarchically stacked into bundles (groups of 2–5 bed-scale cycles) and superbundles (groups of 2–4 bundles; Fig. 4), as can also be clearly seen in the field. The hierarchical stacking pattern of cycles was interpreted as forced by composite eustatic sea-level fluctuations driven by the astronomical beat in the Milankovitch band. The bed-scale cycles correspond to the 20 ky precession cycle, while the bundles and the superbundles correspond, respectively, to the short (∼100 ky) and the long (∼400 ky) eccentricity signals (Raspini, 1998, 2001; D'Argenio et al., 1999). Spectral analysis provided further independent confirmation of the cyclical nature of the Cretaceous shallow-marine carbonates cropping out in the same region of the Southern Apennines (Pelosi and Raspini, 1993; Longo et al., 1994; Brescia et al., 1996; D'Argenio et al., 1997).

A few metres above the "Orbitolina level" and up to about 28 m from the base of the interval studied, no clear hierarchical organization of cycles could be recognized and characean-rich deposits reach their greatest abundance, testifying to a long-lasting low stand of the relative sea-level and consequent cycle condensation. Nevertheless, some bed-scale cycles, composed of restricted lagoonal deposits, record higher frequency sea-level oscillations temporarily allowing for subtidal conditions.

Along the composite section, lithofacies trends within the superbundles frequently show a transgressive/regressive evolution. This permitted the description of superbundles in terms of sequence stratigraphy and the identification of maximum flooding, transgressive and highstand deposits (Fig. 4). D'Argenio et al. (1999) were able to trace and correlate the major exposure surfaces and maximum floodings recognized in the Tobenna-Faito composite section over more than 100 km along the Apennine carbonate platform, defining a similarity in the facies evolution of coeval superbundles and a relationship among their thickness. This reveals a superposition of the hierarchically stacked cyclic units on lower frequency environmental oscillations that reflect longer-term changes in accommodation space shown by the systematic variation of superbundle thickness in tune with the larger-scale vertical evolution of lithofacies and their diagenetic overprint (e.g. Goldhammer et al., 1990; Raspini, 2001; Sandulli and Raspini, 2004; Tresch and Strasser, 2010; Fig. 4). The fact that superbundles have

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been correlated over long distances along the Apennine carbonate platform is a strong argument that processes other than local tectonic activities or local changes in sediment accumulation must have been involved in the systematic variation of superbundle thickness and accommodation space along the correlated sections (D'Argenio et al., 1999; Pittet et al., 2002; Sandulli and Raspini, 2004).

In the Tobenna-Faito section, the progressive thinning-upward of superbundles, coupled with the general trend of facies from subtidal to supratidal settings culminating with the greatest abundance of fresh/brackish water sediments, imply an overall decrease of the accommodation space on the shelf that ends, a few meters above the "Orbitolina level", in a Sequence Boundary Zone (SBZ 1 in Fig. 4). Similarly, after the shift towards the most-open marine lithofacies with minor evidence of emersion-related features – that mark a period of maximum accommodation space and define the maximum flooding zone (mfz in Fig. 4) – the predominance of more inner lagoon sediments forming bed-scale cycles that more frequently show exposure features at their top, together with the progressive thickness decrease of the superbundles, suggest a gradual loss of accommodation culminating with the sequence boundary SB2 that corrresponds to the top of the thinnest superbundle of the Monte Faito section, close to the Aptian-Albian transition (Fig. 4). Obviously, zones of minimum accommodation space on the platform represent the most predictable locations of possible gaps in the stratigraphic record of shallow marine carbonates due to non-deposition and/or erosion (Sandulli and Raspini, 2004; Tresch and Strasser, 2010).

6 Chemostratigraphy

The carbon and oxygen stable isotope record of the Tobenna-Faito composite section used in this study is that published by D'Argenio et al. (2004), who obtained the $\delta^{13}C$ and $\delta^{18}O$ values from bulk samples selected from specimens collected during the sedimentological and cyclostratigraphical study of the Monte Tobenna and Monte Faito successions carried out between 1992 and 1995 (Raspini, 1998, 2001). The C and O

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isotope composition of samples was measured with a VG Micromass-903 mass spectrometer or on a fully automated VG Prism mass spectrometer, that analysed the CO_2 derived by reactions with 100 % phosphoric acid at 50 °C. Reproducibility was ±0.1 ‰ for $\delta^{13}C$ and ±0.2 ‰ for $\delta^{18}O$ (for details on the analytical procedure, please refer to D'Argenio et al., 2004).

The whole carbon isotope curve can be subdivided into five segments (I-to-V in Fig. 4). In segment I (3–25 m), $\delta^{13}C$ is characterized by high-amplitude fluctuations (1.8–4 ‰) and defines a trend that culminates with the negative spike (falling limb) of −1.57 ‰, above the Orbitolina level, where clayey and characean-rich deposits reach their greatest abundance. In segment II (25–40 m) carbon isotope values climb to the positive spike of 4.30 ‰, which parallels a clear facies change from supratidal to subtidal settings with minor meteoric diagenesis recorded in both the Tobenna and Faito sections (Figs. 4). In segments III and IV, on the whole, $\delta^{13}C$ defines a falling limb with varying features: segment III shows sets of $\delta^{13}C$ positive values that decline slowly, oscillating between 3.66 ‰ and 2.42 ‰, while segment IV is characterized by high-amplitude fluctuations (1.7–3 ‰) of carbon isotope values that culminate in a negative spike of −0.58 ‰. Finally, in the last part of the composite section (segment V), after a spike of 2.37 ‰, the $\delta^{13}C$ curve shows low-amplitude fluctuations around an average value of 1.28 ‰, still defining a trend toward lower values.

Although most of the $\delta^{13}C$ values are between 0.45 ‰ and 2.85 ‰ regardless of the different lithofacies associations, it cannot be excluded that the negative $\delta^{13}C$ values between 16–25 m and at 69 m of the composite section (Fig. 4) reflect ^{12}C enrichment of the whole rock carbonate during early diagenesis, and/or are a consequence of a change in the depositional environment and a shift to lower $\delta^{13}C$ values for DIC in the lagoonal waters (Patterson and Walter, 1994; Vahrenkamp, 1996; Holmden et al., 1998; Fanton and Holmden, 2007).

Besides the high-amplitude fluctuations of some carbon isotope values in the lower and upper part of the Tobenna-Faito section, there are clear C-isotopic trends that persist along intervals tens of metres thick and across changes of lithofacies associations, suggesting that they are not induced by local variations of environmental conditions. Moreover, the above trends of $\delta^{13}C$ values are also recorded in coeval sediments cropping out in the Serra Sbregavitelli succession, that is now located more than 100 km from the Faito section and encases the orbitolinid-rich biostratigraphic marker (D'Argenio et al., 2004; Fig. 5a), claiming a forcing at least on a regional scale.

The curves that represent the main trends of $\delta^{18}O$ values of Tobenna-Faito and Serra Sbregavitelli are qualitatively well comparable (Fig. 5b), regardless of diagenetic effects and freshwater inputs the oxygen isotope absolute values locally suffered (e.g. in the upper part of both sections, where repeated emersion-related features occur, and around the "Orbitolina level" at Tobenna-Faito, where characean-rich deposits are diffused) and this lends further support to the regional correlation of Fig. 5a.

In Fig. 6, the trends of $\delta^{13}C$ values of Tobenna-Faito and Serra Sbregavitelli sections are plotted against reference curves of the Tethys (Weissert et al., 1998), Atlantic (Scholle and Arthur, 1980; Bralower et al., 1999) and Pacific (Jenkyns and Wilson, 1999). The trend of decreasing C-isotope values recorded at the base of the Apenninic carbonate sections and culminating above the "Orbitolina level" of the upper Aptian (middle Gargasian) should correspond to the global trend of decreasing $\delta^{13}C$ values in the *G. ferreolensis* to *G. algerianus* zone (Weissert et al., 1998; Weissert and Erba, 2004), whose overall shift is of approximately 2 to 3 ‰ in the selected reference curves. The subsequent long-lasting positive excursion to values of 3–4 ‰ starting in the *G. algerianus* zone is consistent with the shift toward positive $\delta^{13}C$ values defining segment II at Tobenna-Faito (Fig. 4).

7 Discussion

7.1 Response of the shallow carbonate platform to the Late Aptian supraregional changes: the "Orbitolina level"

The comparison between long-term trends of $\delta^{13}C$ values of the Tobenna-Faito and Serra Sbregavitelli sections with reference carbon isotope curves of the Aptian

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(Weissert et al., 1998; Scholle and Arthur, 1980; Bralower et al., 1999; Jenkyns and Wilson, 1999; Fig. 6) permits a possible definition of the paleoenvironmental significance of the "Orbitolina level" of the Southern Apennines within the complex pattern of environmental changes that led to modification of the carbon cycle during the lower Cretaceous as recorded on a global scale (Weissert and Lini, 1991; Takashima et al., 2007; Heldt et al., 2010). In fact, the "Orbitolina level" of the middle Gargasian could, in all likelihood, have settled on the shallow carbonate platform during the deposition of part of the "Niveau Fallot" in a hemipelagic setting connected to the Tethyan Ocean (Friedrich et al., 2003) when the sea level was falling (Haq et al., 1987; Herrle and Mutterlose, 2003; Takashima et al., 2007). A fall in the sea level is accompanied by erosion, seaward transport and oxidation of carbon-rich sediments and, therefore, by a drop in the carbon isotope values (Jenkyns et al., 1994) as is the case for the decrease in $\delta^{13}C$ values of the reference curves in the *G. ferreolensis* to *G. algerianus* zone (Weissert et al., 1998; Bralower et al., 1999; Jenkyns and Wilson, 1999). The Niveau Fallot contains black shales that suggest an enhanced burial of organic matter due to more eutrophic conditions and/or low oxygen conditions at the seafloor (Friedrich et al., 2003).

In the shallow water carbonate strata studied in the Apennines, the vertical evolution of the Late Aptian facies suggests that the "Orbitolina level" also settled during a time of longer-term lowering of the sea level, although it represents large part of the transgression during a superimposed higher-frequency sea-level changes (precessionally-controlled bed-scale cycles; Raspini, 1998; Fig. 4). Moreover, in the Tobenna section at the top of bed-scale cycles, mm- to dm-thick green clayey layers occur from 3 m upward, locally including charophyte-bearing carbonates. The clayey layers show a progressive thickening-up that cuminates with a 40 cm-thick layer located in the middle of an interval showing the maximum abundance of charophyte-rich facies at the top of the studied outcrop, suggesting that a minimum accommodation space on the platform was reached a few meters above (SBZ 1 in Fig. 4).

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In proximal areas of the Apenninic platform (Tobenna-Faito), the 115–175 cm-thick "Orbitolina level" shows an exceptional concentration of flat conical foraminifera. Their high alteration level suggests that the high shelliness of the biostratigraphic marker was possibly related to a reduced rate of sedimentation, rather than to a high population density of shell producers (Kidwell, 1985, 1986; Tomašových et al., 2006), as also testified by *Thalassinoides*-like burrows infilled by marly orbitolinid-rich sediment (Fig. 3a–c). In distal areas of the carbonate platform (Serra Sbregavitelli) orbitolinids are contained in a 150 cm-thick calcareous bed with no (or minor) clayey content, are not crowded as at Tobenna-Faito and are associated with dasycladacean algae, miliolids and echinoderm fragments, suggesting a possible relationship between abundance of orbitolinids and detrital influx. However, the association of flat conical orbitolinids with calcareous algae and echinoderms suggests high trophic conditions (Pittet et al., 2002). Also, considering that the Aptian orbitolinid-rich strata may correlate over hundreds-to-thousands of kilometres around the western Tethys (e.g. Bachmann and Hirsch, 2006; Castro et al., 2008; Vincent et al., 2010), a link to supraregional changes (i.e. which do not only affected the Apenninic carbonate platform) appears to be plausible.

According to Hottinger (1982) orbitolinids lived in symbiothic relationship with photosynthetic algae and, therefore, were considered light-dependent foraminifera. Conversely, other authors have put forward the idea that flat conical orbitolinids have an adaptative trend to ligh reduction with depth – the shallow water forms being smaller and higher that the deeper water ones – and are tipically found in marly/clayey limestones because they throve under conditions of high nutrient supply (Vilas et al., 1995; Pittet et al., 2002; Burla et al., 2008). During the Aptian high nutrient supply to the oceans may have been triggered by increased amounts of carbon dioxide in the atmosphere and ocean basins as a result of the increased tectonic activity and changing paleogeography (cf. Weisset and Erba, 2004). This would have resulted in mesotrophic or eutrophic conditions on carbonate platforms and created perfect conditions for the spread of an opportunistic fauna rich in orbitolinids also featured in the stratigraphic record of the sections studied (cf. Burla et al., 2008).

Recently some authors have suggested that climate variations during the Aptian were a matter of a few degrees and pCO_2 changes of minor importance (e.g. Haworth et al., 2005). Therefore, one would assume minor environmental changes on the shelves which do not agree with the deposition of the 115–175 cm-thick marly sediment with a striking concentration of flat conical orbitolinids encased in the stratigraphic record of a shallow carbonate platform (e.g. Pittet et al., 2002). In addition, though oxygen isotopes are sensitive to diagenesis (and thus often are not reliable tools; Brand and Veizer, 1981) and the resolution of the sampling is rather low, both the reproducibility of δ^{18}O main trends of Tobenna-Faito at a regional scale (Fig. 5b) and the good comparison with reference δ^{18}O curves (Clarke and Jenkyns, 1999; Fassel and Bralower, 1999; Mutterlose et al., 2009; Fig. 7), suggest that the main trends can be plausibly regarded as indicative of excursions of the isotopic composition of the sea water and, consequently, that the "Orbitolina level" settled during a long-term global climate cooling, similarly to the Niveau Fallot in the hemipelagic setting (Takashima et al., 2007).

It is therefore plausible that a mechanism other than volcanic activity, in conjunction with sea level changes, played a decisive role in amplifying the high trophic levels of surficial waters and determining the overall paleoenvironmental deterioration, thus producing definitive stress in the carbonate neritic ecosystem that fostered the settlement of the "Orbitolina level" on the Apenninic carbonate platform.

Examination of the paleogeographic position of the Early Cretaceous Tethys Ocean shows that it was situated between two distinct climate regimes: the southern part of the ocean were affected by the tropical low-pressure system, while the northern parts were dominated by the subtropical high-pressure system (TL and STH, respectively, in Fig. 1; Price et al., 1995; Wortmann et al., 1999). The dry climate and the trade wind system in all probability caused extremely high evaporation rates and, in turn, warm and saline surface waters just north of the Apulia and Apenninic carbonate platforms. It has been suggested that the evaporation rates were sufficient to trigger warm deepwater formation in the shelf areas of the western Tethys Ocean (Barron and Peterson, 1989; Wortmann et al., 1999), where a strong monsoonal circulation may have existed (Oglesby and Park, 1989). This induced changes in the precipitation/evaporation rates on a precessional time scale, increase in wind stress (with higher surface water productivity; Herrle et al., 2003) and, in times of increased precipitation and runoff, a higher nutrient supply to the sea. The relative decrease in evaporation may have also led to a reduction of deep water formation, with oxygen depletion on the seafloor. Both the conditions were able to foster the deposition of black shales in deep water settings (e.g. the Niveau Fallot in the Vocontian Basin; Friedrich et al., 2003). The monsoonal activity of the mid-Cretaceous low latitudes has, however, also been shown by modelling (Oglesby and Park, 1989) and paleoceanographic studies (Wortmann et al., 1999).

Under such a scenario, during the Gargasian, a period of enhanced precipitations and wind stress may have induced a strong reworking of the organic matter (including cm-to-dm-thick clayey deposits at Tobenna-Faito) which was forming over an ever wider area of the exposed platform during the longer-term sea level lowering. This increased the detrital influx and the nutrient levels that were detrimental to carbonate platform development (Hallock and Schlager, 1986; Hallock, 1988), as also documented in modern carbonate environments (Delgado and Lapointe, 1994). Nutrification was also associated with increased rates of bioerosion that further reduce rates of carbonate accumulation (Hallock, 1988). Therefore, during the transgressive phase of high-frequency sea level changes following a period of interrupted (or very low) sedimentation, the stressed shallow lagoonal ecosystem finally responded with the development of orbitolinid-rich fauna that filled *Thalassinoides*-like burrows in the underlying deposits (Figs. 3c and 4).

As previously stated, the shelf areas of the western Tethys during the mid-Cretaceous were influenced by monsoonal cycles which led to changes in the precipitation/evaporation rates on a precessional time scale (e.g. Wortmann et al., 1999). The 20 ky cycle controlled the organization of the bed-scale facies along the Tobenna-Faito composite section (Raspini, 1998; D'Argenio et al., 1999); thus, the marly "Orbitolina

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level", that represents approximatively 75 % of a bed-scale cycle, may reflect the precipitation changes within the precessional cycle.

Accordingly, the Late Aptian "Orbitolina level" of the Southern Apennines is essentially interpreted here as the response of the lagoonal ecosystem to high trophic levels in the sea triggered by supraregional events (the monsoonal activity) that occurred at low latitudes and probably also superimposed on a global dictator (the volcanic activity; Coffin et al., 2002, 2006; Takashima et al., 2007), amplifying its effects during a long term fall of the sea level.

7.2 Response of the shallow carbonate platform to the Late Aptian global events: microbial carbonates

Although the weathering rates due to the injection of CO_2 in the ocean-atmosphere system probably only contributed to the deposition of the "Orbitolina level" of the Southern Apennines, several authors have suggested that the volcanic activity increased during the Late Aptian (Bralower et al., 1997; McArthur et al., 2001; Coffin et al., 2002). It is not excluded, therefore, that the effects of such increasing activity on a global scale (Weissert and Erba, 2004; Kuroda et al., 2011; Najarro et al., 2011) may have influenced the sensitive carbonate factory of the Southern Apenninic platform, leading to the settlement of other peculiar shallow-water facies distributed along the sections studied.

It is possible, for example, that the progressive enhancement of the continental weathering, due to the the acceleration of the global water cycling, was able to cause an increase of dissolved Ca^{2+} and HCO_3^- in the ocean (Kump et al., 2000) which may potentially have facilitated a microbial colonization on large areas of the shallow water environments (Kaźmierczak and Iryu, 1999; Whalen et al., 2002; Rameil et al., 2010). Microbes are, in fact, important contributors within the carbonate system during times of environmental changes and biotic crisis (Whalen et al., 2002). They are able to use HCO_3^- instead of CO_2 as a major source of carbon (Miller et al., 1989; Kaźmierczak et al., 1996) and develop well under high-trophic levels of the waters (Hallock, 1988;

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Mutti and Hallock, 2003). Along the Monte Tobenna section, deposits interpreted as microbial carbonates are well distributed, reaching their maximum thickness above the "Orbitolina level" (Figs. 4, 5 and 7). Similar observations are emerging from the preliminary data on the microbial carbonate distribution along the Serra Sbregavitelli basal section (Figs. 5 and 7). Morever, at Tobenna-Faito, microbial carbonates disappear above the SBZ 1, although tectono-volcanic activity was increasing (Bralower et al., 1997; McArthur et al., 2001). This may have occurred because the longer-term sea level rise (mfz in Fig. 4; see also Fig. 7) had more than offset the effects of the increasing alkalinity on the main carbonate producers (cf. Schlager, 2003; Hallock, 2005), allowing more suitable physico-chemical conditions to be re-established in the seawater and the return of the whole platform to a healthy state. Microbial carbonates have been found again in the upper part of the section, close to the Aptian-Albian boundary; they reach their maximum thickness near to the first occurrence of *Ovalveolina reicheli* (Figs. 4 and 5), around the SB 2, when the long-term sea level lowering induced more restricted marine circulation on the inner platform and unsuitable conditions for the full development of the related main carbonate producers.

Although the overall climate and the tectono-volcanic activity resulted in increasing continental weathering and overall palaeoceanographic conditions which were favourable for the worldwide production and preservation of organic matter in the marine realm close to the Aptian-Albian boundary (Herrle et al, 2003; Takashima et al., 2007; Tiraboschi et al., 2009; Trabucho Alexandre et al., 2010), it is hard to say whether these interrelated events also influencedthe first occurrence of *O. reicheli*, to some extent, since data from other coeval carbonate successions are not yet available at moment.

7.3 *Salpingoporella dinarica* acme: a possible response of the shallow-water platform to changes in seawater chemistry?

As stated previously, at Tobenna-Faito *Salpingoporella dinarica* shows its maximum abundance below the orbitolinid-rich layer, disappearing 10 m above it (Fig. 4).

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Preliminary results indicate that this is also the case for the Serra Sbregavitelli section (Fig. 5), although a better distribution of *S. dinarica* along it is still going on. According to cathodoluminescence and chemical microprobe observations by Simmons et al. (1991), the skeleton of this alga was originally made of low-Mg calcite, with a dark inner layer derived from a primary organic membrane (Carras et al., 2006). Secular changes in the Mg/Ca ratio and absolute concentration of calcium in seawater – driven by changes in rates of deep-sea igneous activity – have strongly influenced the biomineralization of calcium carbonate-producing organisms, similarly to nonskeletal carbonates (Stanley and Hardie, 1998; Stanley, 2006). During the Aptian, seawater was characterized by concomitant low Mg/Ca molar ratio and high concentration of Ca ("Calcite Sea"; Fig. 8a), resulting in accelerated growth for calcitic organisms. From a general point of view, therefore, it is not unreasonable to argue that seawater chemistry of the Early Cretaceous – in particular the Late Aptian (112–121 Ma, Ogg et al., 2004) – affected not only the more complex carbonate-producing organisms (e.g. corals, rudists), but could also have made the production of low-Mg calcite skeleton of *S. dinarica* easier, thus explaining, at least partly, the abundance of this calcareous alga in the shallow-water carbonates of the studied interval and of coeval deposits piled up on the southern Tethys margin (e.g. Varol et al., 1988; De Castro, 1991; Carras et al., 2006; Tasli et al., 2006; Husinec et al., 2009). This may have been the case because *S. dinarica* was not a sophisticated biomineralizer (Lowenstam and Weiner, 1989) and, therefore, seawater chemistry would have exerted a relatively strong effect on its rate of growth and calcification (Stanley, 2006). However, since *S. dinarica* developed from the Berriasian to the Albian but its acme is seen in the Aptian, it may well be that this calcareous alga survived in times when the physico-chemical conditions of the seawater did not favour its mineralogy, but was able to bloom when the seawater chemistry, at least, favoured the secretion of low Mg/Ca skeleton, with the increasing level of Ca^{2+} that may have more than offset the effects of the ocean acidification on *S. dinarica* calcification (Hansen and Wallmann, 2003; Royer et al., 2004; Ridgwell and Zeebe, 2005; Stanley, 2006; Fig. 8b).

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8 Final remarks

In view of the above, it emerges that, during the Late Aptian, long-term sea-level changes played a fundamental role in regulating the carbonate sedimentation in the inner lagoonal environments of the Apenninic platform and the temporal distribution of peculiar facies during a time of increasing volcano-tectonic activity and trophic levels of the water. During the lowering of the sea level microbial carbonates represented a diffused product of the shallow marine ecosystem in a general context of deterioration of the inner lagoon environmental conditions. When trophic levels were too high and the environmental conditions were unsuitable for the main carbonate producers of the inner lagoonal settings – due to a period of increased precipitations linked to a strong monsoonal circulation that enhanced the reworking of the organic matter and the nutrient transfer to the oceans – the "Orbitolina level" formed after a period of interrupted (or very low) sedimentation, just before the minimum accommodation space on the platform was reached and fresh/brackish water environments spread. This makes the *M. parva* and *M. texana*-rich marly level an "anachronistic" facies, "out of the platform sedimentary record", and, consequently, an important litho- and biostratigraphic marker of the carbonate successions cropping out in Central-Southern Apennines.

Lastly, considering the distribution of *S. dinarica* along the sections, it emerges that the neritic ecosystem studied was principally sensitive to changes of alkalinity and trophic levels rather than to ocean acidification during a time of sea level fall. On the contrary, during time of sea-level rise (and early highstand) no or minor microbial carbonates formed in the shallow lagoonal settings that did not suffer the effects of the paleoenvironmental changes induced by the mid-Cretaceous volcanism, and therefore remained in a healthy state.

Acknowledgements. I wish to thank Poppe de Boer for reviewing an early draft of the manuscript and offering helpful comments for its improvement.

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Table 1. Lithofacies and lithofacies associations recognized in the Tobenna-Faito composite section.

A – Bio-peloidal limestones (lagoonal environments with relatively high hydrodynamic energy allowing the development of sand shoals)
A1: Grainstones and packstone/grainstones with bioclasts, peloids and small intraclasts (Fig. 2a).
A2: Packstone/grainstones with intraclasts and peloids, and grainstones with small bioclasts, locally with parallel lamination (Fig. 2b).
A3: Packstones with peloids and miliolids, rare small intraclasts and molluscan shell fragments with crossed to parallel lamination (Fig. 2c).
B – Mili-ostracode limestones (restricted lagoon)
B1: Wackestones with benthic forams, locally with small gastropods and/or pelecypods (Fig. 2d).
B2: Wackestones and mudstone/wackestones with ostracods, small benthic forams and *Thaumatoporella* sp. (Fig. 2e).
B3: Wackestones with "rounded and/or filamentous forms", *Thaumatoporella* sp. and rare ostracods, showing microsparitic patches (Fig. 3f, g).
B4: Cryptalgal bindstones alternating with mm-thick peloidal packstone laminae, showing microsparitic patches (Fig. 3d, e).
C – Char-ostracode limestones (supratidal ponds)
C1: Mudstone/wackestones and mudstones with thick-shelled ostracods and characeans (Fig. 2f).

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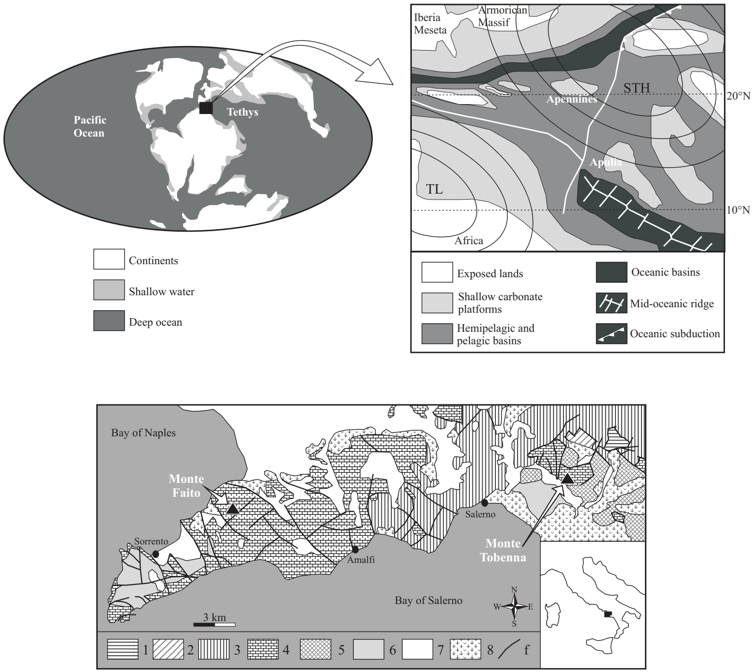

Fig. 1. Paleogeographic reconstructions of the Aptian (world map redrawn from Smith et al., 1994; palinspastic map of the Tethyan realm redrawn and modified from Danelian et al., 2004 and Masse et al., 2004, redrawn and simplified) and location of the studied sections (from Bonardi et al., 1992). (1) Undifferentiated Lagonegro sequences. (2) Carbonatic reworked sediments and cherty limestones. Jurassic. (3) Carbonate platform dolomites and limestones. Late Triassic-Jurassic. (4) Carbonate platform limestones and dolomites. Cretaceous. (5) Calcarenites, sandstones and claystones. Cretaceous-Lower Miocene. (6) Terrigenous deposits. Late Tertiary. (7) Continental deposits. Quaternary. (8) Volcanics. Quaternary. f = fault. TL: tropical low-pressure system; STH: subtropical high-pressure system (from Wortmann et al., 1999).

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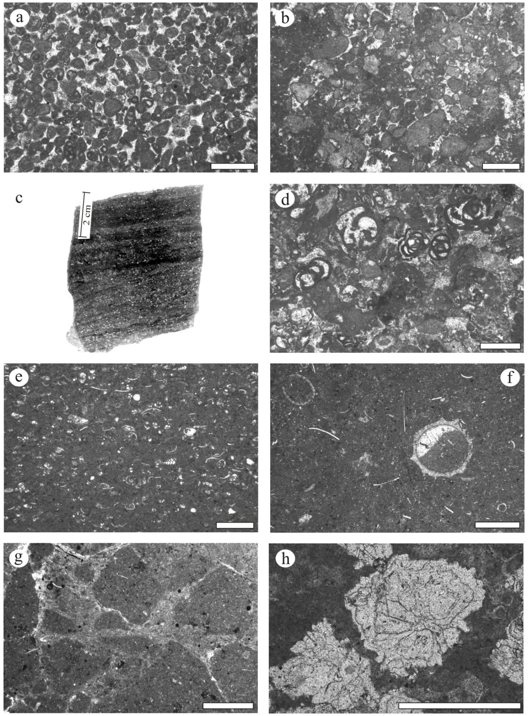

Fig. 2. Lithofacies recognized in the Monte Tobenna-Faito composite section and examples of emersion-related features affecting the sediments; **(a)** lithofacies A1: grainstone with benthic forams, peloids and intraclasts; **(b)** lithofacies A2: packstone/grainstone with intraclasts, peloids and rare bioclasts; **(c)** lithofacies A3: peloidal packstone with miliolids and small intraclasts, showing cross and parallel laminations; **(d)** lithofacies B1: wackestone with benthic forams; **(e)** lithofacies B2: wackestone with ostracods and small benthic forams; **(f)** lithofacies C1: wackestone-mudstone with charophyte and ostracods; **(g)** Microbreccia affecting the C1 lithofacies; **(h)** *Mirocodium*-like structure. Photomicrograph scale bar is 1 mm.

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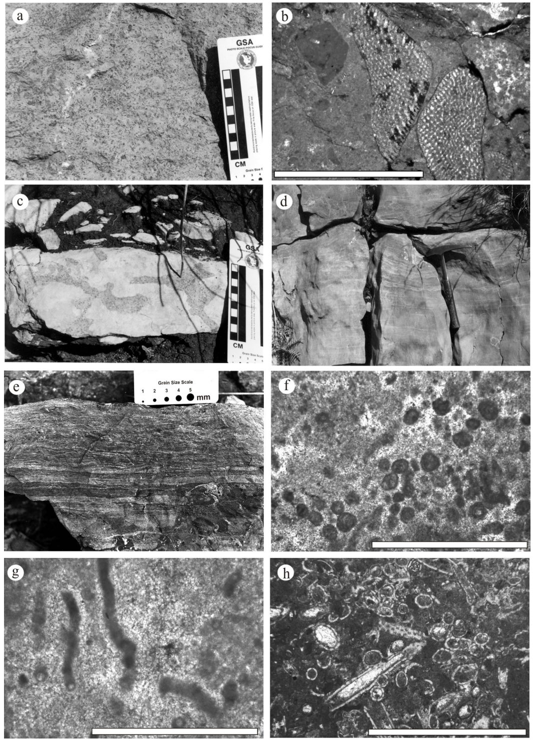

Fig. 3. Some peculiar facies encased in the shallow carbonate platform strata studied: **(a)** the "Orbitolina level" of Monte Tobenna is almost exclusively formed of flat conical foraminifera; **(b)** orbitolinids frequently show framboidal pyrite on their shells. In the top right corner, a lithoclast with clotted peloidal microspar texture can be seen; **(c)** *thalassinoides*-like burrows filled by the orbitolinid-rich marly sediment; **(d)** and **(e)** cryptalgal laminite with low-amplitude hemispheroidal (**d**; hammer is 33 cm long) and slightly wavy **(e)** morphology; **(f)** and **(g)** rounded and filamentous cyanobacteria, respectively, settled in a clotted microsparitic groundmass; **(h)** *Salpingoporella dinarica*-rich wackestone. Photomicrograph scale bar is 2 mm.

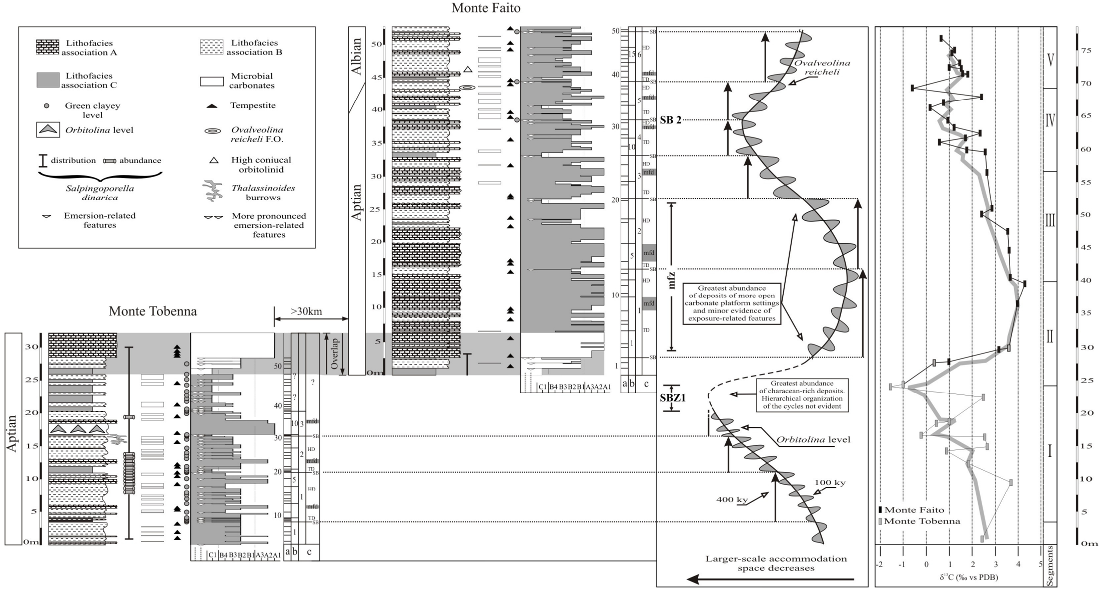

Fig. 4. Main sedimentological features and lithofacies evolution through the Monte Tobenna and Monte Faito shallow-water sections and related carbon-isotope stratigraphy. The sections are now located more than 30 km apart and show an overlap of about 6 m. For both sections A1 to C1 refer to lithofacies (see Raspini, 1998, 2001); the grey curves point out the evolution of the lithofacies and emersion-related features; **(a)** and **(b)** refer, respectively, to bed-scale cycles and bundles, while **(c)** indicates the superbundles and their interpretation in terms of sequence stratigraphy (TD: transgressive deposits; mfd: maximum flooding deposits; HD: highstand deposits; SB: sequence boundary). Larger-scale variations of accommodation space are indicated by the curve on the right, with superimposed qualitative 100 ky higher-frequency sea-level oscillations; vertical black arrows are adjusted to the thickness of the superbundles; SBZ: Sequence Boundary Zone; mfz: maximum flooding zone. Roman numbers (I-to-V) indicate the segments into which the δ^{13}C curve has been subdivided; the thick grey curve represents the three-points moving average of the isotope composition. Sedimentological and cyclostratigraphic data from Raspini (1998, 2001) and D'Argenio et al. (1999); isotopic data from D'Argenio et al. (2004). See text for further explanation.

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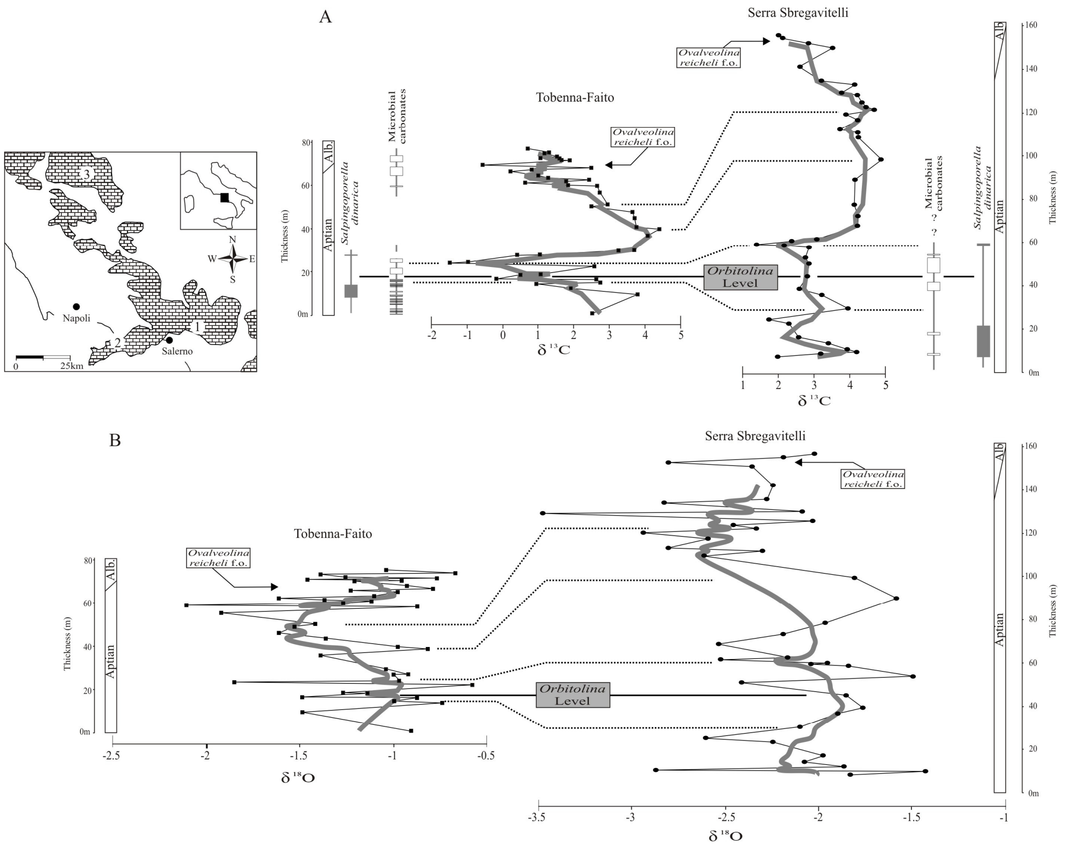

Fig. 5. Correlation of $\delta^{13}C$ **(A)** and $\delta^{18}O$ **(B)** trends of the Tobenna-Faito composite section and the Serra Sbregavitelli outcrop, considering the "Orbitolina level" as tie-point (isotopic data from D'Argenio et al., 2004). The thick grey curves in **(A)** represent the three-points moving average of the C-isotope composition (see Fig. 4); the microbial carbonates (white rectangles), the distribution of *Salpingoporella dinarica* and its acme (grey rectangles), as well as the first occurrence (f.o.) of *Ovalveolina reicheli* in both sections are also indicated. In **(B)** the thick grey curves are the five-points moving average of the O-isotope ratios. Inset in top left corner: 1, Monte Tobenna; 2, Monte Faito; 3, Serra Sbregavitelli.

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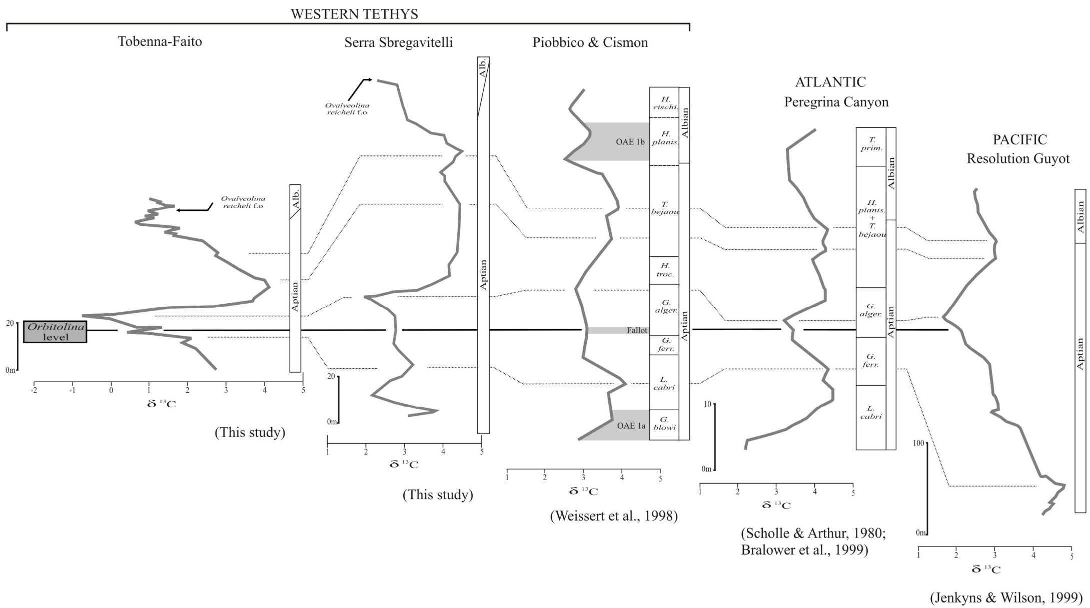

Fig. 6. Trends of δ^{13}C values of Tobenna-Faito and Serra Sbregavitelli sections plotted against reference curves of the Tethys (Piobbico and Cismon, Weissert et al., 1998), Atlantic (Scholle and Arthur, 1980; Bralower et al., 1999) and Pacific (Jenkyns and Wilson, 1999). Note that the planktonic foraminiferal zones refer to different zonal schemes.

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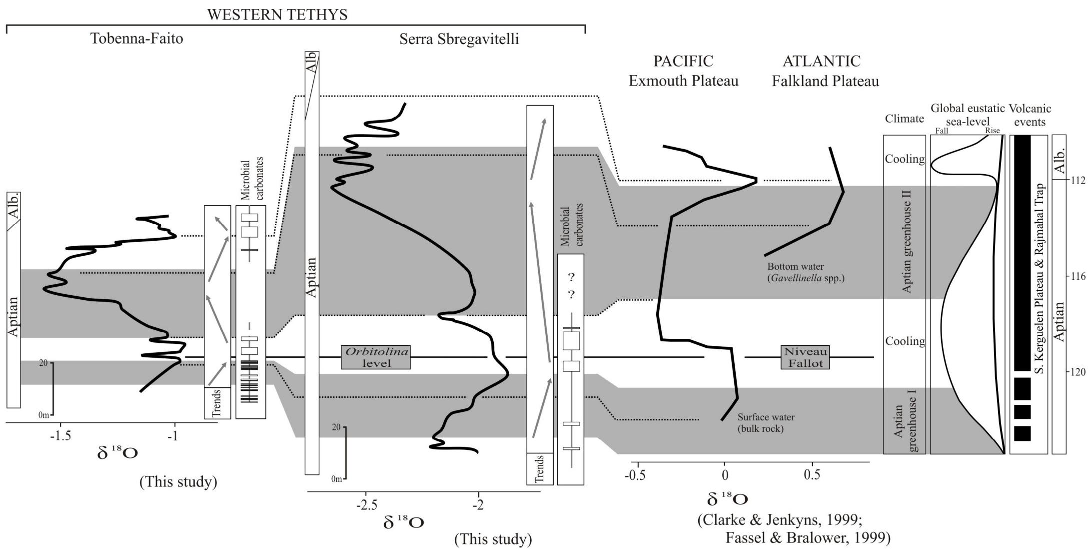

Fig. 7. Trends of δ^{18}O values of the Tobenna-Faito composite section compared to δ^{18}O curves of Clarke and Jenkyns (1995, Exmouth Plateau) and Fassell and Bralower (1999, Falkland Plateau). The distribution of microbial carbonates is as in Fig. 5. Grey and white areas indicate, respectively, the warming (Aptian greenhouse I and II) and cooling events of Weissert and Lini (1991) as reported in Takashima et al. (2007). Global eustatic sea level is from Haq et al. (1987). Volcanic events are from Takashima et al. (2007). Timescale (My) is according to Ogg et al. (2004).

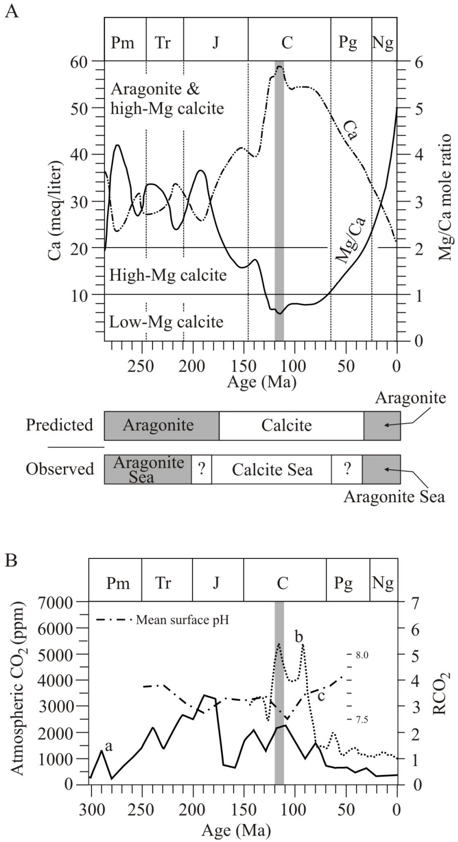

Fig. 8. Evolving physico-chemical conditions of the ocean-atmosphere system during the Mesozoic. In both diagrams, vertical grey bar roughly refers to the Aptian interval of the studied Tobenna-Faito composite section. **(A)**: Ca^{2+} concentration and Mg^{2+}/Ca^{2+} mole ratio in the oceanic waters with nucleation fields for low-Mg calcite, high-Mg calcite and aragonite. The temporal oscillations between calcitic and aragonitic nonskeletal carbonates are also shown (from Stanley et al., 2002 and Stanley, 2006, redrawn and simplified). **(B)**: evolution of the atmospheric CO_2 concentration (a; from Royer et al., 2004), pCO_2 normalized to the current value (RCO_2, b; from Hansen and Wallmann, 2003) and trend of the mean surface pH (c; from Ridgwell and Zeebe, 2005).