Shallow water carbonate platforms (Late Aptian, Southern Apennines) in the context of supraregional to global changes: re-appraisal of palaeoecological events as signs of carbonate factory responses

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Abstract

Sedimentological and cyclostratigraphic analyses previously carried out on the Aptian/Albian shallow water carbonate platform strata from Monte Tobenna and Monte Faito (Southern Italy) have been integrated by further field and laboratory work. This has been addressed to the description and interpretation of facies showing peculiar field appearance and/or fossil content: the "Orbitolina level", the microbial carbonates and the *Salpingoporella dinarica*-rich deposits.

The vertical evolution of textures and diagenetic features and their cyclical organization along the sections, in tune with the related isotopic record framed within global trends and the main volcanic and climatic events of the Aptian, suggests that low frequency sea-level fluctuations played a fundamental role in regulating the deposition of the peculiar facies in the lagoonal environments of the Apenninic carbonate platform. In fact, in a general context of deterioration of the inner lagoon environmental conditions triggered by increasing volcano-tectonic activity and trophic levels of the water, microbial carbonates were a common product of the shallow marine ecosystem only during the eustatic lowering of the sea level. Under such a scenario, when a period of increased precipitations enhanced the nutrient transfer to the oceans, trophic levels were too high and the environmental conditions became unsuitable for the main carbonate producers of the lagoonal settings. This created perfect conditions for the spread of an opportunistic fauna rich in orbitolinids (*Mesorbitolina parva* and *M. texana*), just before the minimum accommodation space on the platform was reached. 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 eustatic sea level rise (and early highstand) no or minor microbial carbonates formed in the shallow lagoonal settings. They easily remained in a healthy state and were not influenced by the environmental changes mostly induced by the mid-Cretaceous volcanism.

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 & Desrochers, 1992; Demicco & 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 sea-water (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 low conical orbitolinids in association with calcareous algae, rare pelecypod shells and echinoderms (De Castro, 1963; Cherchi et al., 1978).

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) and the marker bed correlated between widely spaced (present day distance > 100 km) carbonate platform successions cropping out in Southern Italy (D'Argenio et al., 1999, 2004), 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; Embry et al., 2010; 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 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 low 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; Bachmnn 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 sedimentological and cyclostratigraphical analyses of the Late 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 biota (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).

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 $\delta^{13}C$ values derived from recently published data (D'Argenio et al., 2004). Relationships between positive shifts in the $\delta^{13}C$ record of the above sections and oceanic perturbations of the carbon cycle have already been evidenced (D'Argenio et al., 2004), but if and how the Aptian paleoenvironmental and paleoceanographic changes (Weissert and Lini, 1991; Takashima et al., 2007) influenced the shallow-water carbonate factory of the platform now forming the backbone of Southern Apennines have not previously been examined. For this purpose, the recently published sedimentologic, cyclostratigraphic and chemostratigraphic features of the above successions are resumed, reappraised and finally discussed following an integrated approach.

2 Geological setting

The carbonate successions discussed in this study consist of well-bedded and laterally continuous beds deposited in the central Mesozoic Tethys (Fig. 1). This area was characterized by the development of a broad, intraoceanic carbonate domain (Apenninic Carbonate Platform; Mostardini & Merlini, 1986) that was part of a larger and articulated carbonate platform-basin system (e.g., Patacca & 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 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 (Doglioni, 1994; 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 32 m thick and consists of well bedded carbonate strata in the first 16 m overlying by the “Orbitolina level”, a well known upper Aptian (early?-middle Gargasian) litho and biostratigraphic marker in the carbonate platform successions of the Southern Apennines, rich in *Mesorbitolina texana* and subordinately *Mesorbitolina parva* (De Castro 1963; Cherchi et al. 1978; De Castro 1991; see also Chihaoui et al., 2010; Embry et al., 2010; Schroeder et al. 2010). From about 20 m, clayey layers and marly beds with abundant charophytes alternate and form an interval about 8 m-thick, then overlain by carbonate strata.

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 outcrop. The section studied (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 meters above the “Orbitolina level”. Its basal portion consists of strata thicker than the ones forming the medium and upper portions. 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 6.5 meters and makes it possible to obtain the "Tobenna-Faito composite section" with a total thickness of approximately 79 m.

4 Sedimentology

4.1 Previous data and their interpretation

4.1.1 Methodology

Previous field observations were carried out at cm-scale in order to obtain virtually continuous description of the outcrops (Raspini, 1998, 2001). A metric tape was utilized to measure both bed and lithofacies thicknesses. As a general approach, samples were taken from the base, middle and top of each bed or more frequently whenever field interpretation became difficult, and across any significant lithofacies variation. In the laboratory the cut hand specimens were re-examined after etching using a 10% HCl solution.267 thin sections were prepared for microscope analysis.

4.1.2 Lithofacies and their associations

The previous microstratigraphic (cm-scale) analysis of textures, sedimentary structures and early diagenetic features allowed the identification of eight lithofacies: A – Bio-peloidal limestones; B – Mili-ostracod limestones; C – Char-ostracod limestones. They group eight lithofacies and represent, on the whole, products of deposition in inner lagoonal settings with a discontinuous belt of submerged shoals (Raspini, 1998, 2001; see also D'Argenio et al., 1999). Table 1 lists the lithofacies and lithofacies associations recognized in the Tobenna-Faito composite section 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, were interpreted as the product of storm events that affected the depositional settings in which the lithofacies formed.

Green clayey layers were 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 mm-size cavities filled by calcite and/or with geopetal infills. 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 (Raspini, 1998).

Scattered cavities of irregular shape and less than 1 mm in size that show crystal silt at the base passing upward to sparry calcite characterize the uppermost part of many beds. These features were interpreted as evidence of exposure (Raspini, 1998, 2001). In addition, the microbrecciation affecting the top of some characean-rich beds was interpreted as the effect of wetting and drying processes producing mm-size intraclasts which give rise to an *in situ* breccia, similarly to the examples described by Riding and Wright (1981) in the paleosols of the Lower Carboniferous in southern Britain (Raspini, 1998; Fig. 2g). Calcitic structures comparable to *Microcodium* (cf. Košir, 2004) were found at 76 m of the composite section (Raspini, 1996; Fig. 2h).

4.2 Peculiar facies of the Tobenna-Faito section

Further field observations and laboratory work have been addressed to the description and interpretation of some facies showing peculiar field appearance and/or fossil content: the "Orbitolina level", the lithofacies B4 and B3 and the *Salpingoporella dinarica*-rich deposits. This allowed us to identify distinctive fossil traces in the sediments underlying the orbitolinid-rich layer and to interpret lithofacies B4 and B3 as microbially-induced carbonates, outlining both their and the *S. dinarica*-rich facies distribution along the sections.

4.2.1 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 (Figs. 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. The upper portion is 10-15 cm thick and shows no or minor clay content. It rests on 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 a large number of Orbitolina, mostly *Mesorbitolina texana* and subordinately *Mesorbitolina parva* (Cherchi et al., 1978), showing a high alteration level (e.g., Tomašových et al., 2006) and, frequently, framboidal pyrite on their shell. *Salpingoporella dinarica* (sometimes broken), *Thaumatoporella* sp., *Boueina hochstetteri moncharmontiae*, peloids and benthic foraminifers may also be found.

Orbitolina floatstone with a marly matrix penetrates downward into the carbonate strata, filling the underlying cm-sized cavity-like features. Owing to the abundant vegetal covering that prevented extensive observations, these latter features have been previously interpreted as the product of paleokarstic processes related to a prolonged emersion of the platform subsequently sealed by the orbitolinid-rich marls when marine conditions returned (Raspini, 1996, 1998). By contrast, further field work carried out on a well exposed outcrop along a road cut has revealed that, as a matter of fact, the cavity-like features are sinuous and irregularly anastomosed "tunnels" traced in the deposits underlying the litho and biostratigraphic marker. The "tunnels" may reach 3 cm in diameter and 12 in length and are interpreted as *Thalassinoides*-like burrows (e.g., Seilacher, 2007) filled with orbitolinid-rich sediment (Figs. 3c).

Based on the above observations, the "Orbitolina level" of the Monte Tobenna sequence represents transgressive deposits that settled on the platform following a period of interrupted (or very low) sedimentation.

4.2.2 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 (Figs. 3d and 3e). 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, 2000), or display a microspar groundmass, and are rich in T*haumatoporella* 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).

4.2.3 *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

5.1 Previous data and their interpretation

Based on the vertical organization of depositional and early diagenetic features, three orders of cyclicity were recognized in the stratigraphic record of the Tobenna-Faito composite section: bed-scale cycles, bundles and superbundles (Raspini, 1998, 2001; D’Argenio et al., 1999). Bed-scale cycles are the smallest units whose vertical depositional and/or early diagenetic facies organization defines a cyclic environmental change; they are hierarchically stacked into bundles and superbundles, as can also be clearly seen in the field. Bundles are groups of 2-5 bed-scale cycles, superbundles consist of 2-4 bundles (Fig. 4).

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 was recognized; characean-rich deposits reach here 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 (Fig. 4).

Most of the bed-scale cycles in the composite section show evidence of early meteoric diagenesis developed in their uppermost part. It implies that emersions due to drops of relative sea-level repeatedly interrupted the sedimentary processes, controlling the formation of the bed-scale cycles (Fig. 4). Also, the observed hierarchy of cycles suggested that the superposition of three orders of environmental oscillations controlled the deposition of the studied sections. Composite eustatic sea-level fluctuations driven by the astronomical beat in the Milankovitch band were considered the cause of the hierarchical stacking pattern of cycles. The bed-scale cycles record the 20 ky precession periodicity, 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).

5.2 Sequence stratigraphy

Along the Tobenna-Faito composite section, lithofacies trends within the superbundles frequently show a transgressive/regressive evolution. This permits the description of superbundles in terms of sequence stratigraphy and the identification of maximum flooding, transgressive and highstand deposits (Fig. 4). Maximum flooding is an interval corresponding to the thickest and/or relatively more open lithofacies association forming a bed-scale cycle in each superbundle. Below the maximum flooding interval, transgressive deposits are characterized by thickening upward bed-scale cycles, commonly formed of lithofacies showing a retrogradational evolution. Above the maximum flooding interval, highstand deposits are characterized by thinning upward bed-scale cycles showing aggradational and/or progradational lithofacies evolution. However, these general lithofacies and thickness variations are not always detectable in the sections probably because the Mesozoic carbonate platform interior settings were basically aggrading systems in which sea-level variations linked to the orbitally induced eustatic perturbations were not able to induce facies changes during the formation of each bed-scale cycle (cf. Sandulli and Raspini, 2004).

The systematic variation of superbundle thickness in tune with the larger-scale vertical evolution of lithofacies and their diagenetic overprint reveals a superposition of the hierarchically stacked cyclic units on lower frequency environmental oscillations that reflect longer-term changes in accommodation space (e.g., Goldhammer et al., 1990; Sandulli and Raspini, 2004; Tresch and Strasser, 2010). 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). Then, across the 6.5 m-thick overlapping zone, a sharp shift towards the most-open marine lithofacies is recorded (Fig. 4). These deposits show minor evidence of emersion-related features and form the thickest superbundles recognized in the section studied. They mark a period of maximum accommodation space on the platform and define the maximum flooding zone (mfz in Fig. 4). Subsequently, 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; it corrresponds to the top of the thinnest superbundle of the Monte Faito section, located close to the Aptian-Albian transition (Fig. 4).

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). In this paper, the trends of $\delta^{13}C$ and $\delta^{18}O$ values of the Tobenna-Faito composite section are utilised. The trends have been reproduced applying three and five-points moving averages to the carbon and oxygen stable isotope composition, respectively: they allow a better comparison between the isotopic record of the sections studied and the reference curves, damping the possible local interferences due to environmental/diagenetic effects.

6.1 Regional-to-global significance of the isotopic record

Although the high-amplitude fluctuations of some carbon isotope values in the lower and upper part of the Tobenna-Faito section (where the sedimentary record is also punctuated by an early meteoric diagenesis that repeatedly interrupted the deposition), 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 (Fig. 4). 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 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 crossing the overlapping zone between the Monte Tobenna and Monte Faito sections (see Fig. 4).

7 Discussion

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

In the shallow water carbonate strata studied in the Apennines, the vertical evolution of the Late Aptian facies suggests that the "Orbitolina level" 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; D'Argenio et al., 1999; 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).

In proximal areas of the Apenninic platform (Tobenna-Faito), the 115-175 cm-thick "Orbitolina level" shows an exceptional concentration of low 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 low 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., Graziano, 1999, 2000; 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.

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 (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 early?-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 organic 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).

Although orbitolinids were considered light-dependent foraminifera (Hottinger, 1982), several authors have put forward the idea that low conical orbitolinids have an adaptative trend to light 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; Immenhauser et al., 2005). This would have resulted in mesotrophic or eutrophic conditions on carbonate platforms and in hemipelagic settings, creating perfect conditions for the spread of an opportunistic fauna rich in orbitolinids in the shallow lagoons and the formation of black shales in deeper environments.

Recently some authors have suggested that thermal fluctuations and 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 low 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 $\delta^{18}O$ main trends of Tobenna-Faito at a regional scale (Fig. 5B) and the good comparison with reference $\delta^{18}O$ 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 eustatic lowering of the sea level. 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 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 forcing factor (the volcanic activity; Coffin et al., 2002, 2006; Takashima et al., 2007), amplifying its effects during an eustatic 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 only in part 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; Rowley, 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 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; see also Huck et al., 2010). 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; 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 first data showing the distribution of 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 influenced the 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 metres above it (Fig. 4). First 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; cf. Steuber, 2002), 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; Di Lucia, 2009; 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).

7.4 Summary

The vertical evolution of the facies and their cyclical organization along the Tobenna-Faito composite section suggests that the "Orbitolina level" of the Gargasian deposited in the lagoonal environment of the Apenninic carbonate platform after a period of interrupted (or very low) sedimentation, during a time of long-term eustatic lowering of the sea level. The correlation of the long-term trends of $\delta^{13}C$ and $\delta^{18}O$ values recorded in the studied sections with reference curves of the Late Aptian (Figs. 6 and 7) confirms that the orbitolinid-rich marker settled during a global climate cooling (even though the Late Aptian was a time of increasing volcano-tectonic activity) and is coeval with part of the Niveau Fallot that deposited in a hemipelagic setting connected to the Tethyan Ocean. In the marly biostratigraphic marker of the central-southern Apennines the low conical foraminifera are associated to echinoderms, calcareous algae and rare pelecypods, suggesting high trophic levels of surficial waters. It is argued that high trophic levels in the sea and an overall paleoenvironmental deterioration were induced by a period of increased precipitations linked to a strong monsoonal circulation (supraregional events) that amplified the effects of the volcanic activity (global forcing factor), creating perfect conditions for the spread of an opportunistic fauna rich in orbitolinids in the shallow lagoon during a long term fall of the sea level.

During the lowering of the sea level, however, the volcano-tectonic activity remarkably influenced the stratigraphic record of Monte Tobenna-Faito, as testified by the development of microbial carbonates and the distribution of *Salpingoporella dinarica*-rich deposits along the composite section. The injection of CO_2 in the ocean-atmosphere system and the consequent progressive enhancement of the continental weathering, caused an increase of dissolved Ca^{2+} and HCO_3^- in the ocean which facilitated a microbial colonization on large areas of the shallow water environments. Also, *Salpingoporella dinarica*, whose skeleton was originally made of low-Mg calcite, shows its maximum abundance (acme) below the orbitolinid-rich layer, disappearing above it. Probably, the concomitant low Mg/Ca molar ratio and high concentration of Ca in the Aptian seawater (Fig. 8A) fostered the production of low-Mg calcite skeleton of *S. dinarica* that was able to bloom in the shallow lagoonal environment. Thus, the neritic ecosystem of the Apenninic carbonate platform was principally sensitive to changes of alkalinity and trophic levels rather than to ocean acidification during a period of long-term sea level fall (Fig. 8B).

During the sea-level rise and the early highstand, despite the volcano-tectonic activity, no microbial carbonates formed in the shallow lagoon and also *S. dinarica* disappeared probably because the physico-chemical conditions of the seawater became definitively unsuitable for secreting its skeleton. Therefore, the sedimentary record of the Tobenna-Faito is not punctuated by peculiar facies testifying to a deterioration of the environmental conditions as during the long-term sea level lowering; this suggests that the marine ecosystem was not influenced by the paleoenvironmental changes related to the mid-Cretaceous volcanism and easily remained in a healthy state.

8 Conclusions

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. Under these environmental conditions, microbial carbonates represented a diffused product of the shallow marine ecosystem only during the eustatic lowering of the sea level. 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, the “Orbitolina level” formed after a period of interrupted (or very low) sedimentation. It deposited just before the minimum accommodation space on the platform was reached. 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 of the Central-Southern Apennines coeval with part of the Niveau Fallot that deposited in a hemipelagic setting connected to the Tethyan Ocean during a period of global climate cooling.

Lastly, considering the distribution of *Salpingoporella 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.

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.

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Figure captions

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).

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

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 low 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; 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. The thick grey curve represents the three-points moving average of the carbon 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.

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 values 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.

Fig. 6 Trends of $\delta^{13}C$ values of Tobenna-Faito and Serra Sbregavitelli sections plotted against reference curves of the Tethys (Piobbico and Cismon, in 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.

Fig. 7 Trends of $\delta^{18}O$ values of the Tobenna-Faito composite section compared to $\delta^{18}O$ curves of Clarke and Jenkyns (1999, 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).

Table 1. Lithofacies and lithofacies associations recognized in the Tobenna-Faito composite section (from Raspini, 1998, 2001).