

Biotic and geochemical response to anoxic events: the Aptian pelagic succession of the Gargano Promontory (southern Italy)

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Abstract – Microfossil distribution patterns and high-resolution $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ curves, calibrated against planktonic foraminiferal and calcareous nannofossil data, are provided for the Aptian pelagic Coppitella section of the Gargano Promontory (southern Italy). The succession consists of cyclically arranged couplets of bioturbated grey marlstones and off-white marly limestones, referable to the Marne a Fucoidi. In the lower portion of the section, two thin black shales were recognized. The high-resolution $\delta^{13}\text{C}$ curve presented here correlates with those of other Alpine–Tethyan sections, albeit with lower absolute values. The onset of deposition of organic-rich sediments falls at the top of the interval of unchanging carbon-isotope values, whereas the upper black shale is documented from the interval of the main Aptian positive $\delta^{13}\text{C}$ excursion. According to our biostratigraphic data, the deposition of organic matter in the Gargano Promontory persisted through Early/Late Aptian boundary time. Using a chemostratigraphic definition, only the lower black shale is referred to the Selli Level. As far as the biotic response is concerned, the onset of the ‘nannoconid crisis’ is recorded considerably below the lower black shale, whereas the ‘*Globigerinelloides* eclipse’ is recorded below and within the upper black shale. The distribution of meso-eutrophic indices (*Zygodiscus* spp., radiolaria) vs. moderate-fertility indices (*Rhagodiscus asper* and *Lithraphidites carniolensis*) testifies to a modest increase of surface-water fertility only throughout the stratigraphically higher black shale. The occurrence of a benthic foraminiferal fauna, albeit impoverished, in both the basal and upper black horizons clearly documents dysaerobic rather than completely anoxic conditions on the sea floor. Relative sea-level rise at the time of the Selli Event in the Gargano Promontory is documented by drowning and foundering of the Apulia platform margin, situated adjacent to the basin in which the Marne a Fucoidi accumulated.

1. Introduction

Many stratigraphers have recently focused their attention on the Aptian stage of the Cretaceous Period, because of the co-occurrence of several palaeobiological and palaeoceanographic events. An abnormally high intraplate volcanism during the Early Aptian interval is recorded in the Pacific Ocean (Menard, 1964; Schlanger, Jenkyns & Premoli Silva, 1981; Larson, 1991), which probably caused a huge input of CO_2 to the oceans and atmosphere, leading to an intensified greenhouse effect (e.g. Weissert, 1989; Caldeira & Rampino, 1991; Weissert & Lini, 1991; Larson & Erba, 1999). During the Early Aptian interval, a global episode of black-shale deposition is recorded (Schlanger & Jenkyns, 1976; Jenkyns, 1980) and interpreted as the sedimentary expression of Oceanic Anoxic Event (OAE) 1a or Selli Event (Arthur *et al.* 1990; Jenkyns, 1999). The transfer of the light ^{12}C isotope from the oceans to the sedimentary carbon reservoir would have produced the well-documented Early Aptian positive excursions in the marine carbonate $\delta^{13}\text{C}$ record (e.g. Weissert, McKenzie

& Hochuli, 1979; Scholle & Arthur, 1980; Schlanger *et al.* 1987; Weissert & Lini, 1991; Bralower *et al.* 1994; Marconi, Wezel & Longinelli, 1994; Menegatti *et al.* 1998; Larson & Erba, 1999; Premoli Silva *et al.* 1999). However, there is no exact stratigraphic equivalence between the currently documented black-shale record and the carbon-isotope response, particularly as a pronounced negative carbon-isotope excursion is locally registered immediately before the Selli Event. In this case, release of methane, which is isotopically very negative ($\delta^{13}\text{C} \approx -60\text{‰}$), from dissociation of gas hydrates within continental-margin sediments, may be implicated in controlling the carbon-isotope signature of the ocean–atmosphere system (Jenkyns & Wilson, 1999; Jahren *et al.* 2001). Probably as a consequence of the general transgression during the Early Aptian interval, and changes in the climate and circulation patterns, an evolutionary turnover of the biota, leading to homogenization of Boreal and Tethyan floras and faunas, has been recorded at this time (Bischoff & Mutterlose, 1998; Mutterlose, 1998).

Although a geographically widespread data set has been generated from the analysis of several Lower Cretaceous successions, including both oceanic and land

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sections, many questions remain unsolved. According to some authors, the Aptian black shales originated as a consequence of episodes of increased primary productivity. In this model the humid and warmer climatic conditions accelerated the transfer of nutrients from the continents into the oceans, inducing an increase of primary productivity, particularly of organic-walled plankton, in the surface waters (e.g. Weissert, McKenzie & Channell, 1985; Weissert, 1989, 1991; Erba, 1994; Föllmi *et al.* 1994; Föllmi, 1995; Jenkyns, 1999). Other authors attribute deposition of black shales to widespread stagnation of the water column, related to sluggish oceanic circulation and thermohaline stratification, that enhanced the preservation of organic carbon on the sea floor under dysoxic–anoxic conditions (e.g. Pratt & King, 1986; Bralower & Thierstein, 1987; Roth, 1987; Premoli Silva, Erba & Tornaghi, 1989; Habermann & Mutterlose, 1999).

Recently, stable-isotope (especially C and O) geochemistry has been increasingly applied to the stratigraphy of Cretaceous pelagic sequences (e.g. Scholle & Arthur, 1980; Schlanger *et al.* 1987; Jenkyns, Gale & Corfield, 1994; Menegatti *et al.* 1998; Weissert *et al.* 1998). Because the isotopic composition of carbonate records a global marine signal, long-term variations in $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$, calibrated against biostratigraphic data, represent a powerful chronostratigraphic tool. Moreover, the correlation between geochemical and biotic data can provide insights into palaeoceanographic and biological change.

In this study we present a high-resolution integrated stable-isotope and micropalaeontological stratigraphy of an Aptian succession cropping out at Coppitella near Vieste, in the Gargano Promontory, southern Italy (Fig. 1). The succession, referable to the Marne a Fucoidi, contains black shales in the lower part (Cobianchi, Luciani & Menegatti, 1999). The planktonic foraminiferal and calcareous nannofossil data enable the black shale to be attributed to the upper part of the *Globigerinelloides blowi* and *Chiastozygus litterarius* zones of late Early Aptian age, which suggests that this deposit is the equivalent of the Selli Level of the Umbria-Marche Apennines (Coccioni *et al.* 1987) and represents the sedimentary expression of the global OAE1a or Selli Event (Cobianchi, Luciani & Menegatti, 1999).

The main goals of this study are the following: (1) to provide high-resolution $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ curves, calibrated against planktonic foraminiferal and calcareous nannofossil data, for use as a chronostratigraphic tool; (2) to provide information on palaeoceanographic and biological changes through correlation between geochemical and micropalaeontological data.

2. Geological and stratigraphic setting

The Gargano Promontory belongs, from a palaeogeographic point of view, to the Apulian Platform in the

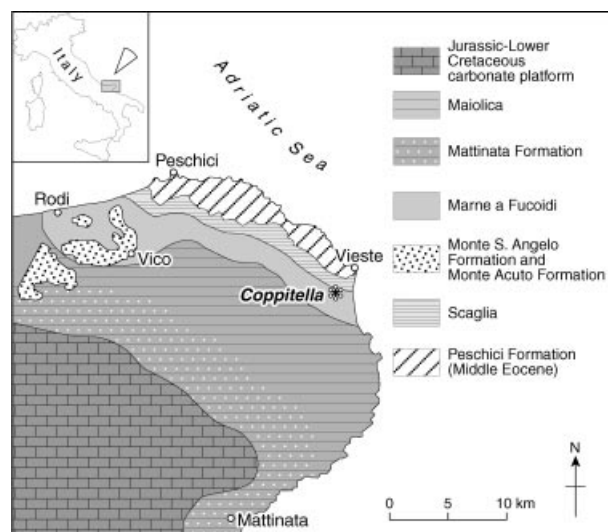


Figure 1. Simplified geological map of the Gargano Promontory and location of the Coppitella section (modified after Cobianchi, Luciani & Bosellini, 1997).

southwest and to the Ionian Basin in the northeast (Fig. 2). The Apulian Platform is part of the stable and relatively undeformed foreland of the Apennine thrust belt and is constituted by Mesozoic shallow-water platform carbonates (Richetti *et al.* 1988); the Ionian Basin contains Lower Jurassic platform carbonates overlain by deeper-water pelagic facies (Bernoulli, 1972). The Gargano Promontory is the only portion of the above-mentioned palaeogeographic domain where the transition between platform and adjacent basin is exposed on land.

The current lithostratigraphic terminology of the Cretaceous basin-and-slope units varies according to different authors who have undertaken modern stratigraphic researches on the Gargano Promontory (e.g. Martinis & Pavan, 1967; Cremonini, Elmi & Selli, 1971; Luperto Sinni & Masse, 1987; Luciani & Cobianchi, 1994; Graziano, 2000). The stratigraphic framework here adopted (Fig. 3) follows Bosellini, Neri & Luciani (1993), Cobianchi, Luciani & Bosellini (1997) and Bosellini, Morsilli & Neri (1999).

The classical Cretaceous succession recognized in the Umbria-Marche Basin, central Italy, can be extended further south to the Gargano Promontory, near the margin of the Apulia carbonate platform (Cobianchi, Luciani & Bosellini, 1997; Cobianchi, Luciani & Menegatti, 1999). The Cretaceous pelagic succession consists of three superimposed stratigraphic units: Maiolica (Valanginian–Lower Aptian), Marne a Fucoidi (Lower Aptian–Upper Albian), and Scaglia (Upper Albian–Coniacian). Near the margin of the platform, the Mattinata Formation, rich in gravity-displaced deposits, laterally replaces the Maiolica; the Monte San Angelo and Monte Acuto formations are also characterized by the presence of redeposited shallow-water material intercalated between pelagic

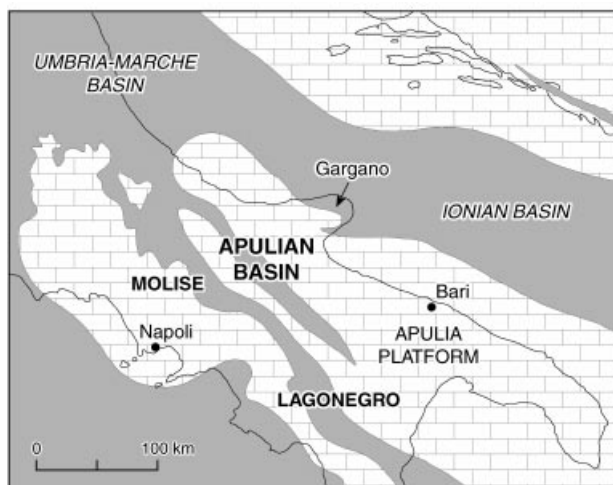


Figure 2. Palaeogeography in southern Italy during Jurassic–Cretaceous times showing the Gargano Promontory divided between the Apulia Platform in the southwest and the Ionian Basin in the northeast (modified after Zappaterra, 1990). Shallow-water carbonate-platform facies indicated by brick ornament; deeper-water pelagic facies by grey shading.

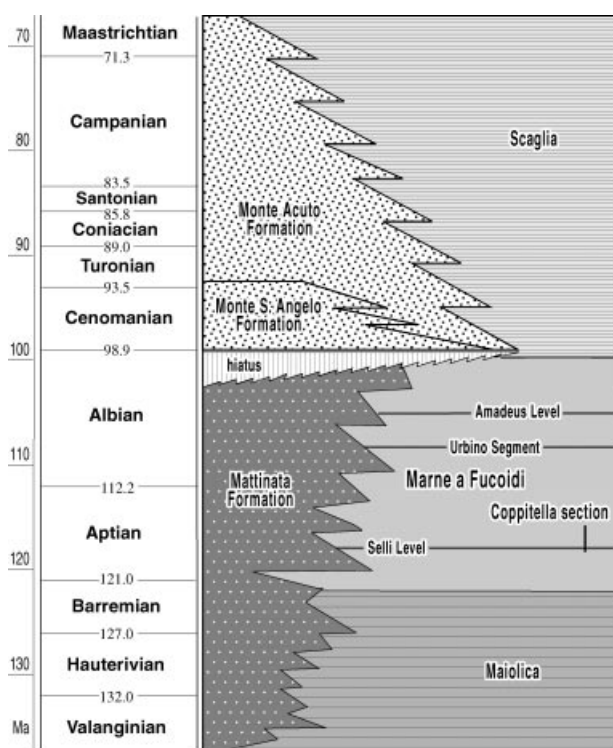


Figure 3. Chronostratigraphic framework and nomenclature for the Cretaceous slope-and-basin deposits of the northern Gargano area (modified after Cobianchi, Luciani & Bosellini, 1997). The vertical solid line indicates the stratigraphic interval investigated in the Coppitella section. Time scale follows Gradstein *et al.* (1994).

carbonates (Bernoulli, 1972; Bosellini, Neri & Luciani, 1993; Luciani & Cobianchi, 1994; Cobianchi, Luciani & Bosellini, 1997; Graziano, 2000).

As in the Umbria-Marche Basin, the Marne a Fucoidi of the Gargano Promontory typically consists of marl–limestone couplets. This alternation shows a major hierarchical arrangement with bundles (~1 m thick) typically made up of five couplets, a bedding pattern suggestive of orbital climatic control (precession and eccentricity cycles; cf. Schwarzacher & Fischer, 1982; de Boer, 1983; Herbert, 1992). In the Umbria-Marche Basin, however, the marls are more abundant and varicoloured and, in the lower portion of the succession, contain radiolarian calcarenitic horizons (Erba, 1988; Erba, Coccioni & Premoli Silva, 1989). This unit contains, in both areas, characteristic black-shale horizons, more common in the Umbria-Marche Basin (Premoli Silva, Ripepe & Tornaghi, 1989; Cobianchi, Luciani & Bosellini, 1997; Cobianchi, Luciani & Menegatti, 1999). The onset of deposition of the Marne a Fucoidi in the Gargano Promontory (Early Aptian) is coeval with drowning of the Apulia Platform margin, a phenomenon perhaps related to eustatic sea-level rise (Luciani & Cobianchi, 1994; Bosellini, Morsilli & Neri, 1999).

3. Methods

3.a. Location and lithology

The Coppitella section, 17.2 m thick, is located along the State Road N.89 (from 104 to 105 km) southwest of the town of Vieste (Fig. 1). The lithostratigraphy of the section was partly described in Cobianchi, Luciani & Menegatti (1999). For the analysis presented here, the section was sampled at high resolution for the integrated micropalaeontological and geochemical analyses according to the procedures described below (Fig. 4).

The succession consists of cyclically arranged couplets of bioturbated grey marlstones and off-white marly limestones (locally silicified) with scattered chert nodules. The chert colour changes from whitish to black above the basal covered tract. The thickness of couplets is *c.* 20 cm. The entire unit can be attributed to the Marne a Fucoidi. Burrows, mainly represented by *Chondrites* and *Planolites*, occur more abundantly in the lower part of the section in the marls and locally at the top of calcareous strata.

The detailed analysis of the succession has revealed, at 4.5 m from the base, just above a covered interval, a lower thin black level, 5 cm thick. About 2.5 m above this, a second black horizon, some 10 cm thick and laminated at a millimetre-scale, is present (Fig. 4). In the interval containing the upper black shale, burrows typically exhibit a dark colour.

3.b. Samples and data collection

Samples from the Coppitella section were collected in order to carry out a detailed analysis of the calcareous nannofossil and foraminiferal content and to determine bulk carbon- and oxygen-isotope values. A total of 89 samples was taken at 20-centimetre intervals in

general, with more dense collecting (2–5 cm) across the interval containing black shales. The same set of samples was used for micropalaeontological and geochemical studies in order to compare the results directly.

Laboratory methods for foraminiferal analysis consisted of disaggregation of marly samples and black shales in Desogen and subsequent washing through a sieve of 38-micron screen in order to avoid the loss of the very small specimens which can be the only component of the fauna within this stratigraphic interval. Unfortunately, the unevenly distributed and generally rare planktonic foraminiferal assemblages do not allow a quantitative analysis. Almost half of the total samples (43) were taken from limestones and cherty limestones and analysed in thin section. Thin sections from marly-limestone samples were also studied in order directly to relate radiolarian and total foraminiferal abundances to the standard percent diagrams of Baccelle & Bosellini (1965).

For the calcareous nannofossil analysis, smear-slides from samples of all the rock-types (marly limestone, marl, calcareous shale and black shale) were prepared. Quantitative estimates of calcareous nannofossil species abundance were carried out using a polarizing light microscope at a magnification of $\times 1250$. For each smear-slide, a standard number of specimens (300) was counted. The abundance of the species was expressed as relative percentage of the assemblage. The relative abundance curves of some selected species, previously interpreted as palaeoecological or diagenetic indices, were drawn and correlated.

Bulk samples for isotopic analysis were first powdered, cleaned with 10% H_2O_2 followed by acetone, and

then dried at 60°C. Powders were then reacted with purified orthophosphoric acid at 90°C and analysed on-line using a VG Isocarb device and Prism Mass Spectrometer at Oxford University. Normal corrections were applied and the results are reported, using the usual δ notation, in per mil deviation from the PDB standard. Calibration to PDB was performed via our laboratory Carrara marble standard. Reproducibility of replicate analyses of standards was generally better than 0.1‰ for both carbon- and oxygen-isotope ratios. Figure 5 shows the results of isotopic analysis.

4. Biostratigraphy

4.a. Planktonic foraminifera

By comparison with the previous preliminary analysis (Cobianchi, Luciani & Menegatti, 1999), the closer rate of sampling provides higher-resolution information on the planktonic foraminiferal assemblages, albeit mainly confirming previous biostratigraphic data. Ten samples are completely devoid of planktonic foraminifera and in many cases only very rare planktonic forms have been observed; scattered washed residues may, however, contain rich and well-preserved assemblages.

Taxonomic criteria for Jurassic–Lower Cretaceous planktonic foraminifera have been recently revised by Banner & Desai (1988) and Boudagher-Fadel *et al.* (1997). These authors include the taxa in two Superfamilies, the *Favosellacea* and *Globigerinacea*. They distinguish families and genera by taking into account, besides disposition of the chambers and aperture features, the wall characteristics, for example,

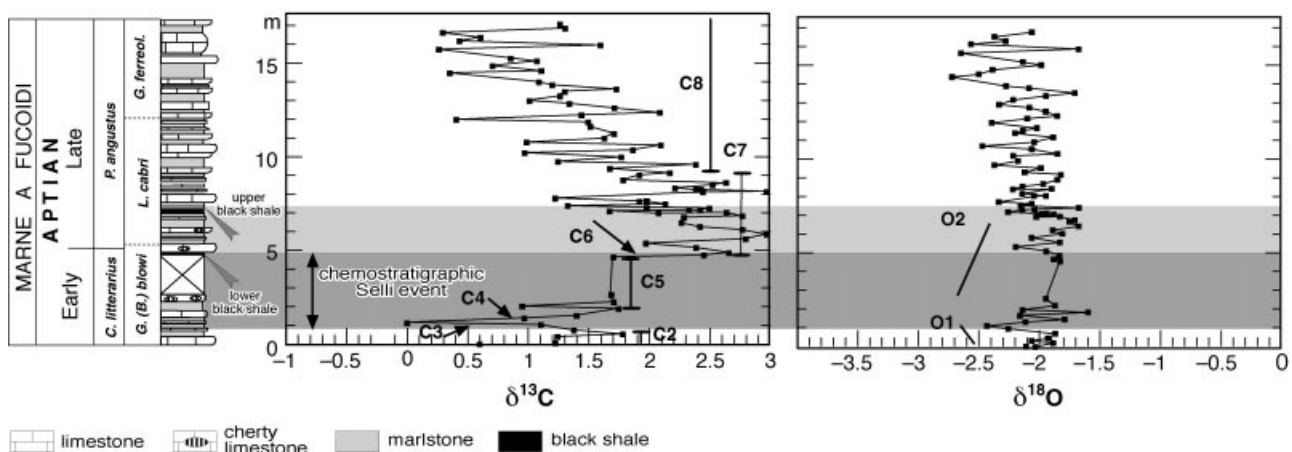


Figure 5. Stratigraphic column of the Coppitella section showing the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ curves of the bulk carbonate matrix. Labels C2–C8 and O1, O2 indicate segments of the stable-isotope curves as distinguished by Menegatti *et al.* (1998) in the pelagic-carbonate sections from Southern Alps of northern Italy (Cismon section) and Swiss Préalps (Roter Sattel section). The darker stippled band indicates the chemostratigraphically defined Selli Event (according to Menegatti *et al.* 1998); the lighter band highlights the entire interval recording dysoxic conditions and enhanced preservation of organic matter.

the composition (presumably aragonitic for the *Favusellacea*), occurrence of pustules, reticulations, micro- and macro-perforations. Because it is rather exceptional to find planktonic foraminiferal assemblages well preserved in Lower Cretaceous sediments, particularly in Tethyan successions typically represented by hard limestones, this classification is not always easily applied, and the range of some species is not yet precisely established. For the Lower Cretaceous assemblages from the Gargano Promontory, the newly proposed generic names are reported in brackets next to the conservative taxonomy. Moreover, with respect to the new classification mentioned above, the species *Hedbergella delrioensis* and *H. aptica* are here retained instead of *H. (Blefuscuiana) infracretacea* and *H. (B.) infracretacea occidentalis* respectively, following Coccioni & Premoli Silva (1994). These species, which show large morphological variability and are closely related, are considered to be synonyms by some but not all authors. Finally, the species '*cabri*' is included in the genus *Leupoldina*, distinguished from *Schackoina* both by Loeblich & Tappan (1988) and Boudagher-Fadel *et al.* (1997) by the bulbous terminations of its elongate chambers.

From the base upward the following biozones of the standard low-latitude zonal schemes (e. g. Caron, 1985; Sliter, 1989a, 1992; Robaszynski & Caron, 1995) were identified (Fig. 4):

Globigerinelloides (Blowiella) blowi Zone p.p. (from the base to 5.20 m). Interval from the FO (first occurrence) of *G. (B.) blowi* and the FO of *Leupoldina cabri*. The species *G. (B.) blowi* is already present at the base of the section, thus indicating that only the upper part of the zone is represented. The top of the zone coincides with the FO of *L. cabri*. This species was almost evenly recorded from sample 37, above the upper black shale, up to sample 67, albeit represented by poorly preserved specimens. However, one specimen, probably referable to *L. cabri*, was observed in the stratigraphic interval between the two black levels (sample 18); the boundary between the *G. (B.) blowi* and *L. cabri* zones has hence been tentatively placed below this sample. The genus *Guembelitra* occurs as rare and small specimens, probably referable to two species, from the base of the section (Cobianchi, Luciani & Menegatti, 1999). *Hedbergella (Blefuscuiana) kuznetsovae* and *Hedbergella delrioensis* are the most abundant forms. *H. (Praehedbergella) sigali*, *Praehedbergella* gr. *ruka*, *H. (Praehedbergella) similis*, *Hedbergella aptica*, *H. (Blefuscuiana) aptiana* and *H. (Blefuscuiana) excelsa* are evenly distributed. *Clavibergellids* (*C. (Lilliputianelloides) eocretacea* and *C. (L.) semielongata*) are rare. Scattered *Leupoldina pustulans* occur in samples 5 and 12. From sample 12 the species *H. (Blefuscuiana) praetrocoidea* was observed. *Gorbachikella kugleri*, *G. anteroapertura*, *Favusella hoterivica* are also present in the assemblages. *Globigerinelloides* are quite common and

represented by the species *G. (Blowiella) gottisi*, *G. (B.) duboisi*, *G. (B.) maridalensis* beside the zonal marker.

Leupoldina cabri Zone (from 5.20 m to 12.50 m from the base). Total range zone. Planktonic foraminiferal assemblages are similar to those of the zone below but enriched in some species, such as *Globigerinelloides cepedai*, *Hedbergella (Lilliputianella) kuhryi*, *Praehedbergella tatianae*, whereas *Globigerinelloides (Blowiella) duboisi* disappears. From sample 20, rare and very small specimens of *Globigerinelloides ferreolensis* also occur for the first time and, in the middle part of the zone (sample 46), the FO of *H. (B.) gorbachikae* was also observed. *Globigerinelloids* reappear from sample 40. Specimens of *H. (B.) praetrocoidea*, morphologically very close to *H. trocoidea*, first occur at the top of this stratigraphic interval. The mean size of planktonic foraminifera slightly increases in the upper part of the zone.

Globigerinelloides ferreolensis Zone p.p. (from 12.50 m to top). Interval from the LO of *L. cabri* 12.50 m above the base, to the FO of *Globigerinelloides algerianus*. This zone is not entirely represented because the species *G. algerianus* was not observed in the succession analysed. Some changes in planktonic foraminiferal assemblages include the LOs of *Hedbergella (Blefuscuiana) kuznetsovae*, *Clavibergella (Lilliputianella) semielongata*, *C. (L.) eocretacea*, *Gorbachikella* spp., *Globigerinelloides (Blowiella) gottisi*, *Favusella hoterivica*, and the FO of *Hedbergella planispira*. Within the *G. ferreolensis* Zone, the zonal marker reaches the greatest size of the species.

4.b. Calcareous nannofossils

Among the 89 samples investigated, only two are devoid of calcareous nannofossils. The assemblages are abundant, moderately well preserved and diversified throughout the section. In sample 17 (5 m from the bottom of the section) *Eprolithus floralis* records its first occurrence. On the basis of this event, two nannofossil zones were identified (Fig. 4): the *Chiastozygus litterarius* Zone p.p. (from bottom to 5 m) and the *Parhabdololithus angustus* Zone (from 5 m to the top).

The *Chiastozygus litterarius* Zone (Thierstein, 1973) corresponds to the stratigraphic interval from the FO of *Rucinolithus irregularis* to the FO of *Eprolithus floralis*. The species *R. irregularis* was recorded from the bottom of the section upwards; *R. angustus* was observed in the nannofossil assemblages from the base of the section. The assemblages are dominated by the *Watznaueria* group, especially in the black shales. Species abundant in this interval include *Assipetra infracretacea*, *Biscutum constans*, *Chiastozygus litterarius*, *Flabellites oblongus*, *Lithraphidites carniolensis*, *Manivitella pemmatoidea*, *Microstaurus chiastius*, *Rhagodiscus asper*, *Rhagodiscus splendens*, *Rhagodiscus angustus*, *Rucinolithus terebrodentarius*, *Zeughrabdothis*

The calcareous nannofossil abundance, diversity and assemblage composition fluctuate widely, but no dramatic changes throughout the Selli Level have been recorded.

5.a. Planktonic foraminifera: palaeoecological behaviour

It is well known that, in modern low-latitude oceans, stable oceanic conditions, expressed by a stratified water-column and a deep thermocline, are characterized by diversified planktonic foraminiferal assemblages, with complex morphotypes occupying deeper environments and simpler morphotypes inhabiting shallower water. The evolution of Cretaceous planktonic foraminifera and their diversification, by reference to modern forms and in part according to stable-isotope data, has been currently related to the progressive colonization of the deepest ecological niches by the large, complex, keeled forms (e.g. Hart, 1980, 1999; Caron & Homewood, 1983; Leckie, 1987, 1989; Premoli Silva & Sliter, 1999). K- and r-selected strategists have been distinguished by categorizing organisms on the basis of their life-strategies as related to use of resources and competition. r-selected opportunists are able rapidly to increase their population in number by an early maturation and faster reproduction and typically proliferate in eutrophic low-stability conditions. K-selected specialists are characterized by low reproductive potential with a consequent longer individual life and take advantage of highly stable, oligotrophic environments where organisms compete by specialization and habitat partitioning (e.g. MacArthur & Wilson, 1967; Valentine, 1973; Hallock, 1985). In between these two extremes there are the organisms adapted to mesotrophic regimes. In planktonic foraminiferal populations, small-sized forms are generally opportunists and related to a high reproductive potential; they rapidly

The models generally applied consider hedbergellids as r-mode opportunist surface-dwellers, probably eutrophic indicators (e.g. Caron & Homewood, 1983; Leckie, 1987, 1989; Premoli Silva, Erba & Tornaghi, 1989; Coccioni, Erba & Premoli Silva, 1992; Premoli Silva & Sliter, 1995, 1999; Hart, 1999). Small representatives of the genus are the unique forms constituting the Lower Albian *Hedbergella planispira* Zone, characteristically found in black shales (Br    ret, Caron & Delamette, 1986; Premoli Silva, Erba & Tornaghi, 1989; Sliter, 1989*b*). The absence of larger taxa (ticinellids) has been interpreted as a response to an expanded oxygen-minimum zone which destroyed the habitats of the relatively larger, less tolerant forms. Some oxygen- and carbon-isotope data seem to support the interpretation of surface habitat for hedbergellids (Huber, Hodell & Hamilton, 1995; Price *et al.* 1998), in particular those showing that *Hedbergella delrioensis*, from the Cenomanian/Turonian interval, was a surface dweller (Corfield, Hall & Brasier, 1990). Apparently contrasting data have recently been published by Norris & Wilson (1998) who, through isotopic analysis on Albian/Cenomanian planktonic foraminifera from the northern Atlantic, demonstrate that hedbergellids, *Praeglobotruncana* and *Rotalipora*, record the coolest temperature and, by implication, were deeper-dwelling, whereas *Ticinella*, *Planomalina* and *Biticinella* grew in surface water. These analyses are referred to the species *Hedbergella delrioensis* and *H. simplex* (Norris & Wilson, 1999) whereas, according to the same authors, the Albian–Cenomanian hedbergellid species *Costellagerina lybica* lived in surface waters. The data of Norris & Wilson (1998), although still to be tested in other localities, suggest that the relationship between morphology and habitat depth is not straightforward. Other information on the palaeoecology of hedbergellids derives from documentation that the onshore epicontinental Cretaceous seas from southwest England, North Sea Basin, northeast Atlantic and United States were populated, if not dominated, by this group (e.g. Eicher & Worstell, 1970; Carter & Hart, 1977; Hart & Bailey, 1979; Hart & Ball, 1986; Leckie, 1987). Finally, the long-lasting genus *Hedbergella* is believed to have survived the K/T boundary mass extinction (e.g. Liu & Olsson, 1992; Keller, Li & MacLeod, 1995; Keller, 1996;

Orue-Etxebarria & Apellaniz, 2000; Keller *et al.* in press). This evidence suggests that hedbergellids were ecological generalists, probably capable of tolerating significant fluctuations in temperature, salinity, nutrients and oxygen. It is possible that this group was able to live in either the surface or subsurface, probably depending upon the depth of highest primary productivity (Norris & Wilson, 1998). Furthermore, Aptian hedbergellids may have been able to change habitats in the water column and tolerate wide environmental variations. Palaeoecological information on Lower Cretaceous planktonic foraminifera is limited, however, and critical isotopic data are not yet available.

Leupoldinids are another group present during the Aptian. In the Cismon core from the Southern Alps of northern Italy, clavate forms and leupoldinids become a consistent component of planktonic foraminiferal assemblages within the Selli Level, especially at its base (Premoli Silva *et al.* 1999). The elongation of the chambers characterizing these groups has been interpreted as an adaptive response to low-oxygen conditions (Premoli Silva & Sliter, 1995; Boudagher-Fadel *et al.* 1997; Magniez-Jannin, 1998; Premoli Silva *et al.* 1999).

Globigerinelloids were perhaps the most specialized, possibly meso-oligotrophic, forms during the Early Aptian interval (Coccioni, Erba & Premoli Silva, 1992). A crisis of this group, named the '*Globigerinelloides* eclipse', has been observed in the upper part of the *G. blowi* Zone in Spain (Coccioni & Premoli Silva, 1994), Umbria-Marche region (Coccioni, Erba & Premoli Silva, 1992) and the Gargano Promontory (Cobianchi, Luciani & Bosellini, 1997; Cobianchi, Luciani & Menegatti, 1999). Globigerinelloids are also very scarce in the Cismon core in the stratigraphic vicinity of the Selli Level. This interval of crisis has been interpreted as the biotic response to the critical conditions related to the Selli Event, possibly associated with a high-fertility episode (Coccioni, Erba & Premoli Silva, 1992).

5.a.1. Planktonic foraminiferal response in the Coppitella section

The lower part of the Coppitella section spans the first steps of planktonic foraminiferal diversification when this group was characterized by very small specimens (mainly < 100 µm) with a thin wall which can be more easily affected by dissolution; their size slightly increases within the late Early Aptian *L. cabri* Zone.

Planktonic foraminiferal abundance has been estimated by comparison with the standard percent diagrams of Baccelle & Bosellini (1965). The abundance in basal levels of the section is generally low and comparable with that of the Lower Aptian successions of the Umbria-Marche Basin (Premoli Silva, Erba & Tornaghi, 1989; Coccioni, Erba & Premoli Silva,

1992). Planktonic foraminifera are generally more common when radiolaria are scarce or absent.

It is possible to distinguish different intervals in the Coppitella section on the basis of abundance and composition of planktonic foraminiferal assemblages from the base upwards (Fig. 6):

(a) In the basal part, below the lower black shale, planktonic foraminifera fluctuate in abundance, reaching a peak up to 7% just below the basal covered tract; they are rather diversified, also containing moderately common *Globigerinelloides*.

(b) The basal thin black shale, just above the covered tract, is not devoid of planktonic foraminifera. In fact, *Favusella hoterivica*, *Gorbachikella anteroapertura*, *Gorbachikella* sp., and *Hedbergella delrioensis*, although represented by very rare specimens, were observed.

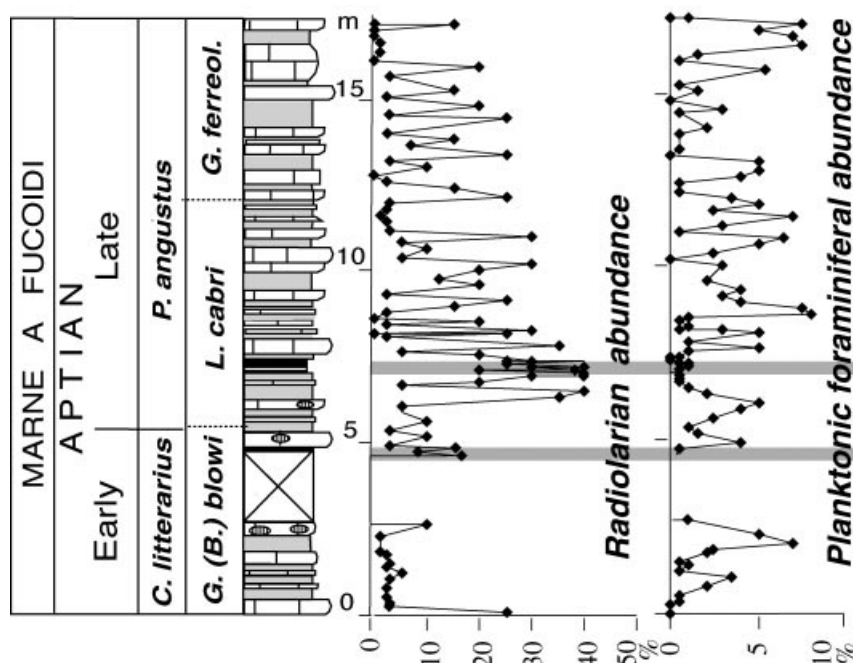
(c) In the first metre above the basal black level, total foraminiferal abundance is quite low, reaching a maximum of 5%, with lowest abundance (1–2%) corresponding to positive peaks of radiolaria. Planktonic foraminiferal assemblages above the basal black shale are, however, diversified and still contain globigerinelloids.

(d) The one-metre interval below the upper black-shale records a critical interval for planktonic foraminiferal assemblages. Planktonic foraminifera are strongly reduced in abundance (max. 1%) and a change in the composition of assemblages is evident: they are constituted mainly by the small hedbergellids/præhedbergellids such as *Hedbergella (Blefuscuiana) kuznetsovae*, *H. (P.) gr. ruka*, *H. (P.) sigali*, *H. delrioensis*, with rare *Gorbachikella* sp. and *Guembelitra*, but globigerinelloids are absent. This variation occurs in an interval characterized by constant high radiolarian abundance and an increase of nannofossil higher-fertility indices. It is possible that the composition of fossil planktonic foraminiferal assemblages may reflect, in this interval, primary ecological conditions, probably related to increased eutrophy causing a perturbation in the ecological niches of the *Globigerinelloides* group.

(e) The upper black shale: this thin interval, very rich in radiolaria, is not completely devoid of planktonic foraminifera, which are represented by small and very rare *H. (P.) kuznetsovae* and possibly *H. (P.) sigali*.

(f) Above the upper black interval, the foraminiferal abundance fluctuates out of phase with radiolaria, reaching a peak in the *G. ferreolensis* Zone. Globigerinelloids reappear one metre above the black shales.

The distribution of planktonic foraminiferal assemblages in the Coppitella section indicates that hedbergellids, gorbachikellids and favusellids were probably ecologically tolerant forms, because they are the only component of the foraminiferal fauna within the black-shale levels. Similar assemblages, though enriched with leupoldinids in selected levels, have been found in the Selli Level from the Cismon section



(Premoli Silva *et al.* 1999). The absence or scarcity of leupoldinids across the Selli Event in the Coppitella section may be the result of the rarity of *L. cabri* at the beginning of its range and/or lack of preservation, because this group appears to be sensitive to dissolution. Dissolution can also explain the apparent differences in zonal attribution of OAE1a which is included in the upper part of the *Globigerinelloides blowi* Zone (e.g. Sliter, 1989*b*, 1999; Bersezio, 1992, 1993; Coccioni, Erba & Premoli Silva, 1992; Bralower *et al.* 1993; Menegatti *et al.* 1998) or placed within the *L. cabri* Zone (e.g. Magniez-Jannin, Br    ret & Delanoy, 1997; Aguado *et al.* 1999; Erba *et al.* 1999; Hochuli *et al.* 1999; Premoli Silva *et al.* 1999) or straddling the upper *G. blowi* and the lower *L. cabri* zones (e.g. Bralower *et al.* 1999; this paper).

The occurrence of a calcareous fauna in the Coppitella section, albeit impoverished, across the stratigraphic interval corresponding to the Selli Event, indicates that extreme conditions in the water masses were not reached. Moreover, the data obtained here confirm that the Selli Event, though related to a perturbation of the biotic signal, did not influence the planktonic foraminiferal evolution, as extinction/radiation episodes among this group have not been

5.b. Calcareous nannofossils

Calcareous nannofossil assemblages are affected by the following: (1) conditions of sea-surface waters (light, temperature, salinity, nutrients etc.); (2) dissolution in the water column or at the sediment/water interface; (3) diagenesis. Several studies have highlighted the fact that quantitative analyses of nannofloras give information on diagenetic history and palaeoceanographic events (e.g. Perch-Nielsen, 1979, 1985; Roth, 1981, 1986, 1989; Roth & Bowdler, 1981; Thierstein, 1981; E. Erba, unpub. Ph.D. thesis, Università di Milano, 1986; Erba, 1992, 1994; Roth & Krumbach, 1986; Premoli Silva, Erba & Tornaghi, 1989; Coccioni, Erba & Premoli Silva, 1992; Bischoff & Mutterlose, 1998; Habermann & Mutterlose, 1999). Specifically, some Cretaceous nannofossil species are used as palaeoceanographic indices. Moreover, preservation, assemblage composition, total abundance and species diversity can provide information on diagenetic overprint (Premoli Silva, Erba & Tornaghi, 1989; Erba, 1992). *Biscutum constans*, *Discorhabdus rotatorius*, *Zygodiscus erectus* and *Zygodiscus diplogrammus* are considered as palaeoecological indices: high relative abundance of these opportunistic taxa indicates higher fertility of surface waters (Index A of Erba, 1992). *Parhabdolithus asper* and *Lithraphidites carniolensis*

indicate moderate fertility and warmer waters (Index B), whereas high abundance of nannoconids records an increase in carbonate productivity (Index C).

With reference to the diagenetic modifications undergone by the sediments, Erba (1992) pointed out that high abundance of *Watznaueria barnesae*, low total abundance of nannofossils, low species diversity and absence or very low abundance of microcrystalline carbonate indicated primary dissolution at the sediment/water interface. Moreover, dissolution and overgrowth during burial are indicated by high abundance of *W. barnesae*, low species diversity, medium to high abundance of nannofossils, and high abundance of microcrystalline carbonate. Because high abundance of *Watznaueria barnesae* is indicative of dissolution/diagenesis, nannofossil assemblages with a relative abundance of this taxon exceeding 40% are considered heavily altered (e.g. Thierstein, 1980; Roth & Bowdler, 1981; Roth, 1984, 1986; Roth & Krumbach, 1986; Erba *et al.* 1992).

5.b.1. Diagenetic overprint

In the section studied, *Watznaueria barnesae* always dominates the nannofossil assemblages, with abundance fluctuating from 10 to 70%. In spite of this, the nannofloras are abundant, diversified and relatively well preserved (Fig. 7). In some samples, *W. barnesae* reaches an abundance of more than 40%, particularly in the stratigraphically higher (younger) black-shale horizon. At this level, the dominance of this taxon is accompanied by low species diversity and low total nannofossil abundance (Fig. 7). These features of the assemblages may be related to dissolution on or below the sea floor, in the latter case perhaps related to the

generation of corrosive waters associated with degradation of large amounts of organic material (Bralower *et al.* 1994). In the other samples, species diversity is quite high with a mean value of 20, indicating minor diagenetic modification.

5.b.2. Nannoconids

The palaeoecological significance of nannoconids is not completely understood, because this group became extinct in the Campanian (e.g. Deres & Achéritéguy, 1980). However, Coccioni, Erba & Premoli Silva (1992) and Erba (1994), by virtue of a comparison with modern nannoplankton, suggested that nannoconids may have been oligotrophic forms, possibly inhabiting the lower photic zone. According to these authors, the concentration of nutrients in the upper euphotic zone during more eutrophic conditions can cause blooms of coccolithophorids at the expense of nannoconids. Moreover, Erba (1994) designated as the 'nannoconid crisis' the interval recorded within the *Chiastocyclus litterarius* nannofossil and *Globigerinelloides blowi* foraminiferal zones, where nannoconids are temporarily absent or rare.

In the Coppitella section, the onset of the 'nannoconid crisis' falls in sample 4 (Figs 4, 7). In the Selli Level from some sections of the Umbria-Marche area and Southern Alps of Italy and the Mid-Pacific Mountains, above the level of onset of the nannoconid crisis, a strong increase in abundance of *Rucinolitus terebrodentarius* and *Assipetra infracretacea* in the marlstones and shaly interbeds has been previously recorded (Erba, 1994; Erba *et al.* 1999; Premoli Silva *et al.* 1999). In the Coppitella section, above the level of onset of the nannoconid crisis (sample 4), only a

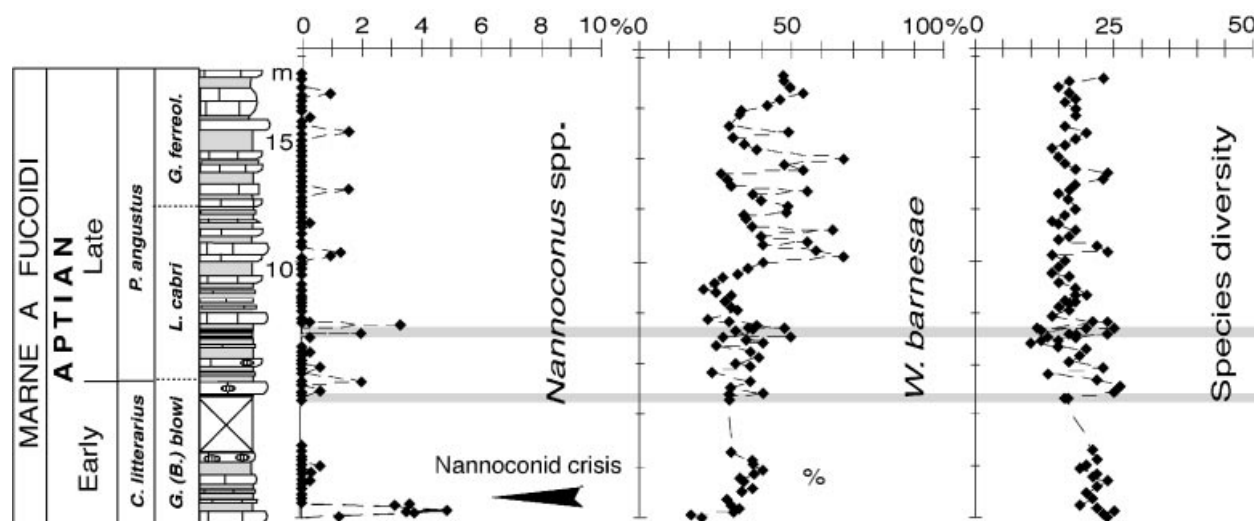


Figure 7. Vertical distribution of nannoconids, *Watznaueria barnesae* and nannofossil species diversity in the Coppitella section plotted against the stratigraphic column, with calcareous nannofossil and planktonic foraminiferal biostratigraphy. The sharp decrease in abundance of nannoconids at the base of the section documents the onset of the 'nannoconid crisis' (Erba, 1994). The stippled bands represent the lower and upper black shales. For the legend of the lithological symbols see Figure 5.

slight increase in abundance of *R. terebrodentarius* and *A. infracretacea*, with percentages from 1–2% to 4–6%, is observed. However, in the section studied, these taxa never reach the high percentages (up to 10% with an abundance peak of 50%; Premoli Silva *et al.* 1999) previously documented for the other sections.

5.b.3. High-fertility indices vs. moderate-fertility indices

Figures 8 and 9 show the relative abundance fluctuations of the palaeoecological indices. The inverse correlation between the abundance of *Z. erectus* and *Z. diplogrammus* and the abundance of *L. carniolensis*

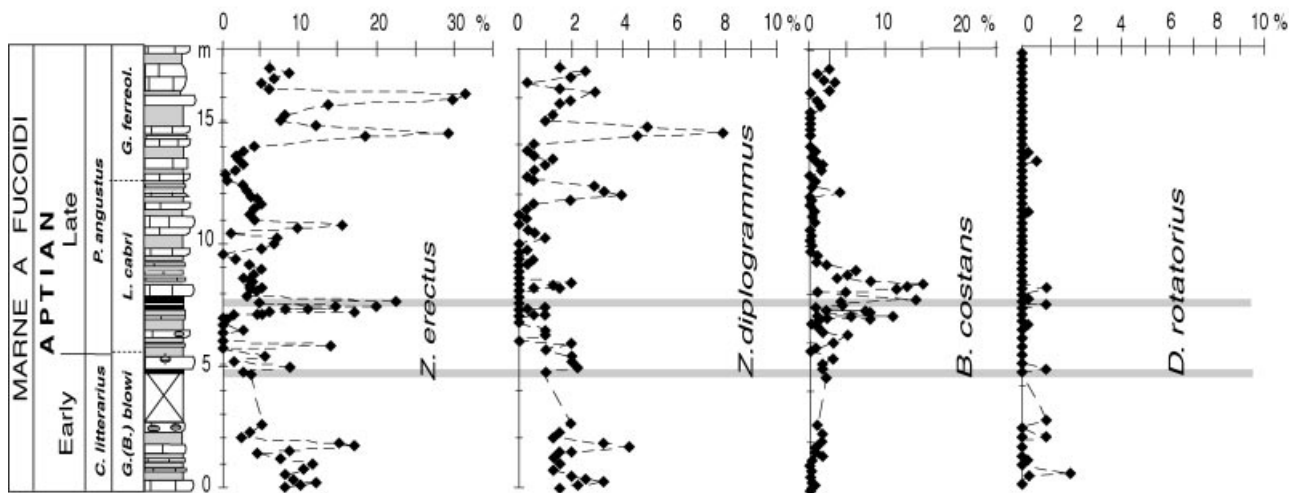


Figure 8. Vertical distribution of high-fertility calcareous nannofossil indices (*Zygodiscus* spp., *Biscutum constans*, *Discorhabdus rotatorius*) in the Coppitella section plotted against stratigraphic column with calcareous nannofossil and planktonic foraminiferal biostratigraphy. These indices stay low throughout the older black shale, whereas their relative abundance records a peak in the younger black horizon. *Zygodiscus erectus* and *Zygodiscus diplogrammus*, however, reach their highest percentage only in the upper portion of the section. The stippled bands represent the lower and upper black shales. For the legend of the lithological symbols see Figure 5.

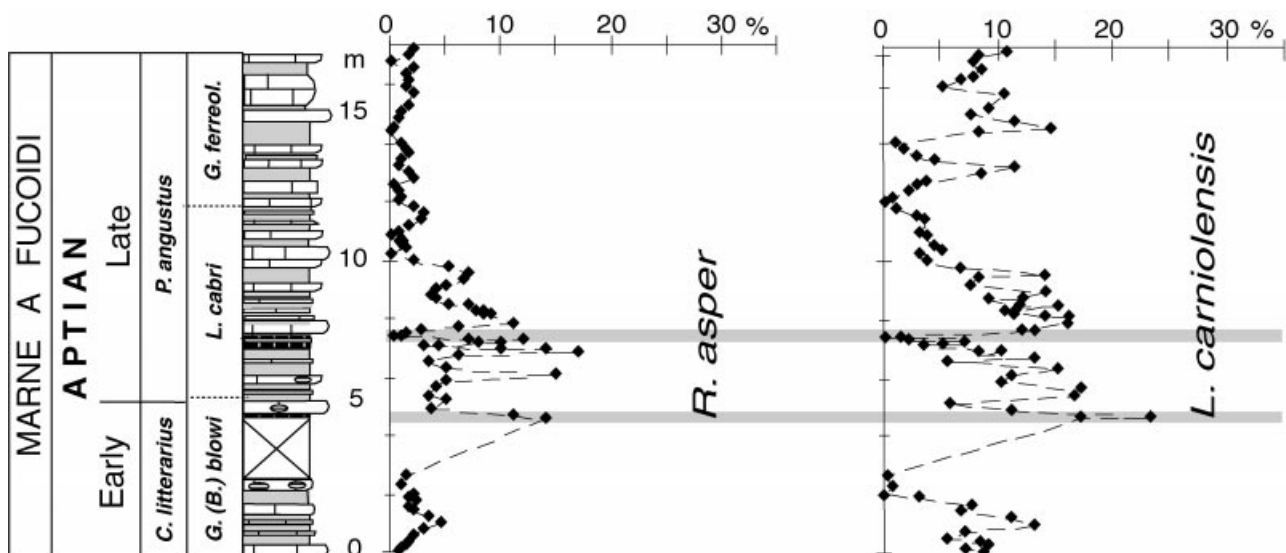


Figure 9. Vertical distribution of moderate-fertility calcareous nannofossil taxa (*Rhagodiscus asper* and *Lithraphidites carniolensis*) in the Coppitella section plotted against stratigraphic column with calcareous nannofossil and planktonic foraminiferal biostratigraphy. The abundance of these indices shows an inverse correlation with the abundance of the high-fertility indices. The moderate-fertility taxa reach their highest percentage in the older black level, whereas they drop to zero in the younger black shale. The stippled bands represent the lower and upper black shales. For the legend of the lithological symbols see Figure 5.

and *Rhagodiscus asper* is notable. *Discorhabdus rotatorius*, which is considered another fertility index, is rare throughout the section studied, whereas *Zygodiscus erectus* records considerable fluctuations, with values ranging locally in excess of 30% of the assemblage.

The section studied can be split into four segments. In the first segment (2.6 m), the inverse relationship between the abundance of the *Zygodiscus* spp. + *B. costans* vs. *L. carniolensis* + *R. asper* is well recorded, suggesting slight fluctuations of the surface-water fertility. Moreover, immediately below the covered tract a first peak of *Zygodiscus erectus* and *Z. diplogrammus* is documented. The second segment (2.5 m) spans the interval between the two organic-rich black-shale horizons. Here, the older black shale displays a peak of moderate-fertility indices, whereas the younger black horizon records an increase of higher-fertility indices.

In the lower portion of the third segment (6.5 m), immediately above the younger black interval, *Zygodiscus* spp. + *B. costans* show high abundance that decreases in the upper portion where values fall to less than 5%, whereas the opposite behaviour is recorded by the moderate-fertility indices. However, many samples in this segment show high abundance of *W. barnesae*, suggesting diagenetic modifications of the taxonomic composition. Finally, in the fourth segment (3.5 m), the assemblages again display rhythmic fluctuations between indices A (higher fertility) and B (moderate fertility and warmer water) and, in some samples, *Z. erectus* and *Z. diplogrammus* reach the highest peaks in abundance.

The quantitative analyses of nannofossil assemblages suggest rhythmic changes from mesotrophic to eutrophic conditions of the surface waters. According to calcareous nannofossil data, the oldest black interval is probably related to a period of warmer waters with stagnation and oxygen deficiency in the water column rather than a high-productivity event.

It must be noted, as highlighted by Cobiانchi, Luciani & Menegatti (1999), that in the younger black-shale interval higher fertility indices show an increase in abundance, even though calcareous plankton are still present. In present-day oceans, nannoplankton become less competitive with respect to diatoms and dinoflagellates in highly eutrophic conditions (e.g. Hallock, 1987). Therefore, the high abundance of the index A around the younger black shale documents a moderate increase in surface-water fertility, but the occurrence of calcareous nannofossils in the organic-rich levels indicates that extreme eutrophic conditions were not reached, as interpreted also by Premoli Silva *et al.* (1999).

The peaks of *Zygodiscus erectus* and *Biscutum costans*, corresponding to the younger black shale and correlatable with the main Aptian positive excursion of the $\delta^{13}\text{C}$ (C7 segment), might also be interpreted as related to an initial decrease in water temperature, possibly correlative with the Late Aptian cooling episode

discussed by Hochuli *et al.* (1999). A change in the composition of the palynofacies, documented during the $\delta^{13}\text{C}$ positive shift subsequent to the Selli unit by Vakhrameyev (1982) and Hochuli *et al.* (1999), has been interpreted to correspond with altered rainfall patterns and a shift to a cooler climate. This event correlates with the positive shift of the $\delta^{18}\text{O}$ (O2 of Menegatti *et al.* 1998), which could indicate a cooling of the ocean water. Oxygen-isotope data from the Coppitella section show this isotopic feature although it is poorly defined (Fig. 5).

5.c. Benthic foraminifera

Benthic foraminifera are always present, although they are not abundant. In some layers they can, however, be the only component of the foraminiferal assemblages, probably because of dissolution, which may have affected planktonic forms more severely. Calcareous hyaline genera are better represented and diversified (*Dentalinoides*, *Gavelinella*, *Gyroidinoides*, *Lagena*, *Lenticulina*, *Marginulina*, *Nodosaria*, *Oolina*, *Pleurostomella*, *Saracenaria*, *Spirillina*, *Vaginulina*) but agglutinated forms also occur (*Clavulinoides*, *Dorothia*, *Marssonella*, *Verneulina*). Benthic faunas are quite monotonous throughout the section. The species *Gubkinella graysonensis*, formerly considered as a planktonic form (e.g. Longoria, 1974) but included by Loeblich & Tappan (1988) in the benthic group, also occurs sporadically up to the *L. (S.) cabri* Zone. The genera *Gyroidinoides* and *Gavelinella*, represented by 1–2 species each, show great variability in size, and are the most common forms. The composition of the benthic assemblage and the dominance of planktonic foraminifera throughout the section suggest a deep-water, bathyal environment (Cobiانchi, Luciani & Menegatti, 1999).

Benthic foraminifera have recently been applied in palaeoecological analysis to investigate their response to dysoxic and/or eutrophic conditions during OAEs (e.g. Koutsoukos & Hart, 1990; Koutsoukos, Leary & Hart, 1990; Coccioni & Galeotti, 1991, 1993; Kaiho, 1993, 1999; Lamolda & Peryt, 1995; Hart, 1996; Erbacher *et al.* 1998, 1999). Results show that low-diversity benthic faunas, composed by hyaline taxa with a thin shell, a high surface-to-volume ratio and/or elongate tests, locally associated with opportunistic agglutinated taxa, apparently tolerate dysoxic environments. However, even if a number of opportunistic genera have been identified, the palaeoecological response of benthic forms to eutrophic vs. oligotrophic and aerobic vs. dysaerobic conditions is not definitely established.

The black-shale horizons of the Coppitella section are not completely devoid of benthic fauna, even though marked changes in assemblages are evident. In the lower black shale, benthic fauna is reduced to very small, rare *Gyroidinoides* and *Gavelinella*. These

As far as the upper black shale is concerned, preliminary analysis (Cobianchi, Luciani & Menegatti, 1999) has highlighted the occurrence of an impoverished fauna containing small *Spirillina*. The closer rate of sampling and the examination of washed residues of the two thin black horizons constituting this segment have also revealed other benthic forms, such as *Clavulinoides*, *Gavelinella*, *Gyroidinoides*, *Marginulina* and *Osangularia*, though very rare and small. The drastic decrease in abundance, composition and size of benthic fauna, again dominated by the opportunistic *Gyroidinoides* and *Gavelinella* (Erbacher *et al.* 1999), suggests the upper black shale formed under dysoxic but not totally anoxic conditions at the sea floor.

Radiolaria occur throughout the section but fluctuate widely in abundance reaching percentages as high as >40% (Fig. 6), with the greatest abundance generally corresponding to the cherty limestones. Different characteristic intervals can be identified. Except for a peak in sample 1 (35%), radiolaria are not common (<15%) in the basal part of the section. In contrast, radiolaria represent the main component of the plankton assemblages across the upper black levels. Within this segment (samples 23–43), in fact, their abundance varies but remains high (up to 40%); the levels with the lowest percentage of radiolaria yield common calcispheres. Above this interval, peaks in radiolarian abundance are apparently cyclical and generally corre-

Previous analyses of calcareous nannofossils, radiolaria and planktonic foraminifera highlighted a crisis of nannoconids and globigerinelloidids and an increase in fertility indices (*Z. erectus*, radiolaria, hedbergellids) in a critical interval across the Selli Level, which is generally devoid of benthos and calcareous plankton (Coccioni, Erba & Premoli Silva, 1992; Erba, 1994). However, Cobianchi, Luciani & Menegatti (1999), Hochuli *et al.* (1999) and Premoli Silva *et al.* (1999) observed, in the Selli Level of the Gargano Promontory (Southern Italy) and of the

Cismon core (Southern Alps) respectively, both a microbenthic and a calcareous foraminiferal planktonic fauna. A calcareous microfossil assemblage has also been recorded in the black shales documenting the Selli Event in the Almadich Formation of south-west Spain (Aguado *et al.* 1999).

Some previous studies presented $\delta^{13}\text{C}$ curves from the Tethyan region showing a coincidence between a positive shift and the Lower Aptian black shale (e.g. Weissert, McKenzie & Channell, 1985; Weissert, 1989; Weissert & Lini, 1991). A subsequent high-resolution stable isotopic analysis been carried out by Menegatti *et al.* (1998) from two Alpine Tethyan sections (Cismon, Southern Alps; Roter Sattel, Swiss Préalpes) and provides considerably more detail. The resulting $\delta^{13}\text{C}$ curves, divided into eight characteristic segments, are very similar in the two sections investigated and represent a significant chronostratigraphic tool for the Early Aptian interval. Moreover, the study of Menegatti *et al.* (1998) underscores the coincidence of most of the black shales (lithological Selli Level) with a period of relatively constant $\delta^{13}\text{C}$ values lasting 500 ka to 1 Ma, albeit as part of a positive excursion. A negative followed by a positive shift in the carbon-isotope curve characterizes the base of the Selli Level and a subsequent positive shift characterizes its top. In the high-resolution study of the Cismon core, carbon isotopes show a similar rising trend, with relatively constant $\delta^{13}\text{C}$ values in the middle of the Livello Selli itself (Erba *et al.* 1999).

As far as the nature of organic matter is concerned, Pratt & King (1986) and Baudin *et al.* (1998) analysed the organic matter from a number of sections through the Selli Level in the Marche-Umbria Apennines and identified the organic matter as dominantly marine. Similarly, Hochuli *et al.* (1999), analysing the organic matter of the Selli Level of the Cismon section, documented the dominance of amorphous organic matter, generally considered to be of bacterial or algal origin.

The genesis of the Lower Aptian black shales is still a matter of an intense scientific debate and two main hypothesis have been postulated. The first assumption (e.g. Bralower & Thierstein, 1984; Roth, 1987, 1989; Bralower *et al.* 1993, 1994; Tyson, 1995) justifies the enrichment of organic matter as due to enhanced preservation under an anoxic water column, related to a sluggish oceanic circulation and to a thermohaline stratification. According to the second hypothesis, episodes of very high productivity caused the increased burial of organic carbon in the sedimentological reservoir. This hypothesis requires efficient circulation and nutrient recycling (e.g. Weissert, 1991; Coccioni, Erba & Premoli Silva, 1992; Erba, 1994; Föllmi *et al.* 1994; Föllmi, 1995; Erba *et al.* 1999; Hochuli *et al.* 1999; Premoli Silva *et al.* 1999). These two alternatives encapsulate the 'enhanced preservation' vs. 'enhanced productivity' models for the accumulation of black shales (Demaison & Moore, 1980; Pedersen & Calvert, 1990).

6.b. The Selli Event of the Gargano Promontory: biotic and chemostratigraphic response

The high-resolution analysis carried out here highlights some differences with respect to the preliminary study of Cobiانchi, Luciani & Menegatti (1999); these are discussed below. Two thin black-shale horizons, separated by a 2 m thick interval, have been recorded from the Aptian interval of the Coppitella section. The lower horizon crops out above a 2 m thick covered tract (Fig. 4). Owing to the more detailed sampling, the FOs of *Leupoldina cabri* and *Eprolithus floralis* are documented between the two horizons, albeit with rare, unevenly distributed and poorly preserved specimens.

The Coppitella $\delta^{13}\text{C}$ curve (Fig. 5) closely correlates with those presented by Menegatti *et al.* (1998) and Erba *et al.* (1999). The same C2–C8 characteristic segments are recognizable. Only the lower black horizon falls within the upper part of the interval of relatively constant carbon-isotope values (C5 segment); the upper black horizon is recorded during the interval of main Aptian positive excursion (C7 segment).

The detailed analyses recently carried out across the OAE1a (e.g. Menegatti *et al.* 1998; Moullade *et al.* 1998; Bralower *et al.* 1999; Erba *et al.* 1999; Hochuli *et al.* 1999; this study), furnish high-resolution data which highlight also some minor discrepancies in the position of the lower and upper boundaries of the OAE1a. These discrepancies are essentially due to different criteria applied and in particular to the use of biostratigraphic, lithological or chemostratigraphic data. In fact, Menegatti *et al.* (1998) defined the chemostratigraphic Selli Event as the interval ranging from the C3 segment to the boundary between the C6/C7 segments (Roter Sattel section, Swiss Préalpes and Cismon section, Southern Alps), even if carbon-rich sediments crop out both below and above this interval. In the Santa Rosa canyon section, northeastern Mexico, Bralower *et al.* (1999) correlate the OAE1a with the C2–C5 segments of the isotopic curve.

Recent biostratigraphic results show some discrepancies in the FOs of the zonal markers near the Selli Event, generally defined as occurring between the nannoconid crisis and the FOs of *E. floralis* and *L. cabri*. As previously pointed out, an earlier occurrence of *L. cabri* below the Selli Level has been mentioned by Moullade *et al.* (1998), Erba *et al.* (1999), Hochuli *et al.* (1999), and Premoli Silva *et al.* (1999). Adopting the $\delta^{13}\text{C}$ curve as a reference, the FO of *E. floralis* also appears to be slightly diachronous because it occurs in the C4 segment in Mexico (Bralower *et al.* 1999) (in that section the OAE1a hence spans the upper *C. litterarius*/*G. blowi* and the *R. angustus*/*L. cabri* zones), in the middle part of the C7 segment or at its base in the Cismon outcrop and core respectively (Hochuli *et al.* 1999; Erba *et al.* 1999) and in the C6 segment in the Coppitella section (this study).

Taking into account the above mentioned data, if we refer to the chemostratigraphic Selli Event defined for the Cismon section between the C3 segment and C6/C7 boundary of the $\delta^{13}\text{C}$ curve, only the lower thin black shale of the Coppitella section represents the Selli Level. However, it must be noted that, in the Gargano Promontory as in other areas, the deposition of organic matter encompasses the FO of *E. floralis* and therefore straddles the Early/Late Aptian boundary.

A final point with respect to the total carbon-isotope profile of the Coppitella section is the fact that the absolute values are both more scattered and lower by some 1–2‰ than those recorded from other Tethyan sections (e.g. Roter Sattel and Cismon) and Mexico (Scholle & Arthur, 1980). Given that diagenesis does not greatly alter carbon-isotope values in pelagic sediments containing little organic matter, as is the case for most of the Coppitella section, these relatively low values are taken primarily to represent the isotopic composition of the watermass/es from which carbonate material was derived (e.g. Marshall, 1992). The proximity of the Coppitella section to the Apulia Platform suggests that the pelagic component may have been diluted by variable input of fine-grained aragonite and calcite of shallow-water origin. Such material may have recorded the carbon isotopic signature of a watermass with somewhat lower values than that of the pelagic domain (cf. Patterson & Walter, 1994). Carbon-isotope values in Greek and Croatian Cretaceous platform carbonates follow global trends but are typically offset negatively by ~1‰ (Grötsch, Billing & Vahrenkamp, 1998; Davey & Jenkyns, 1999).

The $\delta^{18}\text{O}$ profile of the Coppitella section shows too much scatter to be readily interpreted; two segments (O1, probable warming trend; and O2, probable cooling trend) are tentatively recognized (Fig. 5) and correlated with their equivalents in the Cismon and Roter Sattel sections (Menegatti *et al.* 1988). The absolute $\delta^{18}\text{O}$ values are similar to those recorded from Cismon.

7. Summary and conclusions

Figure 10 summarizes and correlates the main biotic and isotopic events recorded in the Aptian interval of the Coppitella section from the Gargano Promontory. The stable-isotope analysis carried out for the Coppitella section provides a high-resolution $\delta^{13}\text{C}$ curve for the Selli Event in the Tethyan realm, which correlates well with those previously published (Fig. 5). Conversely, the sedimentary expression of this event appears to be unusual in the Gargano Promontory. In fact, the base of the chemostratigraphic Selli Event, coinciding with the C4 segment according to Menegatti *et al.* (1998), is not characterized by preservation of organic matter. Nevertheless, the thickness of the interval corresponding to the chemostratigraphic Selli Event is comparable in the

Coppitella section and Cismon section (Menegatti *et al.* 1998; Erba *et al.* 1999). In the section studied, only a first, thin, organic-rich level is present at the top of the C5 segment; however, the section is partially covered in this tract. Moreover, according to our biostratigraphic data, another black level post-dates the FO of *E. floralis* (Fig. 10). Similar evidence for an Upper Aptian organic-rich black level is recorded in northeastern Mexico (Bralower *et al.* 1999).

The crisis of nannoconids is documented below the Selli Level in the Tethyan realm, Boreal realm, and Atlantic and Pacific oceans (Bralower *et al.* 1994; Erba, 1994; Aguado *et al.* 1999; Bralower *et al.* 1999; Cobianchi, Luciani & Menegatti, 1999; Erba *et al.* 1999; Habermann & Mutterlose, 1999; Larson & Erba, 1999; Premoli Silva *et al.* 1999). Our data allow a more precise placement of this event at the top of the C2 chemostratigraphic segment (Fig. 10), as reported also by Erba *et al.* (1999). The crisis of nannoconids appears to be the only global biotic event across this interval. Conversely, other biological distribution patterns vary in the different areas. A crisis of the globigerinelloidid group, showing a drop in abundance below and within the Selli Level from the Gorgo a Cerbara section (Umbria-Marche: Coccioni, Erba & Premoli Silva, 1992) and Cismon core (Southern Alps: Premoli Silva *et al.* 1999), is recorded in the Coppitella section but took place below and within the upper black level in the C7 carbon-isotope segment, above the chemostratigraphic Selli Level. The crisis coincides with a peak of high-fertility indices such as calcareous nannofossils and radiolaria (Fig. 10). This evidence appears to confirm the supposed palaeoecological significance of the globigerinelloidids, considered as a meso-oligotrophic group in this stratigraphic interval (Coccioni, Erba & Premoli Silva, 1992). The acme of leupoldinids at the base of the Selli Level, documented in the Cismon core by Premoli Silva *et al.* (1999), is not recorded in the section investigated here, probably owing to lack of preservation. Sensitivity to diagenesis of *L. cabri* and scarcity at the beginning of its range can probably explain the apparent diachroneity in the FO of the species and, as a consequence, the different zonal attribution of the Selli Level or its equivalents (Magniez-Jannin, Bréheret & Delanoy, 1997; Aguado *et al.* 1999; Larson & Erba, 1999; Premoli Silva *et al.* 1999).

The quantitative analyses of the micropalaeontological content of the section studied highlight several peaks of high-fertility indices (calcareous nannofossils and radiolaria), but only in the C7 segment are they associated with preservation of organic matter (Fig. 10). The occurrence of benthic foraminiferal faunas in both the basal and upper black horizons indicates that anoxic conditions on the sea floor were not obtained; dysoxic environments are, however, indicated by impoverished, small assemblages within the two black levels (see also Premoli Silva *et al.* 1999).

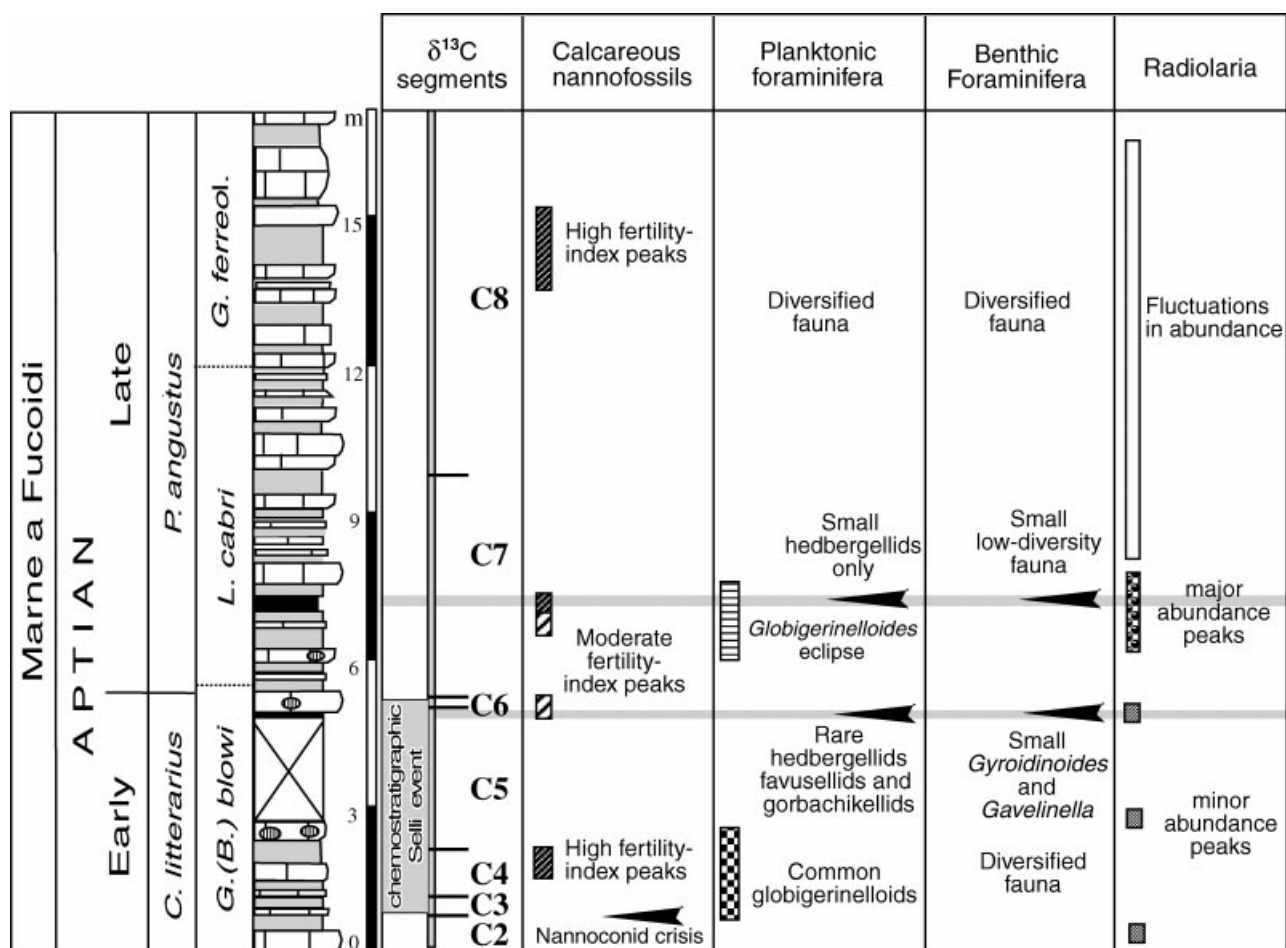


Figure 10. Correlation between lithostratigraphy and stable carbon-isotope and biotic main events in the Coppitella section. The stippled bands represent the lower and upper black shales. For the legend of the lithological symbols see Figure 5. Note that the early part of the Selli Event (chemostratigraphically defined) is not characterized by black-shale deposition. The single biotic change preceding the Selli Event is the 'nannoconid crisis'. The upper black shale corresponds to the main Aptian positive excursion of the carbon-isotope curve (basal part of C7 segment). Note also that the two black-shale levels are not devoid of calcareous plankton and benthos, although microfossil assemblages are impoverished; a major perturbation in the biotic signal is registered within the upper black shale. An increase of high-fertility indices (*Z. erectus*, *Z. diplogrammus*, *B. costans* and radiolaria) occurs exclusively in the upper black shale and in the upper part of the section.

Differences in the biotic distribution patterns, TOC content and lithological features emerge from the recent studies of the Selli Event in different basins (Bralower *et al.* 1994; Jenkyns, 1995; Menegatti *et al.* 1998; Aguado *et al.* 1999; Bralower *et al.* 1999; Cobianchi, Luciani & Menegatti, 1999; Habermann & Mutterlose, 1999; Jenkyns & Wilson, 1999; Larson & Erba, 1999; Premoli Silva *et al.* 1999). Enhanced organic-matter preservation in the sedimentary record depends on many factors, such as physiography of the basin, climate, terrestrial organic input, marine organic productivity, dissolved oxygen levels, oceanic circulation, sedimentation rate and water depth. The episodes of organic-matter preservation in the geological record are caused by the co-occurrence of many of the above-mentioned factors, presumably with the local dominance of one of these; nevertheless, the different causes

are not easily distinguishable from one another, even using diverse stratigraphic approaches.

An intense scientific debate exists as to the causality of Oceanic Anoxic Events, and the potential global mechanisms have been widely discussed. The Selli Event was likely associated with an increased flux of CO₂ into the atmosphere, induced by rapid sea-floor spreading and emplacement of mid-plate plateaus, which may have produced warmer, humid conditions (mid-Cretaceous 'greenhouse'). These factors may have led to an intensified runoff of nutrients from the continents, and possibly a thermohaline stratification of the water-column (e.g. Schlanger & Jenkyns, 1976; Jenkyns, 1980, 1995, 1999; Weissert, 1989; Larson, 1991; Tarduno *et al.* 1991; Larson & Erba, 1999).

Many authors relate the increased preservation of organic matter in the sedimentary record during the

Selli Event to enhanced primary productivity (Coccioni, Erba & Premoli Silva, 1992; Erba *et al.* 1999; Hochuli *et al.* 1999; Jenkyns, 1999; Larson & Erba, 1999; Premoli Silva *et al.* 1999). A transition from oligotrophic to more fertile conditions can probably be supported for the Aptian oceans, though highly eutrophic conditions were not generally reached (Menegatti *et al.* 1998; Premoli Silva *et al.* 1999). In the present oceans, calcareous plankton becomes less competitive with respect to diatoms and dinoflagellates only in highly eutrophic environments (e.g. Hallock, 1987). Consequently, the occurrence of calcareous planktonic faunas across the Selli Level in various areas testifies to the fact that extreme globally fertile conditions were not achieved during this interval (e.g. Aguado *et al.* 1999; Cobianchi, Luciani & Menegatti, 1999; Erba *et al.* 1999; Premoli Silva *et al.* 1999). According to the data available, high-fertility taxa showing fluctuations during the Selli Event are probably of local significance. The high-productivity model requires an efficient circulation and nutrient recycling; it is thus possible that upwelling may have taken place locally, being related to peculiar conditions such as circulation patterns and basin geometry.

The black shales deposited during Oceanic Anoxic Events are commonly associated with transgressive facies, documented by drowning events of carbonate platforms adjacent to the basins investigated (e.g. Jenkyns, 1991; Erbacher & Thurow, 1997; Weissert *et al.* 1998; Bralower *et al.* 1999; Davey & Jenkyns, 1999). Flooding of landmasses and creation of shelf seas may have locally enhanced productivity, causing expansion of the oxygen-minimum zone (Jenkyns, 1980; Jenkyns, Gale & Corfield, 1994). In the Gargano Promontory, the lower/upper Aptian carbon-rich horizons are coeval with a drowning of the Apulia Platform margin (Luciani & Cobianchi, 1994; Bosellini, Morsilli & Neri, 1999). This drowning is illustrated by a wedge of Lower Aptian pelagic limestone in the northern Gargano (Cagnano-Varano areas) disconformably overlapping rudist mounds associated with oolitic grainstones of Berriasian age, in turn overlain by rudstone rich in orbitolinids and large rudist fragments (Bosellini, Morsilli & Neri, 1999). Additional evidence is documented in the southern Gargano. Here, the Hauterivian–Albian palaeo-slope and its connection with the platform are exposed on the southern side of the Val Carbonara (type section of the Mattinata Formation, Fig. 3). A wedge of pelagic mudstone subdivides the Mattinata 1 from the Mattinata 2 sequences (according to Bosellini, Morsilli & Neri, 1999), clearly representing a drowning event which caused the temporary inactivity of bioclastic export. Biostratigraphic data demonstrate that the wedge is of late Early Aptian/early Late Aptian age and it precisely spans the upper *C. litterarius* and lower *P. angustus* calcareous nannofossil zones (Luciani & Cobianchi, 1994). Drowning correlates

with the onset of deposition of the Marne a Fucoidi in the basin and with the Selli Event.

Although sea-level rise has often been linked to both Oceanic Anoxic Events and the drowning of carbonate platforms, globally high temperatures are another factor common to both phenomena (Jenkyns, 1999; Jenkyns & Wilson, 1999). High global temperatures can affect weathering patterns on the continents, input rate of nutrients to the oceans, intensity of wind-driven upwelling, and hence control plankton productivity and development of carbon-rich shales. Temperatures much above 30 °C also deleteriously affect those carbonate-producers containing photosynthetic symbionts, hence suppressing production of shallow-water carbonate.

Elucidating principal causative mechanisms for both oceanic anoxic events and platform drowning in the face of so many apparently related phenomena remains a major challenge for Mesozoic palaeoceanography which can only be answered by the acquisition of high-resolution stratigraphic data.

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