

Riv. It. Paleont. Strat.	v. 97	n. 3-4	pp. 455-484	Aprile 1992
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CALCAREOUS NANNOFOSSIL DISTRIBUTION IN PELAGIC RHYTHMIC SEDIMENTS (APTIAN-ALBIAN PIOBBICO CORE, CENTRAL ITALY)

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Key-words: Calcareous Nannofossils, Aptian-Albian, Pelagic rhythmic sediments, Piobbico core, Scisti a Fucoidi, Marche, Central Italy.

Riassunto. La Formazione aptiano-albiana degli Scisti a Fucoidi dell'Italia centrale rappresenta un esempio spettacolare della cosiddetta sedimentazione pelagica ciclica. Questa unità è costituita da alternanze multicolori di marne, argille marnose e calcari marnosi, con subordinati calcari e frequenti livelli di "black shales". Per chiarire i meccanismi responsabili delle ritmicità litologiche gli Scisti a Fucoidi sono stati studiati multidisciplinariamente in dettaglio nella carota di Piobbico (Marche).

Tre segmenti della carota sono stati analizzati quantitativamente per il loro contenuto in Nannofossili calcarei allo scopo di discernere tra fluttuazioni primarie delle associazioni e modificazioni indotte dalla diagenesi. Questi tre intervalli sono stati selezionati in quanto casi limite di tre tipi diversi di cicli litologici. I conteggi effettuati sulle nannoflore hanno permesso di individuare tre gruppi di indici: un Indice di Diagenesi, un Indice di Dissoluzione Primaria, Indici Paleoecologici di moderata e relativamente alta fertilità, di produttività carbonatica, di acque relativamente più calde e più fredde.

Negli Scisti a Fucoidi l'Aptiano superiore, rappresentato da calcari marnosi rossi con intercalazioni verdi, essenzialmente registra fluttuazioni di produttività carbonatica data dai nannoconidi, in un ambiente globalmente più ossigenato. Le argille marnose con frequenti "black shales" dell'Albiano basale sono affette da dissoluzione estremamente severa, ma i nannoconidi registrano ancora alcuni episodi di produttività carbonatica. L'Albiano superiore, rappresentato da calcari marnosi grigio-verdi con livelli di "black shales" modulati ciclicamente, registra lievi fluttuazioni di fertilità delle acque superficiali. Correlazioni tra la distribuzione degli Indici Paleoecologici dei Nannofossili calcarei, la litologia e la distribuzione dei Foraminiferi e delle tracce fossili indicano come causa dei cicli le variazioni dei parametri orbitali in grado di influenzare la circolazione e le caratteristiche chimico-fisiche ed ecologiche degli oceani.

I "black shales" ritmici di questo intervallo probabilmente si sono accumulati perchè la circolazione oceanica era limitata a causa di gradienti di temperatura più deboli, in un regime più caldo.

Abstract. The Aptian-Albian Scisti a Fucoidi Formation from Central Italy represents a spectacular example of pelagic cyclic sedimentation. It consists of a varicolored sequence of marlstone, marly claystone, and marly limestone, with subordinate limestone. Several black shale layers are scattered throughout the formation. In order to clarify the mechanisms responsible for the rhythmicity, the Scisti a Fucoidi Formation was multidisciplinary investigated in detail in the Piobbico core (Marche, Central Italy).

Calcareous nannofossil assemblages were quantitatively analyzed in three segments of the core in order to discern paleoceanographic fluctuations. These intervals were selected as representative lithologic end members characterized by three different types of cyclicity. On the basis of nannofossil assemblages, the following indices were identified: a Diagenesis Index (dissolution and overgrowth during burial), a Primary Dissolution Index (dissolution mainly at the sediment/water interface), Paleoecological Indices of higher and moderate fertility, of carbonate productivity, and of warmer and cooler waters.

Within the Scisti a Fucoidi, the Upper Aptian, consisting of red lithotypes with interbedded green layers, is strongly affected by diagenesis. However, nannoconids still record fluctuations of carbonate productivity probably in a cooler more oxygenated paleoenvironment. Lowermost Albian maroon claystones with frequent interbedded black shales, are affected by extremely severe dissolution but a few episodes of increased carbonate productivity are recorded by changes in nannoconid abundance. Upper Albian greenish-gray marly limestones with cyclically modulated black shales, record slight rhythmic fluctuations in surface water fertility. Correlations between the distribution of nannofossil indices and lithology along with foraminifer and trace fossil patterns point to a response to orbital perturbations capable of triggering changes in ocean circulation, chemistry, and ecology. The rhythmic black shales of this interval probably accumulated because of an increase in stratification or decrease in oxygenation related to weaker temperature gradients and warmer waters, respectively.

Introduction.

Middle Cretaceous pelagic sequences, in a variety of paleoenvironments and paleodepths record unusual organic carbon-rich facies (Schlanger & Jenkins, 1976; Schlanger & Cita, 1982; Arthur et al., 1990). These pelagic sequences are commonly characterized by well developed cyclicity expressed by limestone-marlstone couplets and redox rhythms. Several authors have tried to identify the mechanisms responsible for the accumulation and preservation of such a large amount of organic matter, and to decipher the origin of the rhythmic variability. Interpretations include productivity cycles, changes in bottom water oxygenation, dissolution cycles, dilution cycles due to terrigenous clastic input, rhythmic input of terrestrial organic matter, and winnowing cycles (e.g., ROCC group, 1986; Arthur et al., 1990; Fischer et al., 1990).

A core was drilled through the Aptian-Albian Scisti a Fucoidi Formation at Piobbico (Marche, Central Italy) to gain a better understanding of these problems. This formation is a land-outcropping analogue of the deep-sea sequences recovered in the Atlantic, Pacific, and Indian Oceans (Arthur & Premoli Silva, 1982; Arthur et al., 1984). A detailed multidisciplinary study was carried out on the Piobbico core including sedimentology, organic and inorganic geochemistry, calcareous nannofossil and foraminifer biostratigraphy and assemblage studies, and paleomagnetism (Fischer et al., 1985; Herbert & Fischer, 1986; Herbert et al., 1986; Pratt & King, 1986; Erba, 1986, 1988; Herbert, 1987; Premoli Silva, Erba et al., 1989; Premoli Silva, Tornaghi et al., 1989; Tornaghi et al., 1989; Napoleone & Ripepe, 1989; Ripepe, in press).

The aim of the present paper is to examine the calcareous nannofossil evidence for: 1) the type and the intensity of diagenetic modifications, and 2) the paleoceanographic conditions which led to cyclicity in Scisti a Fucoidi, and fluctuations of these conditions through the Aptian-Albian time interval. In fact, nannofloral abundance, composition, and preservation can provide climatic and paleoceanographic information along with constrains on diagenetic effects on primary signals. For this purpose semi-

quantitative and quantitative analyses were carried out on calcareous nannofossil assemblages to identify indices related to dissolution and diagenesis, and fluctuations of surface water parameters such as temperature and fertility.

Lithostratigraphy.

A 84 meter section was cored at Le Brece, located 3 km West of the town of Piobbico, Marche, Central Italy (Fig. 1). The core penetrated the entire Scisti a Fucoidi Formation including the upper and lower transitions and the uppermost portion of the Maiolica Formation. The recovery was excellent (98%) and the total thickness, corrected for the average dip of 23°, is 77.70 m of which 75.83 m correspond to the Scisti a Fucoidi, and 1.87 m to the underlying Maiolica Formation (Fig. 2).

The Scisti a Fucoidi Formation consists of a cyclically interbedded pelagic sequence of marlstone, marly limestone, marly claystone, and black shale (black sediment, usually with a low carbonate content and organic carbon higher than 1%) with subordinate limestone. On the basis of detailed analyses of colors, carbonate content, and occurrence or absence of black shale, 18 lithologic units were distinguished within the Scisti a Fucoidi; the oldest unit of the core corresponds to the Maiolica (Unit 19) (Fig. 2). For a complete description of the Piobbico core lithostratigraphy, see Erba (1988) and Tornaghi et al. (1989).

A total of 154 black shale layers are recorded in the cored sequence: 143 layers occur within the Scisti a Fucoidi Formation, and 11 within the Maiolica Formation. Black shales are not evenly distributed through the core. They are frequent, usually cyclically modulated, in units dominated by greenish-gray (Units 2, 4, 6, 8, 10, 12), olive gray (Unit 7), and marron (Unit 11) lithotypes. Black shale layers are absent in units characterized by red to reddish-brown colors (Units 5, 13, 15, 17). In units consisting of varicolored reddish and greenish lithotypes (Units 1, 3, 9, 14, 16) black shale is extremely rare. Unit 18, whose lower portion is correlatable with the regional marker Selli Level (Wezel, 1985; Coccioni et al., 1987, 1989) contains several black shale layers occasionally characterized by common fish remains and pyrite nodules. Frequent black shales are recorded in the Maiolica (Unit 19).

Biostratigraphy and chronostratigraphy.

A high resolution time scale is the key starting point for any estimate of accumulation rates, timing of rhythms, reconstruction of paleoceanographic conditions and their changes, and correlation of events. The chronology of the Piobbico core is based on integration of calcareous nannofossil (Erba, 1988) and planktonic foraminiferal (Tornaghi et al., 1989) biostratigraphy. On the basis of nannofossils, 10 biohorizons and 7 interval zones were identified, whereas 11 foraminiferal biozones were recognized (Fig. 2).

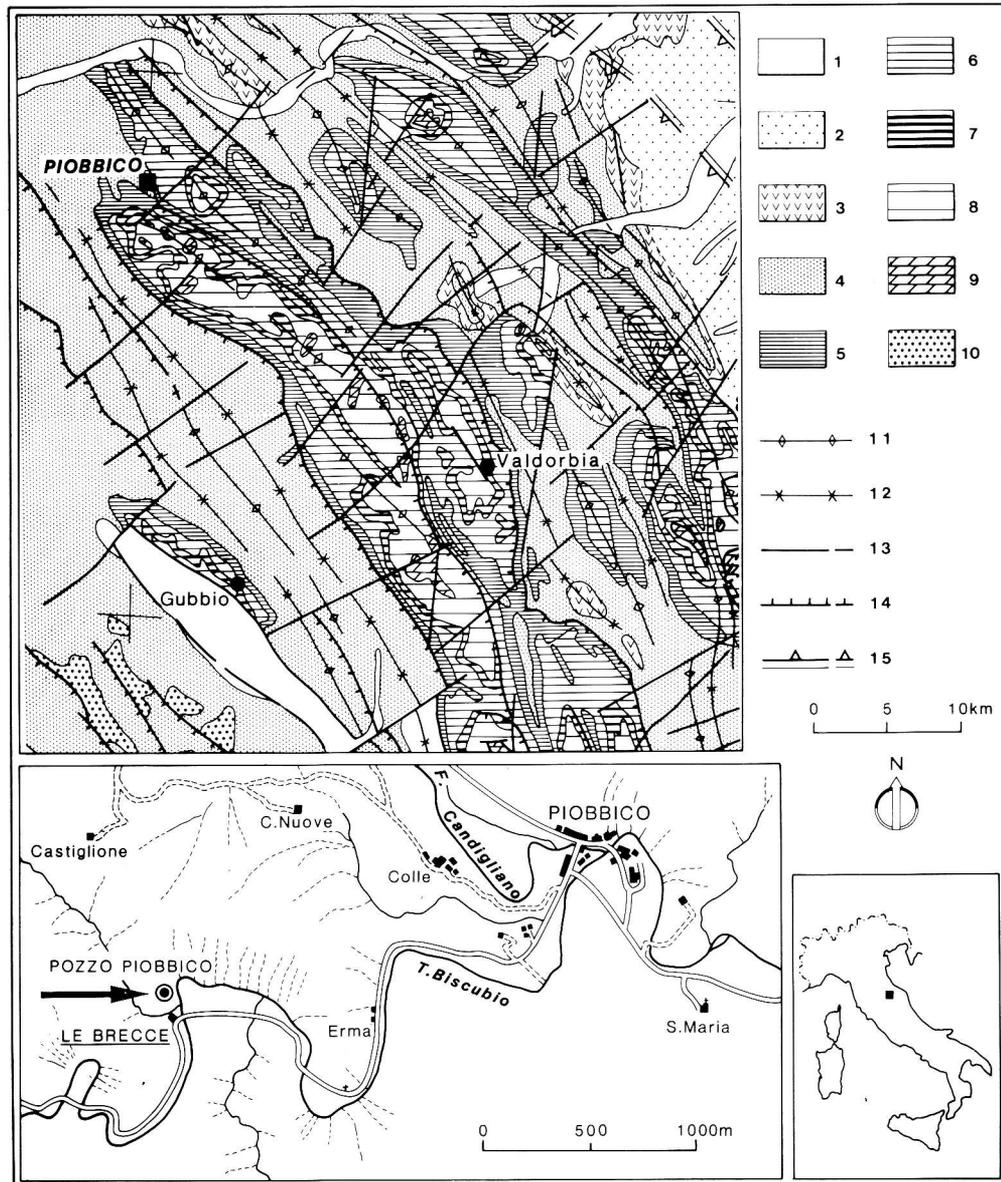


Fig. 1 - Geological map of the investigated area and location of the Piobbico core (after Erba, 1988). 1) Quaternary-Pliocene continental facies; 2) Quaternary-Pliocene marine terrigenous facies; 3) Messinian evaporitic facies; 4) Miocene marine terrigenous facies; 5) Oligocene-Paleocene pelagic facies; 6) Upper Cretaceous pelagic facies; 7) mid-Cretaceous pelagic facies (= Scisti a Fucoidi Formation); 8) Lower Cretaceous-Lower Jurassic pp. pelagic facies; 9) Lower Jurassic pp.-Upper Triassic carbonate platform facies; 10) allochthonous units; 11) anticline; 12) syncline; 13) fault; 14) thrust; 15) buried inverse fault.

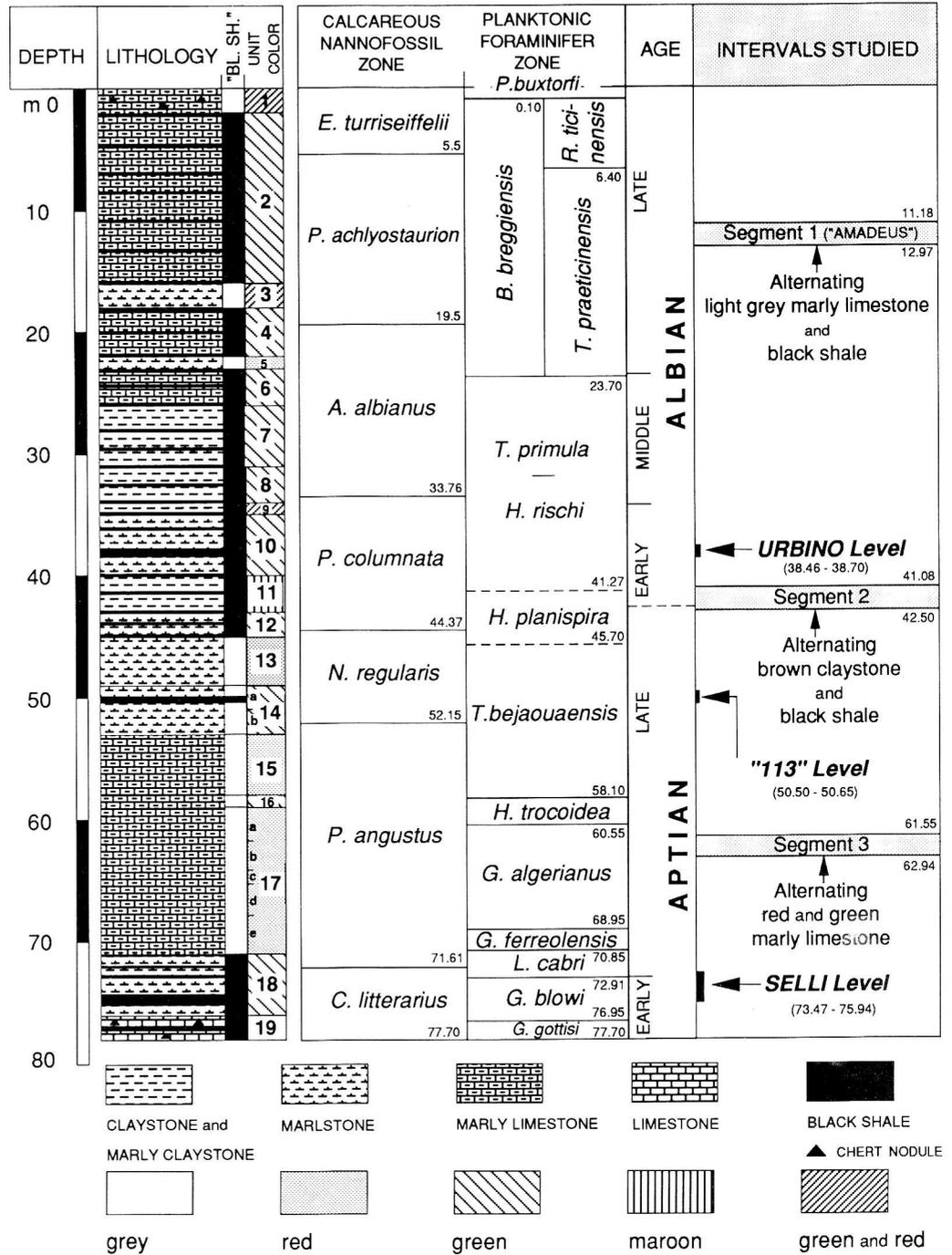


Fig. 2 - Lithostratigraphy and biostratigraphy of the Piobbico core. The intervals quantitatively studied for the nannofossil content are marked in the right column which reports also the position of the three distinctive regional marker black shale levels. Numbers indicate meters below surface. "BL.SH." indicate the occurrence of black shale layers.

Br  h  ret et al. (1986) and Delamette et al. (1986) changed the position of the Aptian/Albian boundary with respect to the calcareous planktonic biozones in sections from the Vocontian Trough (SE France), containing ammonites along with calcareous nannofossil and planktonic foraminifers. According to these authors, the Aptian/Albian boundary falls within the lower portion of the *Prediscosphaera columnata* nannofossil Zone (see also discussion in Erba, 1988). In the Piobbico core the Aptian/Albian boundary was estimated to fall at about -43 meters, within the lower portion of the peculiar maroon claystone of Unit 11. The Barremian/Aptian boundary was not reached and presumably occurs below the base of the core.

The Scisti a Fucoidi at Piobbico represent most of the Aptian-Albian interval. Fischer et al. (1985) estimated a duration of 18 My for the cored sequence and therefore calculated a mean accumulation rate of some 5m/My.

Middle Cretaceous nannofossil paleoecology.

In spite of their potential paleoceanographic indices, relatively few studies on middle Cretaceous calcareous nannofossil paleoecology have been carried out. In fact, most specialists have focused mainly on taxonomy and biostratigraphy. Some observations on Cretaceous nannofossil paleoecology were reported by Thierstein (1976). They include differences among assemblages from different paleolatitudes and settings (oceanic versus marginal). Perch-Nielsen (1979, 1985) summarized the information regarding the paleobiogeography and paleoecology of Cretaceous calcareous nannofossils and Late Cretaceous nannofossil biogeography was discussed by Thierstein (1981). Detailed paleoceanographic studies on mid-Cretaceous nannofloras were carried out by Roth & Bowdler (1981), Roth & Krumbach (1986), and Roth (1981, 1986, 1989). They systematically investigated paleobiogeography and paleoecology of the Atlantic, Pacific, and Indian Oceans by means of quantitative assemblage analyses and multivariate statistical techniques and could identify forms related to surface water fertility and temperature. Marginal seas were investigated by Watkins (1986, 1989) who studied the mid-Cretaceous of the Western Interior, Mutterlose (1987, 1989) and Mutterlose & Harding (1987a, b) who carried out semiquantitative and quantitative analyses on mid-Cretaceous phytoplankton from Germany, and by Erba, Guasti et al. (1989) and Erba, Castradori et al. (in press) who studied the Albian Gault Clay from Southern England.

Although our knowledge of middle Cretaceous nannofossil paleoecology is still relatively limited, a few useful indices have been identified. In fact, nannofossil distributions show both paleolatitudinal and oceanic-neritic gradients. High-latitude assemblages are characterized by high abundance of *Seribiscutum primitivum*, *Sollasites falklandensis*, *Biscutum constans*, *Zygodiscus elegans*, *Lithastrinus floralis*, *Corollithion* sp.; *Rucinolithus irregularis* is typically a tropical form. Oceanic assemblages consist of abundant *Watznaueria barnesae*, *Parhabdololithus asper*, and *P. splendens*, whereas *Broinsonia* spp., *Braarudosphaera* spp., *Micrantholithus* spp., *Nannoconus* spp. show prefer-

ences for continental margins and epicontinental seas. The paleoecological affinities of *Nannoconus* spp. are not completely understood (e.g., Erba, 1989), but they are carbonate rock-forming nannoliths and seem to have been Tethyan-derived forms suggestive of warmer surface water temperature. Also *P. asper* and *C. surirellus* seem to be related to warmer waters.

Continental margin assemblages characterized by common *B. constans*, *Z. elegans*, *Z. erectus*, *Z. diplogrammus* are indicative of paleo-upwelling sites.

Material and methods.

Calcareous nannofossil assemblages were semiquantitatively investigated in 80 samples from different lithologies throughout the Piobbico core, using a polarizing light microscope at 1250 X magnification. Visual estimates of assemblage preservation were performed according to the dissolution/overgrowth scale developed by Roth & Thierstein (1972) and Roth (1973, 1978).

In order to investigate diagenetic alteration and possible primary fluctuations of nannofossil assemblages related to paleoceanographic changes, quantitative analyses were performed in three intervals of the Piobbico core (Fig. 2). These intervals were selected as representative lithologic end members which display three different types of cyclicity.

SEGMENT 1 corresponds to -11.18 to -12.97 m (Unit 2). It consists of a cyclic sequence of light gray to greenish gray marly limestone and black shale, dated as Late Albian (*Parhabdolithus achlyostaurion* nannofossil Zone; *Ticinella praeticinensis* foraminiferal Zone). This segment overlaps with part of the section studied in detail by Fischer et al. (1985), Herbert & Fischer (1986), Herbert et al. (1986), Herbert (1987), Premoli Silva, Erba et al. (1989), Premoli Silva, Tornaghi et al. (1989), Napoleone & Ripepe (1989), and Ripepe (in press). Recently Coccioni & Galeotti (1991) named this portion of the Scisti a Fucoidi the "Amadeus Segment" to celebrate the second centennial anniversary of the death of Wolfgang Amadeus Mozart. I also use this name because the peculiar lithologic rhythms of the whitish marly limestone and black shale simulate a piano keyboard.

SEGMENT 2 corresponds to -41.08 to -42.50 m (Unit 11). It consists of maroon marly claystone with frequent interbedded black shale which correlate to the Early Albian *Prediscosphaera columnata* nannofossil Zone and *Hedbergella planispira* foraminiferal Zone.

SEGMENT 3 corresponds to -61.55 to -62.94 m (Unit 17). It consists of reddish marly limestone with interbedded greenish gray limestone, dated as Late Aptian (*Parhabdolithus angustus* nannofossil Zone; *Globigerinelloides algerianus* foraminiferal Zone).

A total of 170 samples (68 from segment 1, 43 from segment 2, and 59 from segment 3) were analyzed. They were collected every 2 cm and occasionally the sampling was even more closely spaced depending on changes in color, carbonate content,

and foraminiferal and radiolarian abundance. Particular attention was paid to avoid individual bioturbations, in order to prevent, or at least to minimize, mixing of different lithologies. Individual laminae were sampled from laminated intervals.

Sample preparation was kept simple to retain the original nannofossil assemblages and petrographic composition of sediments. For this reason neither size fractionation or ultrasonic cleaning were applied. Samples were ground using mortar and pestle, with distilled water. A drop of dispersed sediment was spread and dried on a cover glass and mounted with Canada Balsam for light microscope investigation. Smear slides were prepared as homogeneously as possible and thus the concentrations of different slides are comparable. For each smear slide 300 specimens were counted in randomly selected traverses. Samples from segment 2 in some cases contained such a depauperated nannoflora that 300 specimens could not be counted in a whole smear slide, thus a smaller number of nannofossils were counted. Nannofossil assemblage analysis was repeated on all samples excluding the dominant species, *W. barmesae*, from counts of 300 specimens.

Preservation of nannofloras.

Because calcareous nannofossils are the major constituents of pelagic carbonates, their preservation provides information on the type and degree of diagenesis undergone by the sediments. Visual estimates of etching and overgrowth in the Piobbico core indicate a moderate to poor preservation of the nannofloras, with fluctuations strongly related to lithology. According to Thierstein & Roth (1985, 1991) marlstone (40 to 55 % carbonate by weight) displays the best preservation and only minor dissolution evidence is present. In lithotypes with higher carbonate content sediments are dominated by diagenetic micarb and nannofossils are mostly overgrown. In lithotypes characterized by less than 40% carbonate, nannofloras mainly show evidence of dissolution. Micarb consists of micron-sized crystals deriving from disintegration of fragile planktonic foraminifers and coccoliths through dissolution along their sutures. Therefore they increase in abundance during progressive burial (Cook & Egbert, 1983) and can be considered as a measure of dissolution during burial.

In all the studied samples the assemblages are dominated by *Watznaueria barmesae* which varies in abundance from 30% to 100% of the total assemblage. High abundance of this taxon is usually regarded as indicative of dissolution/diagenesis and the boundary-value of 40% of *W. barmesae* was proposed to distinguish heavily altered nannofloras (Thierstein, 1980; Roth & Bowdler, 1981; Roth, 1984, 1986; Roth & Krumbach, 1986).

In spite of the abundance of *W. barmesae* in the Piobbico core, the nannofloras are relatively well diversified and solution-susceptible taxa are present and relatively abundant.

Further studies of nannofossil preservation were carried out on the three selected segments in order to identify indices of primary dissolution and diagenesis

taking into account also the total abundance of nannofossils, their preservation, the species diversity, the assemblage composition, and the abundance of micarb.

In order to quantify the relative fluctuations in the total abundance of calcareous nannofossils, I considered the average nannofossil abundance in each field of view. This parameter reflects both pulses in nannofossil productivity and flux changes in clastic fraction, as well as diagenetic impoverishment. Also the species diversity, equated to the number of species observed, is related to both surface water conditions and to diagenetic modification. The composition of the assemblages (i.e. the ratio between the dissolution-resistant and the susceptible forms) adds further information on the degree of diagenesis. The abundance of micarb was estimated as percentage of the total amount of carbonate particles.

Segment 1 ("Amadeus").

The Upper Albian segment 1 contains common to abundant calcareous nannofossils characterized by moderate preservation. As mentioned above, etching and overgrowth vary according to the various lithotypes. In Fig. 3 the fluctuations in the total abundance are plotted versus the carbonate content. The two curves are not directly correlated and thus the CaCO_3 content is not directly a function of nannofossil abundance. Indeed sediments are largely composed by micarb as shown in Fig. 3 displaying a direct correlation between the contribution of micarb and the carbonate content. A similar pattern was recorded by Thierstein & Roth (1991) for deep-sea rhythmic sequences of Early Cretaceous age.

The species diversity (i.e. number of species observed) is fairly high and the mean value (= 22) is the highest of the entire core. A slight inverse correlation was noted between species diversity and relative abundance of *W. barnesae* ($r = -.327$) (Fig. 4) suggesting minor diagenetic effects on nannofossil assemblages. In dissolved nannofossil assemblages Roth & Krumbach (1986) observed concurrent increase in abundance of *W. barnesae* and decrease in assemblage diversity. Watkins (1989) noted a very low correlation between these parameters suggesting that diagenesis had minor or no effect on nannofossils assemblage composition from the mid-Cretaceous Western Interior Basin.

A total of 30 species were identified; the relative abundance of the most common nannofossils are shown in Fig. 5. *W. barnesae* is the dominant form fluctuating between 31% and 75% of the assemblage, with a mean value of 57% (standard deviation = 9.8). Abundance of *W. barnesae* generally affects the abundance patterns of all the other species but patterns and amplitude of the fluctuations of the remanent taxa might still testify original inputs.

A slight inverse relationship between the relative abundance of *W. barnesae* and *Biscutum constans* was noted (Fig. 6). The same relationship was observed between *W. barnesae* and *Discorhabdus rotatorius* (Fig. 7). It must be noted that the inverse correlation is shown also when the relative abundances of *B. constans* and *D. rotatorius* from

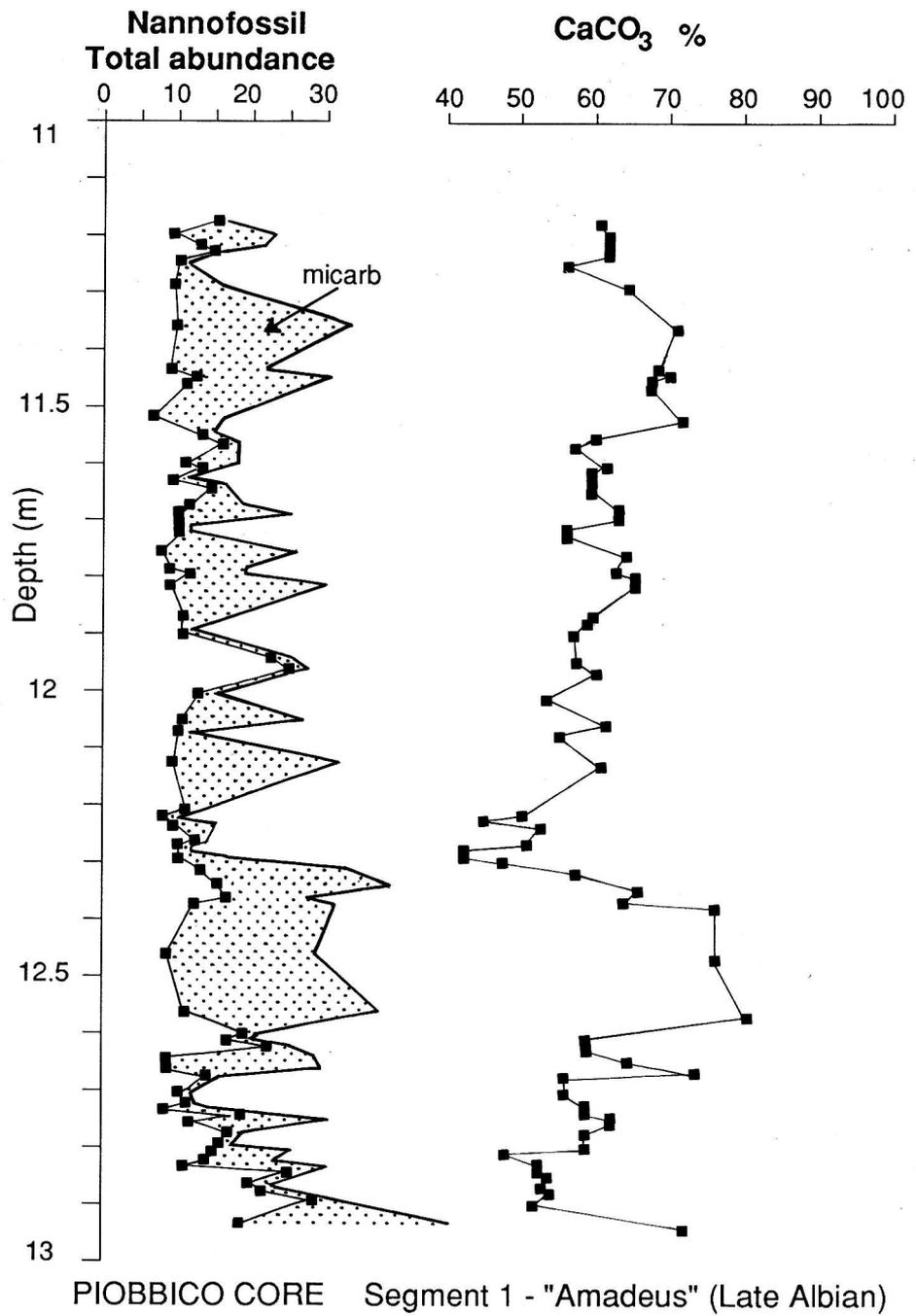


Fig. 3 - Fluctuations of nannofossil total abundance (equated to the average number of specimens in one field of view) and micarb plotted versus the carbonate content in segment 1 "Amadeus" (Late Albian).

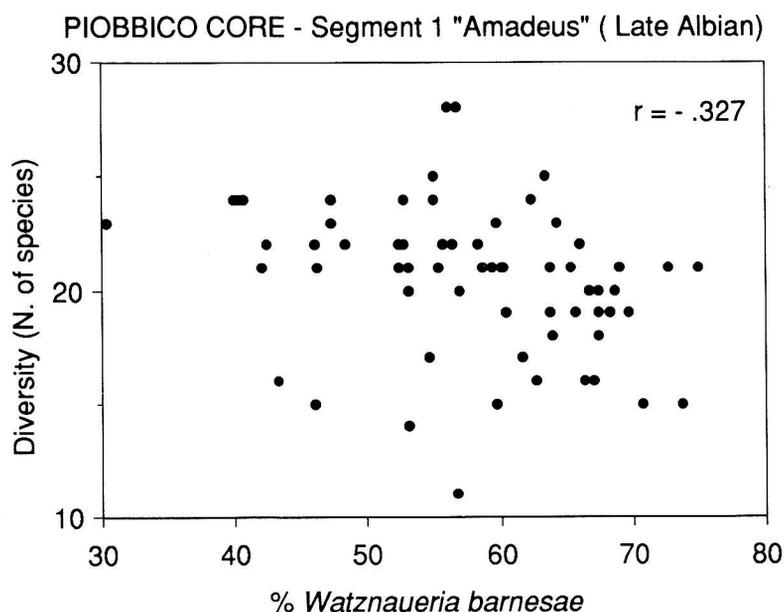


Fig. 4 - Abundance of *W. barnesae* plotted against species diversity in segment 1 "Amadeus" (Late Albian). Percentages are related to counts of 300 specimens including *W. barnesae*.

assemblages excluding the dominant species, *W. barnesae* are plotted. Fig. 8 reports the relative abundance of *W. barnesae* plotted versus the sum of *B. constans* + *D. rotatorius* + *Zygodiscus* spp. It must be noted that these relationships are confirmed by the countings of nannofossil assemblages excluding the dominant *W. barnesae* and therefore are not simply the result of a close sum problem. Roth & Krumbach (1986), Roth (1986, 1989), Erba, Guasti et al. (1989), Erba, Castradori et al. (in press), Watkins (1989) considered *B. constans* and *Zygodiscus* spp. as indicative of higher surface water fertility. This interpretation is supported by the paleontological and geochemical data from the Piobbico core. In fact increases in abundance of *B. constans* usually occur in samples enriched in radiolarians and/or characterized by high abundance of hedbergellids considered as indicative of more heterotrophic conditions (Premoli Silva, Erba et al., 1989; Tornaghi et al., 1989). Moreover, increases in abundance of *B. constans* (up to 50%) and *D. rotatorius* (up to 25%) are recorded in the black shales of the Urbino Level and "113" Level, both characterized by high organic carbon content (5% TOC) and organic matter of marine origin suggesting increases of primary productivity (Premoli Silva, Erba et al., 1989; Erba, Premoli Silva et al., 1989).

Parhabdolithus asper fluctuates from 0.5% to 12% of the nannofossil assemblage, with a mean value of 5%. Other common species are *Rucinolithus irregularis* (mean abundance of 5%) and *Parhabdolithus embergeri* (mean abundance of 4%). The latter form is resistant to diagenesis and therefore its distribution pattern could be controlled

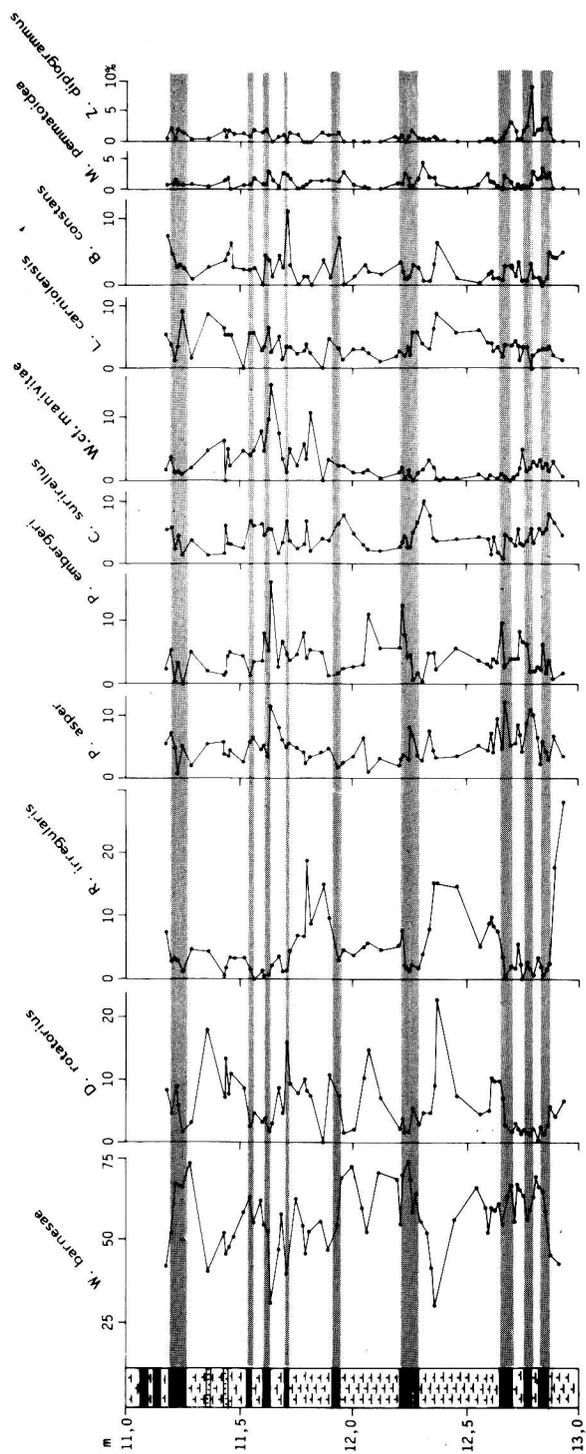


Fig. 5 - Distribution of the most abundant nannofossil taxa in segment 1 "Amadeus" (Late Albian). Percentages are related to counts of 300 specimens including *W. barrerae*.

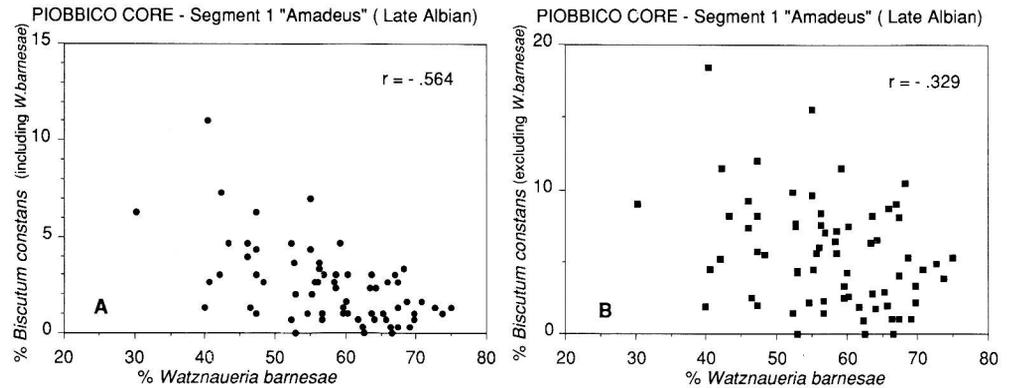


Fig. 6 - Relationship between abundance of *W. barnesae* and of *B. constans* in segment 1 "Amadeus" (Late Albian). A) Percentages of *B. constans* calculated including the dominant species *W. barnesae* in counts of 300 specimens; B) percentages of *B. constans* calculated excluding the dominant species *W. barnesae* from counts of 300 specimens.

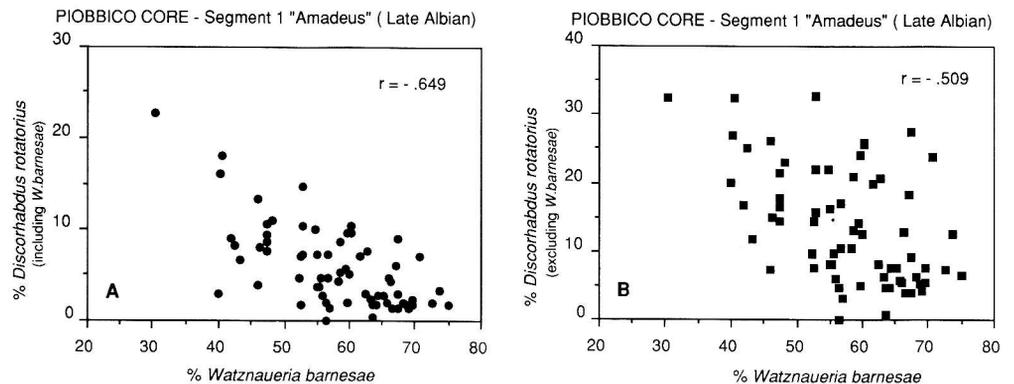


Fig. 7 - Relationship between abundance of *W. barnesae* and of *D. rotatorius* in segment 1 "Amadeus" (Late Albian). A) Percentages of *D. rotatorius* calculated including the dominant species *W. barnesae* in counts of 300 specimens; B) percentages of *D. rotatorius* calculated excluding the dominant species *W. barnesae* from counts of 300 specimens.

by secondary alteration and, indeed, a direct correlation with *W. barnesae* was recorded. Paleoecologic affinities have not been ascertained for *R. irregularis*, but this is a tropical form (Thierstein, 1976) which could be related to warmer waters.

Only five other species record a mean abundance of at least 1% of the nannofloras. They are *Cretarhabdus surirellus*, *Watznaueria* cf. *manivitae*, *Lithraphidites carnioleensis*, *Manivitella pemmatoidea* and *Zygodiscus diplogrammus*.

The relationships between the abundance of *W. barnesae* and the occurrence of black shale is not clear. In five out of ten black shale layers, this taxon increases in

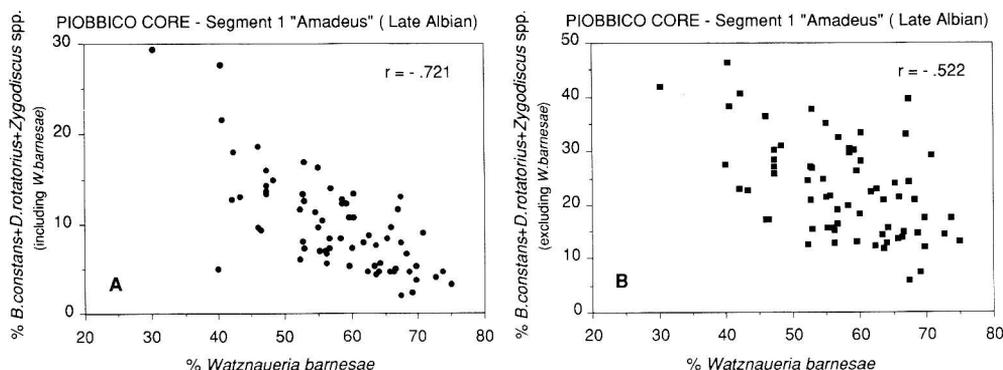


Fig. 8 - Relationship between abundance of *W. barnesae* and of *B. constans* + *D. rotatorius* + *Zygodiscus* spp. in segment 1 "Amadeus" (Late Albian). A) Percentages of *B. constans* + *D. rotatorius* + *Zygodiscus* spp. calculated including the dominant species *W. barnesae* in counts of 300 specimens; B) percentages of *B. constans* + *D. rotatorius* + *Zygodiscus* spp. calculated excluding the dominant species *W. barnesae* from counts of 300 specimens.

abundance and most likely the enrichment is due to dissolution. This interpretation is substantiated by the co-occurrence both of a lower diversity and a poorer preservation. In the other cases, *W. barnesae* decreases in abundance passing from marly limestones to black shales, whereas diversity and preservation do not change. In these black shale layers a higher abundance of *P. asper* and/or *L. carniolensis* was observed. Since both taxa are considered intermediate with respect to dissolution (Thierstein, 1980; Roth & Bowdler, 1981; Roth & Krumbach, 1986) their increases in abundance might reflect warmer waters.

Segment 2.

Segment 2 contains rare calcareous nannofossils and some layers are completely barren. The carbonate content is the lowest of the entire sequence, fluctuating from 0.6% to 51%, with a mean value of 17.5%.

Nannofossil abundance shows a direct correlation with carbonate content (Fig. 9). Micarb is extremely rare throughout this segment. In samples recording the lowest CaCO_3 content, common-abundant rhombohedral crystals of dolomite were observed. Roth (1984) reported an analogous situation for coeval sediments drilled in the southern Angola Basin and hypothesized an in situ growth during burial and a high dissolution-resistance of dolomite.

Calcareous nannofossils are characterized by extremely poor preservation with strong evidence of etching. Species diversity is very low (mean value = 6 species), the lowest of the entire core. Fig. 10 shows the fluctuations of the most abundant nannofossils (mean value > 1%). Excluding the samples barren of calcareous nannofossils,

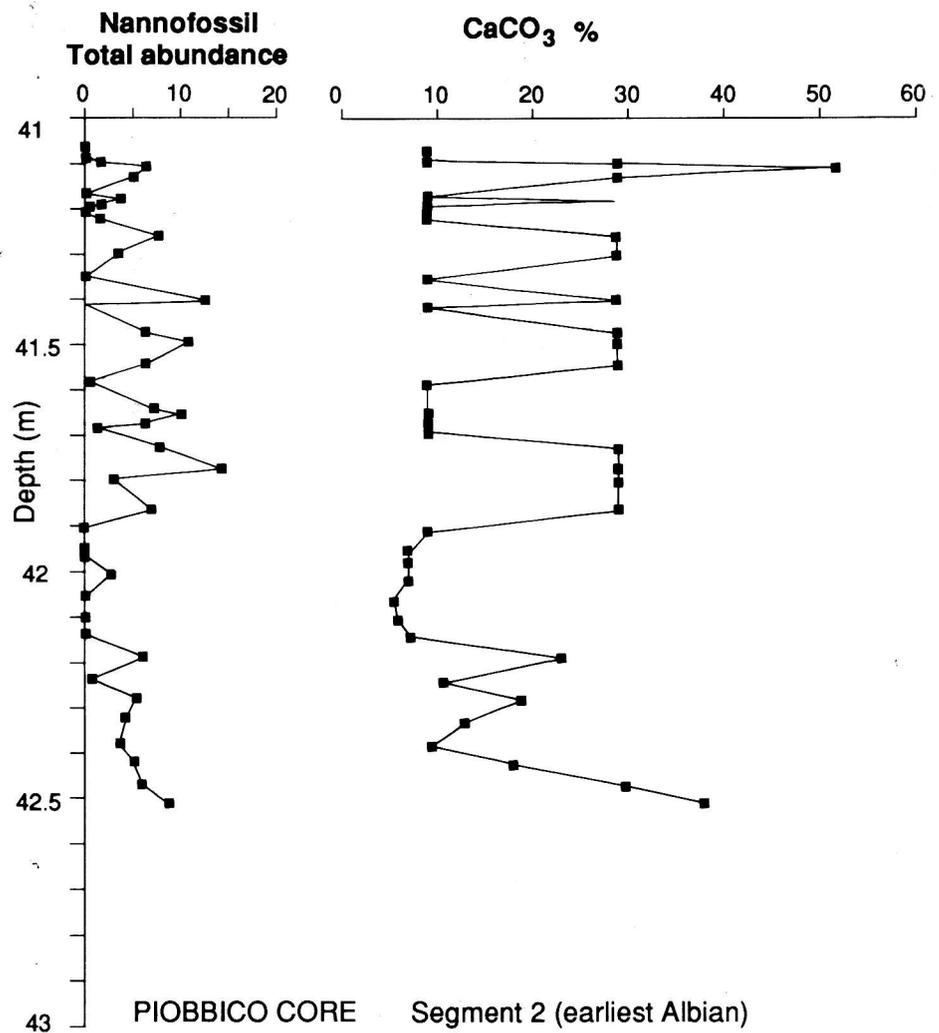


Fig. 9 - Fluctuations of nannofossil total abundance (equated to the average number of specimens in one field of view) and of the carbonate content in segment 2 (earliest Albian).

W. barnesae varies from 12.5% to 100% of the nannofloras (mean value 72.5%). *P. embergeri* is the second most abundant taxon and fluctuates between 0% and 7%, with a mean value of 2.2%. Both *R. irregularis* and *Nannoconus* spp. record a mean relative abundance of 2% and fluctuate independently from *W. barnesae*. The correlation coefficient between *W. barnesae* and *R. irregularis* is $r = .116$, whereas between *W. barnesae* and nannoconids is $r = .162$ (Fig. 11). This implies that the distribution of *Nannoconus* spp. is not necessarily dependent on diagenetic modification (i.e. induced by sample

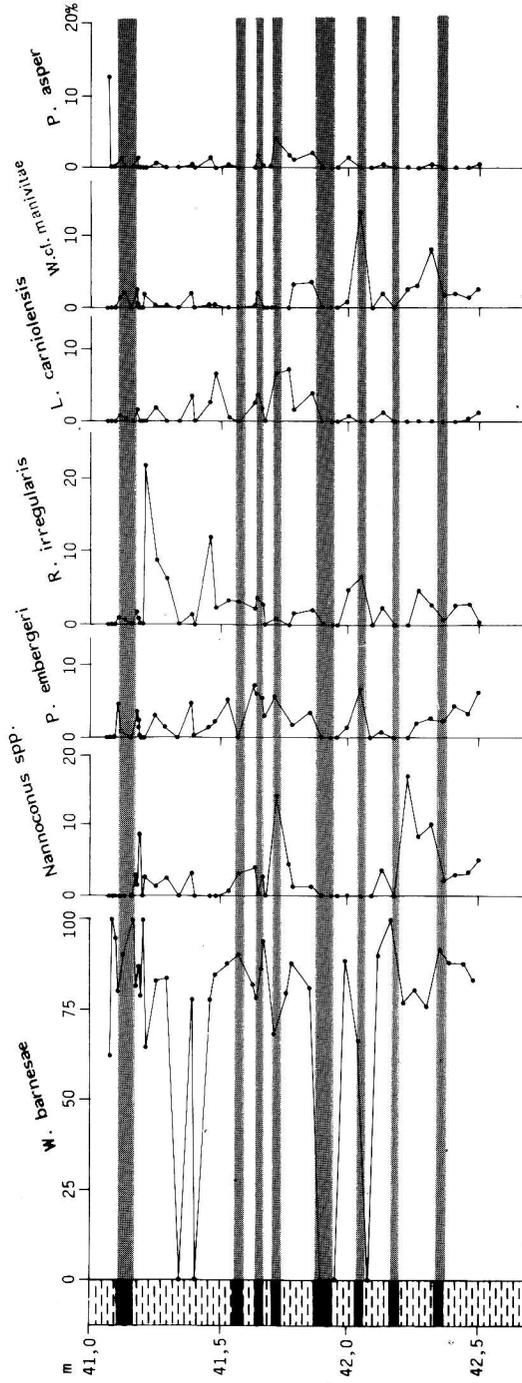


Fig. 10 - Distribution of the most abundant nannofossil taxa in segment 2 (earliest Albian). Percentages are related to counts 300 specimens including *W. b. parvius*.

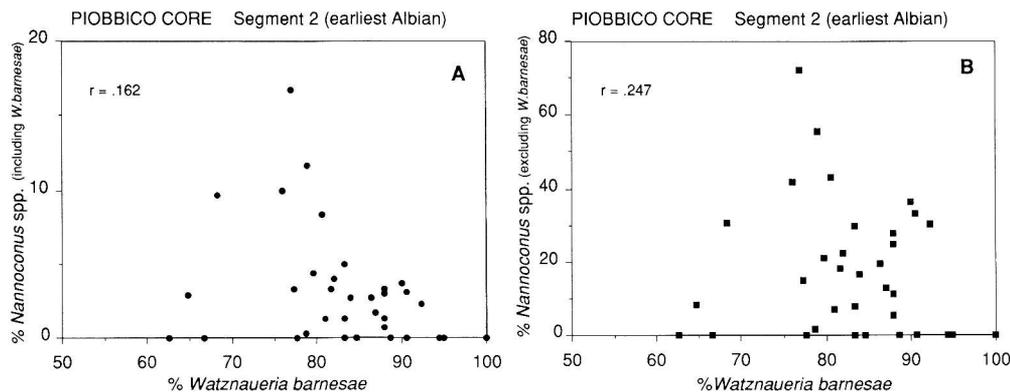


Fig. 11 - Relationship between abundance of *W. barnesae* and of *Nannoconus* spp. in segment 2 (earliest Albian). A) Percentages of *Nannoconus* spp. calculated including the dominant species *W. barnesae* in counts of 300 specimens; B) percentages of *Nannoconus* spp. calculated excluding the dominant species *W. barnesae* from counts of 300 specimens.

preservation) also because nannoconids are characterized by a very low susceptibility to dissolution (Thierstein, 1976; Noel & Melguen, 1978). The abundance pattern of *Nannoconus* spp. is peculiar because, following the stratigraphic order, they record three discrete "peaks" approximately equally spaced every 50 cm corresponding to some 100,000 years. Nannoconids may retain a primary signal related to fluctuations in carbonate productivity.

Among all the other forms, only *W. cf. manivita* and *L. carniolensis* display a mean value of 1%. The nannofossil assemblages of this segment are interpreted as modified by primary dissolution at the sediment/water interface and during burial to such an extent that paleoceanographic interpretations should not be attempted.

Segment 3.

Calcareous nannofossils are common to abundant in the Upper Aptian segment 3. Their total abundance is compared with the CaCO_3 content in Fig. 12. The fluctuations in nannofossil abundance are quite limited and are mostly inversely correlated to the carbonate content. In fact, a large amount of micarb was observed and its contribution to sediments is somewhat inversely correlated to the nannofossil contribution, as previously pointed out for segment 1 but not for segment 2. Micarb is abundant in samples recording a carbonate content higher than 55%. The species diversity is fairly low (mean value = 14) and is inversely correlated with the abundance of *W. barnesae* ($r = -.47$) (Fig. 13). Preservation is moderate to poor; etching and overgrowth are dependent upon the lithologies. *W. barnesae* is again the dominant form ranging from 53% to 82% with mean percentage of 68% (Fig. 14).

The relative abundance of the most common species is reported in Fig. 14. These abundances are strongly affected by the content of *W. barnesae*. *Watznaueria*

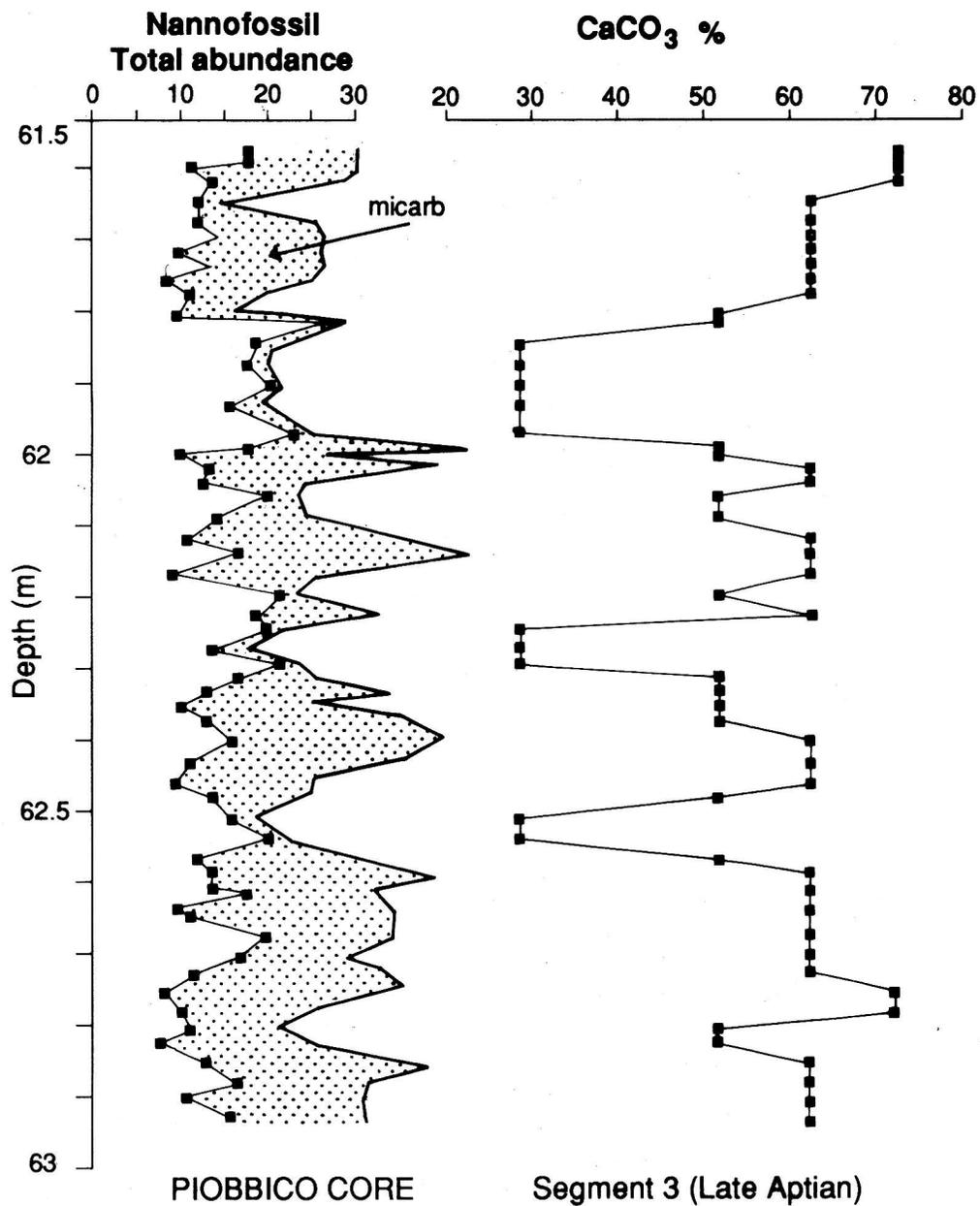


Fig. 12 - Fluctuations of nannofossil total abundance (equated to the average number of specimens in one field of view) and micarb plotted versus the carbonate content in segment 3 (Late Aptian).

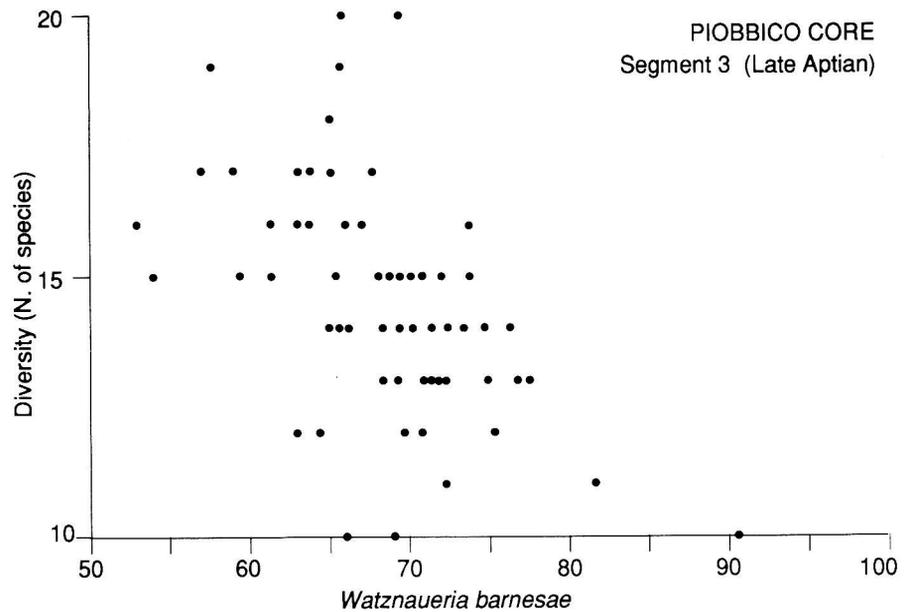


Fig. 13 - Abundance of *W. barnesae* plotted against species diversity in segment 3 (Late Aptian).

supracretacea has a mean abundance of 5.7% and its distribution is inversely correlated to the dominant form. *P. asper* fluctuates from 2% to 10% of the assemblages (mean abundance of 5%), displaying an inverse relationship with *W. barnesae*. As previously pointed out for segment 1, the pattern of *P. asper* is analogous to the distribution of *L. carniolensis* (mean abundance of 4%). *P. embergeri* and *D. rotatorius* record mean relative abundances of 5%. Peaks of abundance of the latter taxon are recorded in samples also containing few *B. constans* and *Zygodiscus* spp. otherwise absent in this portion of the core. Moreover, an inverse relationship between the abundance of *D. rotatorius* and *D. rotatorius* + *B. constans* + *Zygodiscus* spp. versus *W. barnesae* is illustrated in Fig. 15 and 16, respectively. *R. irregularis* has a mean relative abundance of 3% and its distribution is independent from *W. barnesae*. Relatively high fluctuations in abundance are recorded by *Nannoconus* spp. ranging from 0% to 9% (mean value = 2%) and are independent from the dominant species (Fig. 17). As previously pointed out for segment 2, layers completely barren of nannoconids alternate with relatively rich ones. Also in this segment, maxima are equally spaced approximately every 50 cm corresponding to some 100,000 years.

L. floralis has a mean abundance of 1.3% and its relative abundance is the highest of the entire core. This taxon is a dissolution resistant form (Roth, 1984) displaying a strong affinity for high paleolatitudes (Roth & Krumbach, 1986) and therefore for relatively colder waters. Increases in abundance of *L. floralis* could suggest a diagenetic control or a cooling of surface waters.

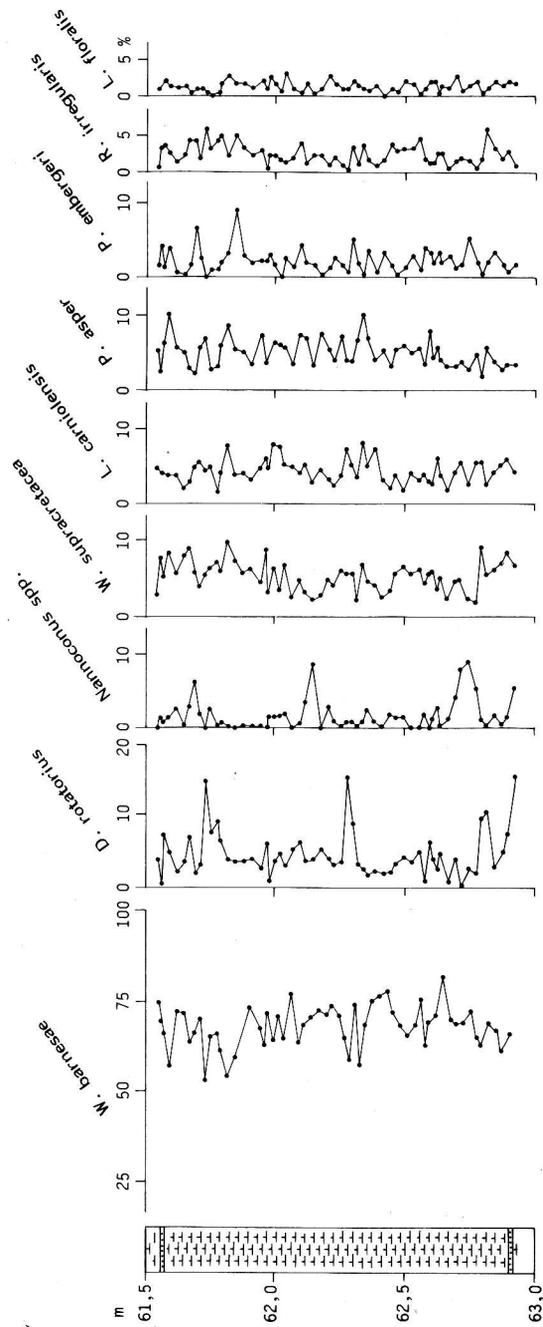


Fig. 14 - Distribution of the most abundant nannofossil taxa in segment 3 (Late Aptian). Percentages are related to counts of 300 specimens including *W. barnesae*.

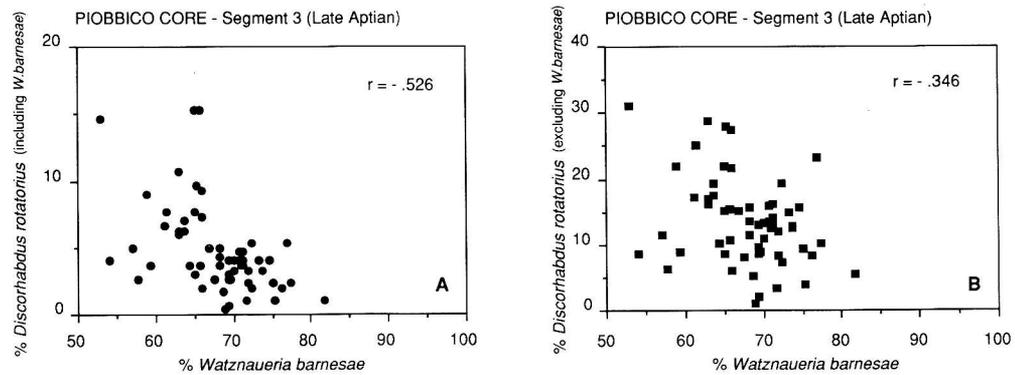


Fig. 15 - Relationship between abundance of *W. barnesae* and of *D. rotatorius* in segment 3 (Late Aptian). A) Percentages of *D. rotatorius* calculated including the dominant species *W. barnesae* in counts of 300 specimens; B) percentages of *D. rotatorius* calculated excluding the dominant species *W. barnesae* from counts of 300 specimens.

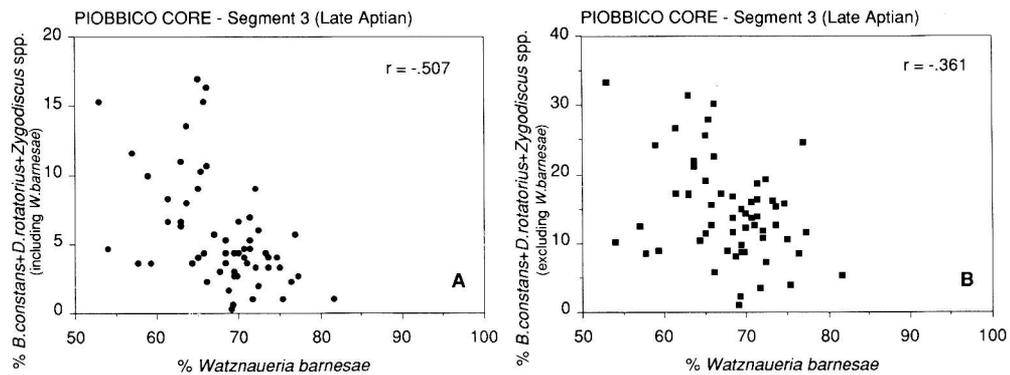


Fig. 16 - Relationship between abundance of *W. barnesae* and of *B. constans* + *D. rotatorius* + *Zygodiscus* spp. in segment 3 (Late Aptian). A) Percentages of *B. constans* + *D. rotatorius* + *Zygodiscus* spp. calculated including the dominant species *W. barnesae* in counts of 300 specimens; B) percentages of *B. constans* + *D. rotatorius* + *Zygodiscus* spp. calculated excluding the dominant species *W. barnesae* from counts of 300 specimens.

Diagenesis, primary dissolution, and paleoecological indices.

Quantitative analyses allow some constraints to be placed on the diagenetic history and paleoceanographic events recorded by the Scisti a Fucoidi.

- The *Diagenesis Yndex* (dissolution and overgrowth during burial) is identified by high abundance of *W. barnesae* (% total nannofloras), low species diversity, medium to high abundance of nannofossils, and high abundance of micarb.

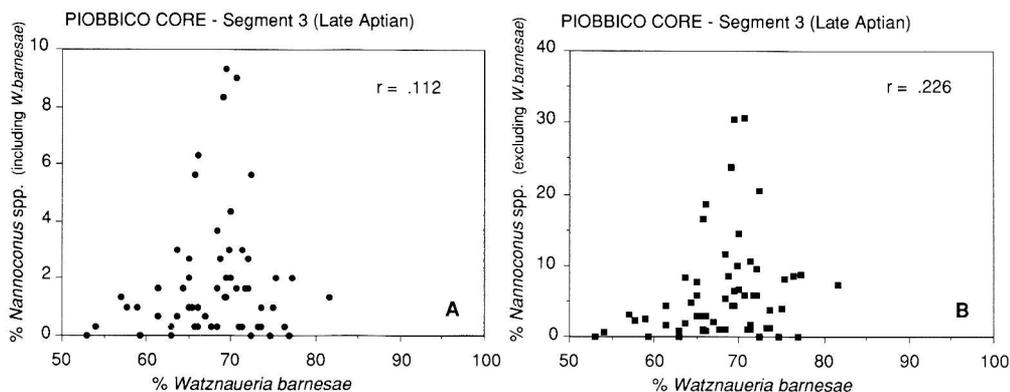


Fig. 17 - Relationship between abundance of *W. barnesae* and of *Nannoconus* spp. in the segment 3 (Late Aptian). A) Percentages of *Nannoconus* spp. calculated including the dominant species *W. barnesae* in counts of 300 specimens; B) percentages of *Nannoconus* spp. calculated excluding the dominant species *W. barnesae* from counts of 300 specimens.

- High abundance of *W. barnesae* (% total nannofloras), low total abundance of nannofossils, low species diversity and absence or very low abundance of micarb characterize the *Primary Dissolution Index*. Most probably this primary dissolution took place at the sediment/water interface preventing micarb formation during burial.

- The fluctuations in abundance of various species yielded some *Paleoecological Indices*. *Index A*, typified by *B. constans*, *D. rotatorius*, and *Zygodiscus* spp., indicate higher fertility of surface waters. *P. asper* and *L. carniolensis* correspond to *Index B* suggestive of moderate fertility and warmer waters. *Index C* is marked by nannoconids recording increases in carbonate productivity.

Diagenesis, primary dissolution, and paleoecological indices are not evenly distributed in the three segments. Premoli Silva, Erba et al. (1989) discuss in detail the relationships between these indices, CaCO_3 content, planktonic foraminifer and radiolarian distribution, and geochemical data.

Diagenesis mostly affects segment 3, whereas segment 1 is only partially modified by diagenesis. Segment 2 is characterized by an intense primary dissolution, evidence of which are absent both in segment 1 and 3.

Samples from segment 1 record indices A and B (Fig. 18). On the basis of their occurrence, this portion of the core can be split into three parts. In the upper part from -11.18 to -12 m, the fertility Indices A and B are very closely spaced and they alternate with some rhythmicity. In the central 20 cm Index A is not recorded and Index B occurs only in 2 samples, whereas both Indices A and B characterize the lower portion of the segment, from -12,20 to -12,97 m. Index B usually occurs within black shale layers, whereas Index A is always recorded in limestones.

Segment 2 records Index C which never occurs in black shales and nannoconids are always associated with higher CaCO₃ content.

Segment 3 shows evidence of diagenetic modification but records Index C. Also in this portion of the Piobbico core nannoconids are related to higher carbonate contents.

Nannofossils and carbonate cycles.

The distribution of calcareous nannofossils in the Piobbico core displays high frequency fluctuations comparable to the lithologic rhythms studied by Fischer et al. (1985), Herbert & Fischer (1986), Herbert et al. (1986) who showed that they correlate with Milankovitch cycles. Undoubtedly primary dissolution and diagenesis altered the sediments and therefore cycles might be diagenetically enhanced. However, the data collected here show that the changes in composition of nannofossil assemblages still retain some primary characteristics. For example a few species show patterns not directly controlled by the solution-resistant taxon, *W. barnesae*.

In Upper Aptian segment 3 and Lower Albian segment 2, nannoconids record relatively high fluctuations in abundance directly correlatable to the carbonate content. Therefore in these intervals lithologic cycles seem to be related to nannofossil carbonate productivity. Upper Albian segment 1 is less affected by diagenesis and nannofossil assemblages display rhythmic changes in composition evidenced by rhythmic alternations of Indices A (higher fertility) and B (moderate fertility and warmer waters) (Fig. 18). Although Bralower & Thierstein (1984) suggested globally low average productivity in the middle Cretaceous, the present work suggests slight fluctuations of surface water fertility on the basis of nannofossil assemblages. Increases of the higher fertility indices (*B. constans*, *D. rotatorius*, and *Zygodiscus* spp.) can not be only induced by differential better preservation because these are more abundant in the limy layers where evidence of overgrowth is usually observed and because the same fluctuations are shown also when the solution-resistant dominant species, *W. barnesae*, is excluded from nannofossil counts. Rhythmic relative increases in fertility are also suggested by the foraminiferal assemblages characterized by hedbergellids indicative of more heterotrophic environments (Premoli Silva, Erba et al., 1989; Premoli Silva, Tornaghi et al., 1989; Tornaghi et al., 1989).

Other mid-Cretaceous rhythmic sequences from different basins have been investigated in their calcareous nannofossil content. Watkins (1989) studied the nannofossil assemblage composition of Cenomanian-Turonian marlstone-chalk cycles from the Western Interior Basin. Nannofossil assemblages are not affected by diagenesis and a direct correlation was pointed out between the relative abundance of *B. constans* and *Zygodiscus* sp. and lithologic rhythms. Watkins interpreted the cyclicity as the result of high frequency changes in surface water fertility. Also Roth (1989) noted temporal fluctuations in mid-Cretaceous nannofloral assemblages from the Atlantic Ocean and inferred high frequency fluctuations in surface water fertility and vertical mixing. Re-

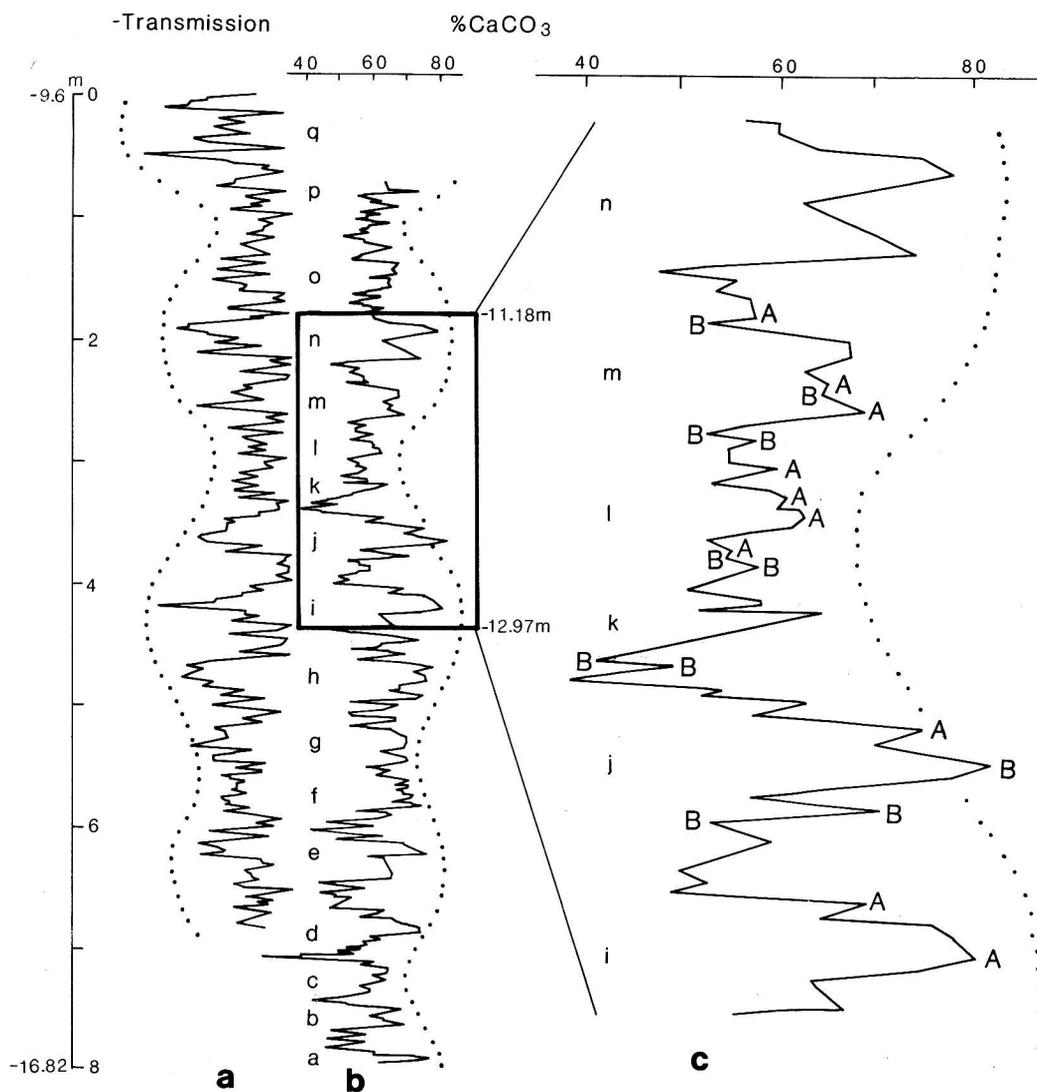


Fig. 18 - Distribution of nannofossil indices of higher fertility (A) and moderate fertility under warmer waters (B) in segment 1 "Amadeus" (Late Albian) (After Premoli Silva, Erba et al., 1989). This segment corresponds to the central portion of the interval studied by Herbert & Fischer (1986) for lithologic cycles and Premoli Silva, Tornaghi et al. (1989) for cycles in foraminiferal distribution. a) Light transparency; b) carbonate content; c) enlarged carbonate curve. Letters refer to cycles identified as bundles (100,000 y) by Herbert & Fischer (1986), dotted lines mark the 400,000 y envelopes.

cently, Thierstein & Roth (1991) published a multidisciplinary study of Early and middle Cretaceous carbonate cycles in deep-sea sediments from the Atlantic and Pacific Oceans. After inspection of changes in oxygen and carbon isotopes, lithology, organic carbon and carbonate content, as well as nannofossil assemblage composition, they concluded that the investigated sequences are dominated by diagenetic effects. Nannofossil assemblages vary little pointing to stable ecologic condition of oceanic surface waters. Lithologic cycles seem to be related to bioturbation intensity suggestive of varying deep-water and oxygen renewal rates. A quantitative study of trace fossil distribution was performed on the Upper Albian "Amadeus" segment of the Piobbico core (Premoli Silva & Erba, 1991, in prep.). Spectral analyses performed on changes in type and density of bioturbation showed periodicities correlatable with Milankovitch cycles. Moreover, the trace fossil density is directly correlated with the carbonate content. These data have been interpreted as the result of orbital perturbations. High seasonality, leading to a better stirring of the oceans, is responsible for both increased carbonate productivity and enhanced bottom water ventilation resulting in whitish bioturbated limestones. On the contrary, when seasonality is weak, carbonate productivity is lower and bottom waters less oxygenated, as represented by the black shale layers. Also the rhythms in nannofossil and foraminiferal assemblage composition are interpreted as reflecting climate sensitivity to forcing by insolation cycles. This implies that changes of orbital parameters are capable of triggering changes in ocean circulation and ecology. During times of high seasonality, vigorous circulation is characterized by higher fertility resulting in whitish bioturbated limy lithotypes recording nannofossil higher fertility indices and hedbergellids. During times of low precession and low seasonality more sluggish circulation is represented by black shales containing nannofossil indices of moderate fertility and warmer waters together with diverse more oligotrophic foraminiferal assemblage (Premoli Silva, Erba et al., 1989; Premoli Silva, Tornaghi et al., 1989; Tornaghi et al., 1989).

Conclusions.

In order to discriminate primary paleoceanographic signals from secondary diagenetic modifications recorded in the Aptian-Albian Scisti a Fucoidi Formation, semi-quantitative and quantitative analyses were carried out on calcareous nannofossil assemblages. Preservation, total abundance, species diversity, and assemblage composition provided information on the type and intensity of secondary modifications. A Diagenesis Index (dissolution and overgrowth during burial) and a Primary Dissolution Index (dissolution mostly at the sediment/water interface) were identified. Although diagenetic changes affected the nannofloras, some primary signals may still be recorded. Paleoecological Indices related to slight changes of fertility regime, temperature, and carbonate productivity were determined. These indices are not evenly distributed. The Late Aptian was characterized by fluctuations in carbonate productivity, recorded by changes in the relative proportion of nannoconids, possibly under cooler

and more oxygenated water conditions also indicated by absence of black shale horizons. Primary dissolution strongly affected the maroon claystones of earliest Albian age. However, peaks of nannoconids point to temporary increases in carbonate productivity. During the Late Albian, slight increases in fertility apparently occurred with some rhythmicity. Correlations with lithology, foraminifer and trace fossil distribution point to a response to orbital perturbation capable of triggering changes in ocean circulation and ecology. Further studies are required to more precisely estimate the periodicities of the nannofossil changes which possibly correlate to Milankovitch rhythms.

The black shale layers of this portion of the Scisti a Fucoidi are cyclically modulated and seem to be related to moderate fertility and warmer waters. Their organic carbon content is 1-2% by weight and the organic matter, of mixed marine and non marine origin, could accumulate as a result of increased stagnation related to weaker temperature gradients.

Acknowledgements.

On this occasion I wish to warmly thank all the friends of the Piobbico core and in particular Al Fischer, Isabella Premoli Silva, and Giovanni Napoleone who believed in their dreams and made cyclostratigraphy a working tool.

In the last nine years I greatly benefitted of discussion, help, and support by Lisa Pratt, Tim Herbert, Maurizio Ripepe, and Milly Tornaghi. I also wish to extend acknowledgements to Barbara Quadrio, Maurizio Orlando and the students who helped in cutting the Piobbico core.

A very special thank is extended to Tim Bralower for valuable advice, discussion and revision, and Prof. C. Rossi Ronchetti for the careful review of the manuscript.

This project was supported by a PhD fellowship to E.E. and M.P.I. 40% to I. Premoli Silva.

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