

Paleoenvironmental evolution of the eastern Mediterranean during the Messinian: Constraints from integrated microfossil data of the Pissouri Basin (Cyprus)

T.J. Kouwenhoven^{a,*}, C. Morigi^b, A. Negri^b, S. Giunta^b,
W. Krijgsman^c, J.-M. Rouchy^d

^a Department of Earth Sciences, Utrecht University, Budapestlaan 4, 3584 CD Utrecht, The Netherlands

^b Dipartimento di Scienze del Mare, Università Politecnica delle Marche, Via Brecce Bianche, 60131 Ancona, Italy

^c Paleomagnetic Laboratory 'Fort Hoofddijk', Faculty of Geosciences, Utrecht University, Budapestlaan 17, 3584 CD Utrecht, The Netherlands

^d Muséum national d'Histoire naturelle, Département Histoire de la Terre, 43, rue Buffon, 75231 Paris Cedex 05, France

Received 18 July 2005; received in revised form 24 January 2006; accepted 20 February 2006

Abstract

Integrated data of calcareous nannofossils, as well as planktonic and benthic foraminifera from the Pissouri Motorway section on Cyprus allow the reconstruction of surface- and bottom-water paleoenvironments of the eastern Mediterranean during the interval preceding the Messinian salinity crisis (MSC). Contrary to deeper-water locations, where benthic foraminifera faunas are suppressed or absent just after the Tortonian–Messinian boundary, sediments deposited at intermediate water depths do contain benthic assemblages. From the earliest Messinian onwards, a development towards increasingly unfavourable paleoenvironments is reflected in the planktonic and benthic microfossil records of the Pissouri section and proceeds with rather discrete time steps that can be correlated to sequences throughout the Mediterranean. Shortly after the Tortonian–Messinian boundary a transition is recorded in the sedimentology and the open marine, deeper-water taxa disappear from the benthic foraminifera assemblages; subsequently, the diversity of all fauna groups diminishes. The changes recorded at species level in both surface-water and sea-floor dwelling taxa suggest decreasing circulation of the bottom waters, associated with changes in the surface waters, most likely due to increasing stratification. From ~6.73 Ma onwards, our data indicate a prominent change to more restricted conditions and increasing salinity at the sea floor together with intermittently rising surface water salinity. The dominance of oligotypic and monospecific assemblages and the frequent shifts in assemblage compositions of all microfossil groups indicate severely stressed environments after ~6.4 Ma, probably related to increased salinity. The major changes in paleoenvironmental conditions, including oxygen deprivation due to stagnation and hypersalinity, can be explained by hydrographical changes in the Mediterranean basin, which are probably caused by tectonic movements in the Rif Corridor acting in concert with astronomical cyclicity. Evaluation of the paleodepth proxies indicates that the depth of the Pissouri Basin remained rather constant at ~300–500 m, with a minimum of 200 m, until deposition of the “barre jaune”, the transitional interval towards the evaporites and that early shallowing to neritic depths, as was proposed before, is highly unlikely.

© 2006 Elsevier B.V. All rights reserved.

Keywords: Messinian; Mediterranean; paleoecology; paleoceanography; calcareous nannofossils; foraminifera

* Corresponding author. Tel.: +31 30 253 5148; fax: +31 30 253 2648.
E-mail address: tkouwenh@geo.uu.nl (T.J. Kouwenhoven).

1. Introduction

The Messinian salinity crisis (MSC), affecting the Mediterranean area during the latest Miocene, has been the focus of numerous studies. Evaporites deposited during this relatively short-lived period (~630 ky; Krijgsman et al., 1999a) are presently seen in outcrop throughout the area and were already described by Mayer-Eymar (1867). Seismic studies combined with coring in the Mediterranean (DSDP Leg XIII, 1973) led to discovery of the so-called M-reflector, representing the top of the evaporite facies in the marine domain. In the same year, several potential scenarios were presented to explain the massive deposition of evaporites during the MSC (Hsü et al., 1973a,b; Nesteroff, 1973).

By now the temporary constraints of the MSC and the period preceding the salinity crisis have been clarified (e.g. Hilgen and Krijgsman, 1999; Krijgsman et al., 1999a; Sprovieri et al., 1999; Sierro et al., 2001). The actual events eventually leading to evaporite deposition remain, however, essentially debated, and current hypotheses concerning the evaporitive phase can still be traced back to the first scenarios formulated in 1973. Recently, Flecker and Ellam (in press) challenged both the desiccation and the brine concentration models based on their measurements of the tracer $^{87}\text{Sr}/^{86}\text{Sr}$ and postulated that actual triggering of evaporite deposition was caused by increased inflow of Atlantic waters, i.e. transgression.

Restricted environmental conditions started well before the MSC, as has long been known from deposition of diatomites and black shales and associated faunal and isotopic changes in the early Messinian (e.g. Cita, 1976; Vergnaud-Grazzini et al., 1977; Van der Zwaan, 1982; Van der Zwaan and Gudjonsson, 1986; Głaçon et al., 1990). The role of basin configuration, connections to surrounding (oceanic) basins and astronomical forcing has also long been recognized, although the relative importance of either of these is still discussed. Accurate dating of events is important in this respect and increasingly high-resolution studies have provided more insight in the actual correlation of events. Krijgsman et al. (1999a) showed that onset of the Messinian salinity crisis was synchronous throughout the Mediterranean, contrary to the onset of diatomite deposition (Hilgen and Krijgsman, 1999). Salinity increase preceding the MSC remains difficult to prove, but has been inferred to start as early as ~6.8–6.7 Ma in the surface waters (e.g. Santarelli et al., 1998; Bellanca et al., 2001) and perhaps even as early as 7.167 Ma in bottom-water environments in the deepest Mediterranean basins (e.g. Seidenkrantz et al., 2000; Kouwenhoven et al., 2003).

Microfossils have proven to be reliable indicators of past environments and many high-resolution microfossil studies of the pre-MSC Messinian have been presented in recent years. In the Sorbas Basin (SE Spain) these studies revealed a detailed covariance of sedimentological characteristics (Vazquez et al., 2000) and the distribution of planktonic taxa (Sierro et al., 2003; Flores et al., 2005) with precessional cyclicality and the trophic state of the surface waters. The geochemical study by Filippelli et al. (2003) confirmed findings of Sierro et al. (2003) that sapropels in the Sorbas Basin were deposited under low-productivity, and diatomites under high-productivity regimes. Pérez-Folgado et al. (2003) found that the planktonic foraminiferal successions were essentially the same in the eastern Mediterranean Metochia section (Gavdos, Greece) despite the different sedimentary expression of precessional cyclicality, and thus presented evidence for a cyclic control of paleoenvironments throughout the Mediterranean.

Due to virtual absence of benthic life in the deeper-water Messinian sections many previous studies mainly or exclusively concentrated on planktonic organisms. In deeper-water Messinian sections, for instance on Sicily (e.g. Sprovieri et al., 1996a,b; Blanc-Valleron et al., 2002) and Gavdos (unpublished data), benthic foraminifera are often scarce and very irregularly distributed and it cannot always be excluded that those benthic taxa that were encountered were displaced. In intermediate-water sections, however, benthic foraminifera are often present and provide additional paleoecological information (e.g. Goubert et al., 2001; Sánchez-Almazo et al., 2001 (Sorbas Basin); Seidenkrantz et al., 2000; Kouwenhoven et al., 1999, 2003 (central and eastern Mediterranean)). Environmental changes recorded by benthic foraminifera can be correlated throughout the Mediterranean and traced back to 7.167 Ma, well before the onset of diatomite and black shale deposition (Kouwenhoven et al., 1999, 2003; Seidenkrantz et al., 2000) and preceding clear changes in planktonic assemblages.

We here present integrated microfossil data from the eastern Mediterranean Pissouri Motorway Section on Cyprus. This section offers the opportunity to study the assemblage composition of benthic foraminifera together with the planktonic foraminifera and the calcareous nannofossils. Our record from Cyprus comprises the time slice between 7.65 (latest Tortonian) and 5.98 Ma, based on the age model published by Krijgsman et al. (2002) and ends just prior to the deposition of the 'barre jaune', which precedes the actual start of the salinity crisis (at 5.96 ± 0.02 Ma (Krijgsman et al., 1999a)). Our aim is to approximate longer-term changes in the

surface and deep-water masses preceding the MSC based on the microfossil records, in order to contribute to a reliable reconstruction of the development of the Mediterranean towards the MSC.

2. Materials and methods

2.1. Lithology and stratigraphy

The Pissouri Motorway section is located in the Pissouri sub-basin on the island of Cyprus in the eastern Mediterranean (Fig. 1). Several Messinian outcrops are present on Cyprus and have been subject of extensive sedimentological and paleoecological studies. These studies predominantly focused on the evaporite and Lago Mare facies of the MSC, and on the Messinian–Zanclean transition (e.g. Bizon et al., 1979; Orszag-Sperber et al., 1980, 2000; Di Stefano et al., 1999; Rouchy et al., 2001). An integrated stratigraphy and preliminary fauna data from pre-evaporite sediments of the Pissouri Motorway section were presented in Krijgsman et al. (2002) and Merle et al. (2002).

A detailed description of the Pissouri Motorway section is given in Krijgsman et al. (2002); for clarity

the main characteristics are repeated here (Fig. 2). The pre-evaporitic sediments generally consist of cyclic alternations of indurated calcareous beds and softer marls, developed in response to astronomical climate forcing (see for instance Hilgen et al., 1995; Vazquez et al., 2000). The marly levels of the Pissouri section can be correlated to grey and sapropelitic sediments (after Kidd et al., 1978; true sapropels containing >2% organic material) in contemporaneous sections throughout the Mediterranean. The sedimentation rate increased in the course of the late Miocene from 2.6 cm/ky in the latest Tortonian to around 5 cm/ky in the top of the section. Bedding-parallel shear planes and centimeter- to decimeter-thick detrital layers of reddish gypsiferous sands and are present in the interval following the Tortonian–Messinian boundary (at 41.5 m). Sapropelitic layers occur in two intervals, in cycles PC 25–22 (33.8–32.2 m) and cycles PC 9–5 (17.5–10.5 m; the ‘lower’ and ‘upper organic-rich interval’ respectively in Krijgsman et al. (2002); “l.o.r.i.” and “u.o.r.i.” in Figs. 2–7). The marls in the upper 32 m of the section (cycles PC 22–1) have a diatomitic appearance. The slumped interval between PC3 and 4 (10–6.5 m) laterally contains reef limestone blocks.

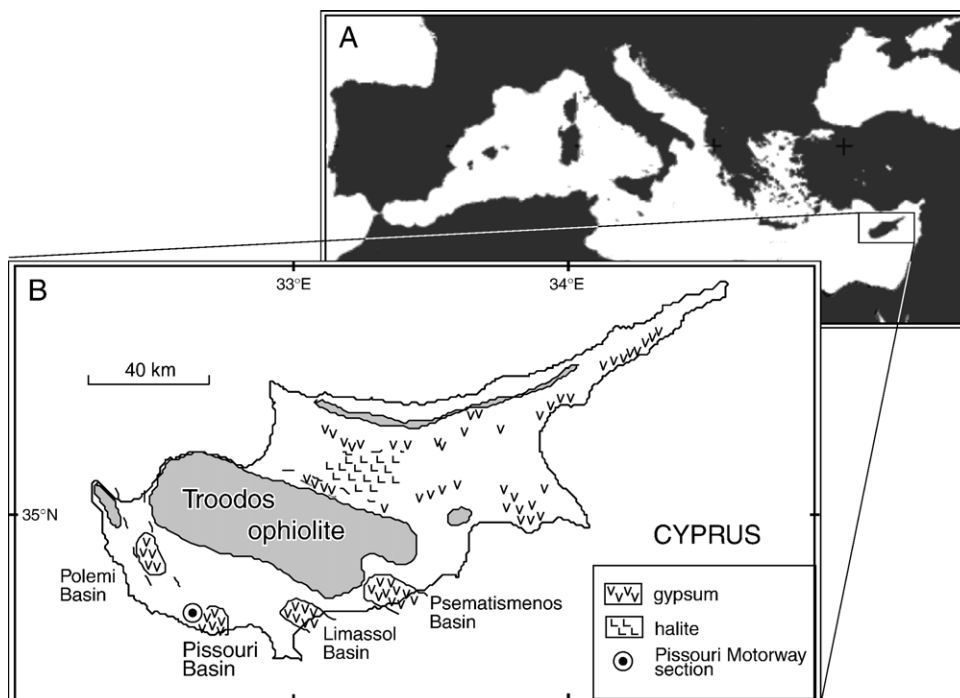
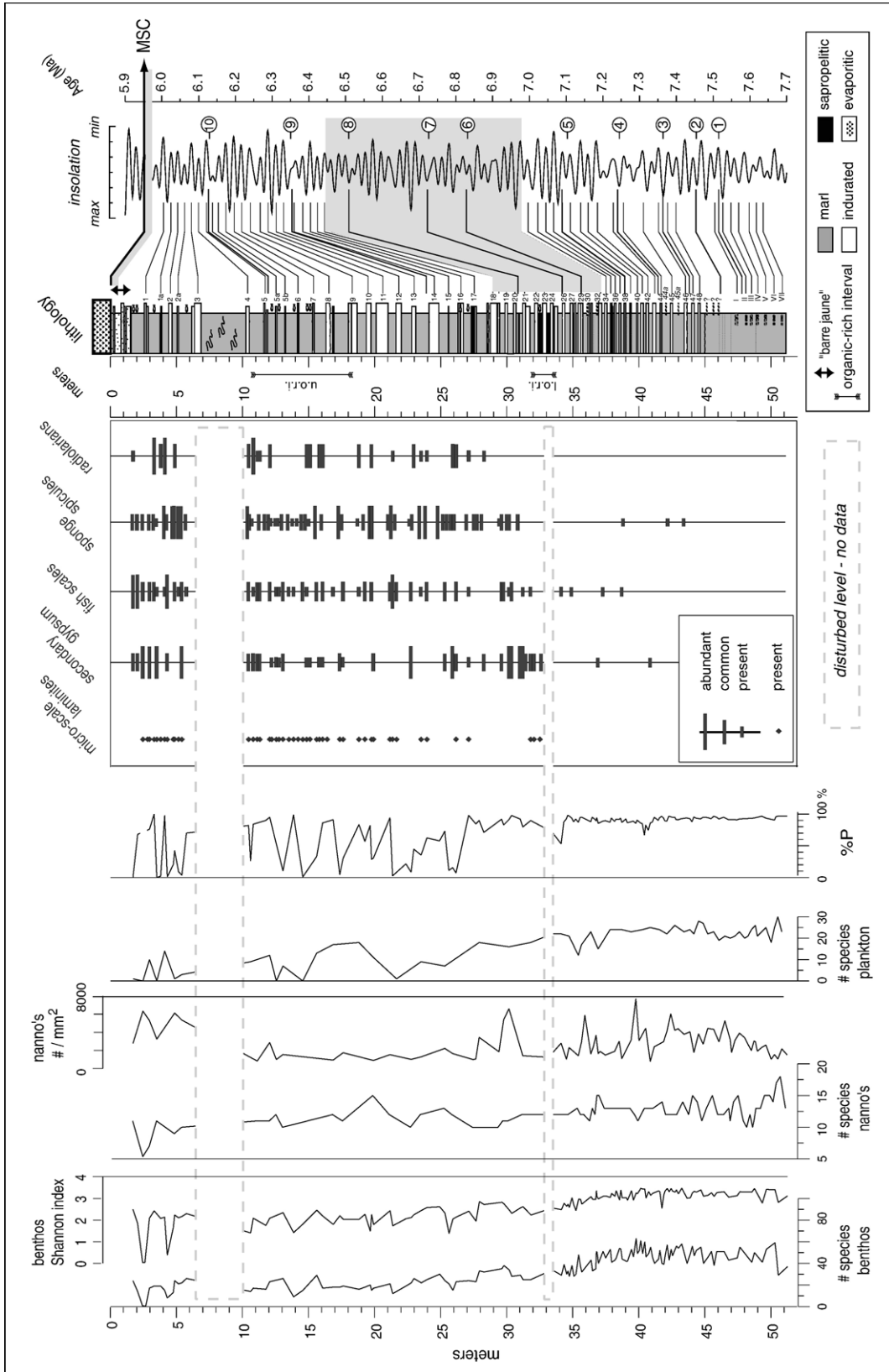


Fig. 1. (A) Generalised map of the Mediterranean Sea, modified after ODP. The Mediterranean Sea is at present connected to the Black Sea (to the northeast) through the Bosphorus and the Sea of Marmara, and to the Atlantic Ocean (to the west) through the Gibraltar Strait. The island of Cyprus is located in the eastern Mediterranean. (B) Map of Cyprus. The pre-Neogene basement outcrops among others in the Troödos ophiolite complex. Neogene basins and Messinian evaporitic deposits are schematically indicated. The Pissouri Motorway section is located in the Pissouri Basin near the SE coast of the island (modified after Krijgsman et al., 2002).



The transition from cyclic carbonates and marls towards evaporites is a 1.5 m thick interval of laminated carbonates interpreted as stromatolitic limestone. This interval is commonly referred to as the “barre jaune” in the nearby Polemi Basin; a term adopted here. The latter two intervals were not sampled. Ages given in Krijgsman et al. (2002; see Figs. 2, 6 and 7) were obtained by astronomical tuning. In the grey interval astronomical tuning is not fully resolved.

2.2. Sample preparation and collection of data

2.2.1. Calcareous nannofossils

Sample preparation followed a methodology assuring a uniform distribution of the sediment on the cover glass. For this purpose, 1 mg of sediment was resuspended in 10 mL of buffered water, corrected to pH=8. After 30 s, 1 mL of the suspension was collected with a micropipette and left to dry on a cover glass at 50 °C. Counts were performed with the use of a light microscope at 1250× magnification by counting at least 300 specimens per sample. Results were converted to numbers per mm² according to Baumann et al. (1998), and to relative frequencies. Giunta et al. (in press) discuss the advantages of using numbers per mm² compared to percentages. A taxonomic reference list for the calcareous nannofossils is given in Appendix A.

2.2.2. Foraminifera

For foraminiferal counts the sediment samples were disintegrated in water and washed over 63, 125 and 595 micromesh sieves. The foraminiferal species were identified and counted from a sub-sample of the 125–595 µm standard aliquot, obtained by splitting. The ratios between planktonic and benthic foraminifera counted in a sample split (P/B ratios) are expressed as %P=100 × {P/(P+B)} (Fig. 2; e.g. Wright, 1978; Van der Zwaan et al., 1990). In the lower part of the section the %P was used to estimate the paleodepth by

applying the regression formula of Van der Zwaan et al. (1990).

Analyses of planktonic foraminifera have been conducted on 65 samples. A variable number (mean 210 specimens) of planktonic foraminifera tests was counted. Whole samples were counted when the number of foraminifera was small. Diversity of the planktonic foraminiferal assemblages is expressed as the number of taxa encountered per sample. The census counts were converted to relative frequencies. A taxonomic reference list of planktonic foraminifera is given in Appendix B.

Counts of benthic foraminifera are included from 129 samples. Most samples allowed identification of 200–400 benthic specimens. Whole samples were counted when the number of foraminifera was small. Samples yielding less than 200 specimens were included in the analyses if oligotypic assemblages occurred, unless the number of tests was below 50. Diversity of the benthic foraminiferal assemblages is expressed as the number of taxa encountered per sample, and as Shannon–Weaver index ($H(S) = \sum_i p_i \ln p_i$ with $H(S)$ =diversity, and p_i =the relative percentage of the i th species; see Murray, 1991). All counts were transferred to relative frequencies. A taxonomic reference list of benthic foraminifera is given in Appendix C.

2.2.3. Selection of samples

A Q-mode cluster analysis of all samples revealed no correlation between microfossil taxa and/or groups and lithological characteristics (marls; calcareous, indurated strata; laminated or dark levels; not shown). Consequently, we decided to include all samples in the analysis regardless of the lithology they were taken from.

3. Results

3.1. General observations and paleobathymetry

The preservation of the microfossils is rather variable due to diagenetic alteration, and especially in the

Fig. 2. Left panel: Diversity of the microfossil groups expressed as number of species counted per sample. For benthic foraminifera, the Shannon–Weaver index is also given ($H(S) = \sum_i p_i \ln p_i$; with $H(S)$ =diversity, and p_i =the relative percentage of the i th species; see Murray, 1991). For calcareous nannofossils, the number of nannofossils per mm² is calculated. The percentage of planktonic foraminifera (%P) of the total foraminiferal association is expressed as %P=100 × {P/(P+B)}. Middle panel: records of micro-laminated sediment grains, and semi-quantitative estimates (present, common or abundant) of secondary gypsum, fish scales, sponge spicules and radiolarians. Right panel: simplified lithological column correlated to 65°N summer insolation, and positions of planktonic foraminifera events (numbers 1–10 in circles), taken from Krijgsman et al., 2002. Grey field indicates a period for which age reconstruction could not be resolved in detail. The ‘barre jaune’ is indicated just below the evaporites at the top of the section. ‘l.o.r.i.’ and ‘u.o.r.i.’: lower and upper organic-rich intervals. For more details of lithology see text, and Krijgsman et al., 2002. (Planktonic foraminifera events: (1) LO *G. menardii* 4; (2) LO *G. falconarae*; (3) FO *G. menardii* 5; (4) FRO *G. miotumida* group; (5) LCO dominantly sx. *G. scitula*; (6) FO *G. nicolae*; (7) LO *G. nicolae*; (8) LO *G. miotumida* group; (9) sx/dx coiling change *N. acostaensis*; (10) 1st influx (>80%) of sx. neogloboquadrinids).

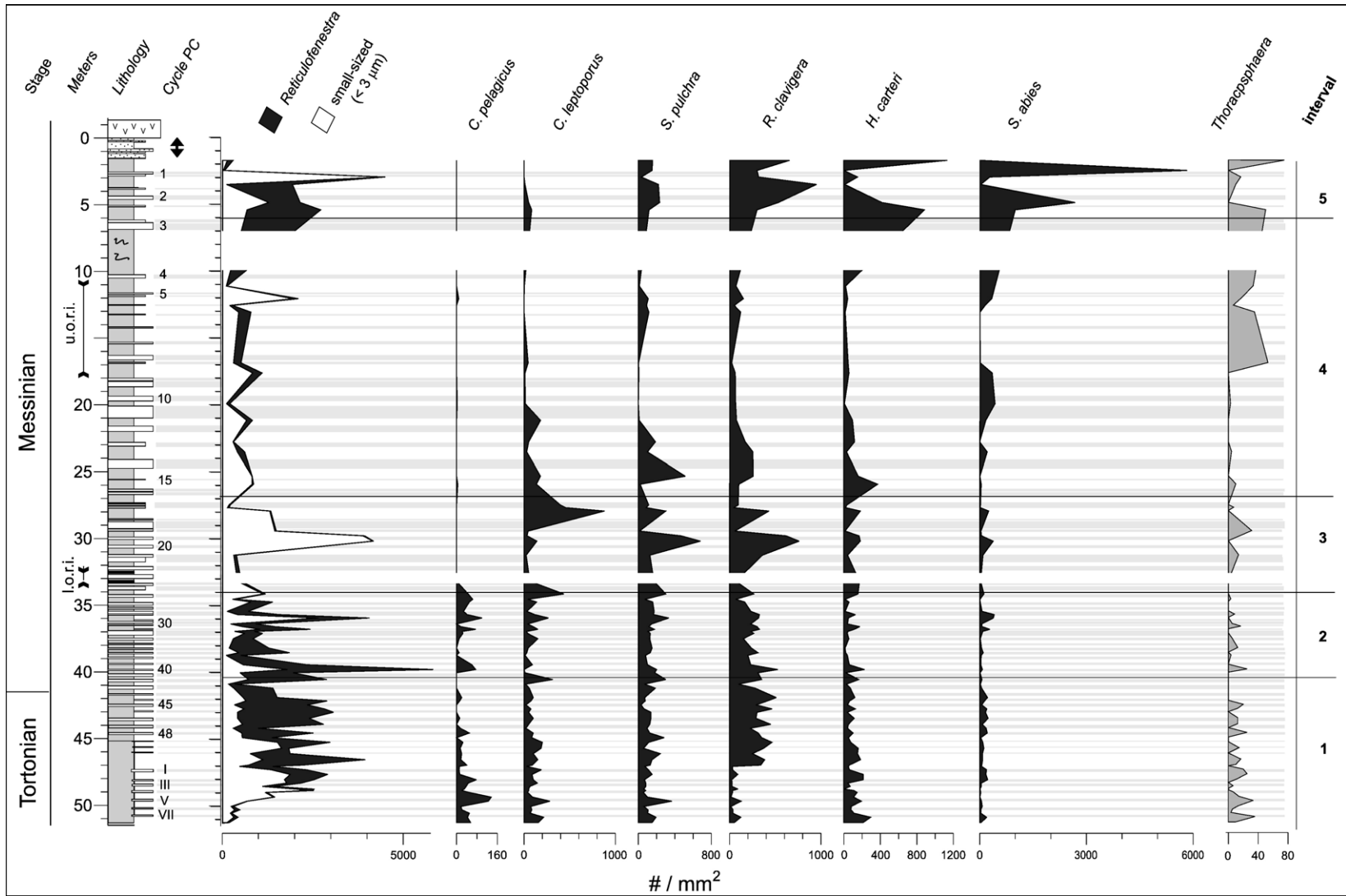


Fig. 3. Distribution of relevant calcareous nannoplankton taxa against stratigraphy of the Pissouri section. Please note differences in scaling. Grey bands indicate the indurated levels, which correlate to homogeneous (non-sapropelitic) levels in time-equivalent sections.

indurated strata the data coverage decreases towards the top of the section. At several levels poor preservation of nannofossils as well as foraminifera precludes reliable counts. In a number of samples where benthic foraminifera could be quantified, reliable counts of planktonic foraminifera were not feasible. Some down-slope transportation is recorded in samples throughout the section and may explain isolated minor occurrences of planktonic and benthic taxa in the younger part of the section.

Above the sheared level around 33 m (micro-) laminites occur, and the wash residues contain gypsum (crystalline as well as pseudomorphs; Fig. 2). Together with the presence of pyrite and the preservation of silica and abundant fish scales this suggests that the bottom-water chemistry had changed and the bottom waters had become increasingly dysoxic. The benthic assemblages have lost a number of species at this level (Figs. 2 and 5) and decreasing diversity of the planktonic taxa becomes apparent (Fig. 2).

Since paleobathymetric variations can cause shifts in assemblage compositions that may be confused with other environmental signals, we first estimated the paleobathymetry using the %P. In the lower part of the section, until about 27 m the %P remains relatively constant and decreases only temporarily around 40 and 34 m (Fig. 2). Applying the regression in Van der Zwaan et al. (1990), we would arrive at a paleodepth of 800–1000 m. Based on benthic marker species however, we arrive at a paleodepth not exceeding ~500 m and possibly less (e.g. Van Hinsbergen et al., 2005). Above 27 m the %P shows frequent and high-amplitude shifts, not likely to be caused by sea level fluctuations, as they would repeatedly indicate sea level changes exceeding the depth of the basin, often within less than a precessional cycle.

3.2. Distribution of calcareous nannofossil assemblages

The calcareous nannofossils are moderately to poorly preserved, the diversity is generally low to moderate and the abundance shows a considerable decrease between ~30 and ~10 m (Fig. 2). Trends of representative taxa are plotted in Fig. 3. In the lower part of the section the assemblage is relatively well diversified and contains *Coccolithus pelagicus*, *Calcidiscus leptoporus*, *Syracosphaera pulchra*, *Rhabdosphaera clavigera*, *Sphenolithus abies*, *Helicosphaera carteri*, *Umbilicosphaera* spp., “normal sized” reticulofenestrads (including *Reticulofenestra haqii* Backman, 1978, *R. pseudumbilicus* (>7 µm), *R.* spp. (5–7 µm), and *R.* spp. (3–5 µm)), and “small sized” reticulofenestrads (<3 µm). Subordinate

and in some cases spotwise occurrences are recorded for *Reticulofenestra rotaria*, *Helicosphaera stalis*, *Helicosphaera orientalis*, *H. sellii*, *Geminilithella rotula*, *Amaurolithus delicatus*, *Amaurolithus primus*, and the genus *Discoaster*. The calcareous dinocyst *Thoracosphaera* occurs in low numbers. These taxa show fluctuating abundances until 34.5 m, where the normalized reticulofenestrads strongly decrease. At 33.15 m *C. pelagicus* disappears abruptly. Around 30 m the small-sized reticulofenestrads are extremely numerous and at 28 m *C. leptoporus* shows a spike in abundance. After 27 m many taxa show a strong decline and at ~20 m the assemblage has almost completely collapsed.

Above 20 m the nannoflora is poorly preserved and very scarce. *Thoracosphaera*, however, is relatively common above 15 m, and from ~6 m upwards we observe a re-entry of several species, such as the “normal sized reticulofenestrae”, *H. carteri*, and *R. clavigera*. Some samples show monospecific assemblages consisting almost completely of sphenoliths (*S. abies*).

3.3. Distribution of foraminifera assemblages

3.3.1. Planktonic foraminifera

The planktonic foraminifera assemblages are moderately well preserved and well diversified in the part of the section below ~34 m and are dominated by *Globigerinoides* spp. Trends of representative species are plotted in Fig. 4. Low abundances of keeled and unkeeled globorotaliids characterize the lowermost 15 m of the section. *Globorotalia scitula* disappears around 40 m. *Globigerina nepenthes* shows a relatively high but scattered occurrence up to 35.5 m, above which it is discontinuously present. *Globigerina bulloides* and *Globoturborotalita decoraperta* show a similar trend along the major part of the section; up to 30 m these species together form almost 30% of the association. In the upper part their distribution is more scattered and whereas *G. decoraperta* disappears in the top levels, *G. bulloides* reaches very high abundances. *Globigerinoides* spp. are particularly abundant up to 34.7 m. Until 16.5 m they are discontinuously recorded, and after a peak abundance of nearly 60% at 19 m this group almost disappears. *Globigerinoides obliquus* and *Globigerinoides trilobus/quadrilobatus* form the major part of the *Globigerinoides* spp. sum. Whereas the distribution of *G. obliquus* is very similar to the distribution of the *Globigerinoides* group, *G. trilobus* has a more scattered distribution and above 28 m it is only found in two levels, at 27 and 17 m.

The distribution of planktonic foraminifera is discontinuous along the upper part of the section

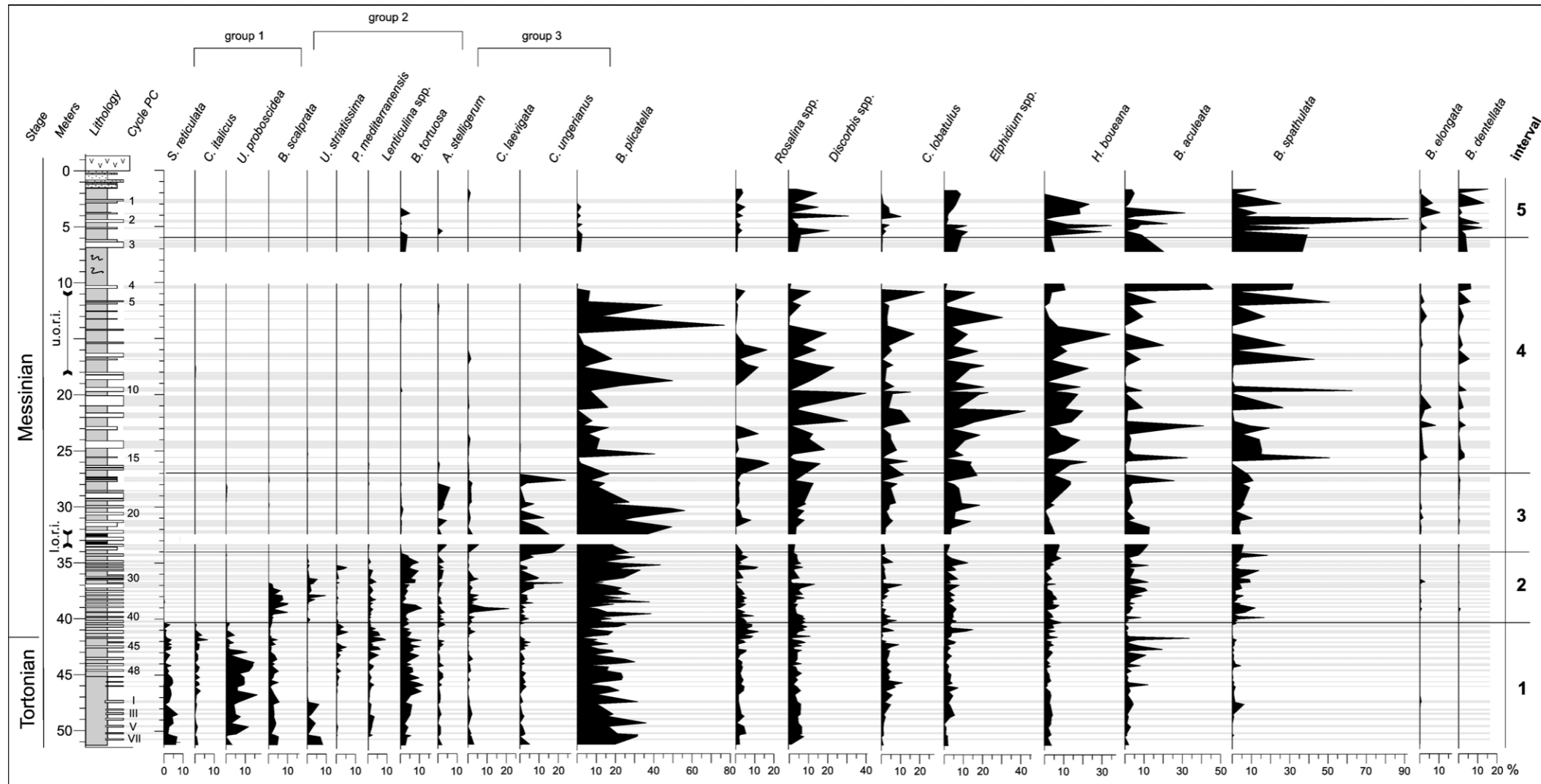


Fig. 5. Distribution of relevant benthic foraminifera taxa against stratigraphy of the Pissouri section. Groups no. 1–3 refer to groups of taxa that successively exit the record (for details see text). *Bolivina plicatella* = *B. plicatella mera* + *B. cf. B. pseudoplicata*. Grey bands indicate the indurated levels.

and in several intervals the preservation is poor. Some samples have very scarce fauna or are altogether barren of planktonic foraminifera. From ~34 m to the top of the section the diversity decreases and the dominant species, apart from *Globigerinoides*, are *Neogloboquadrina acostaensis*, *Turborotalita multiloba*, *Turborotalita quinqueloba* and *Orbulina* spp. The first occurrence of *T. multiloba* is at 25.3 m; subsequently it appears in a few levels with high abundances. *T. quinqueloba* shows a distribution similar to *T. multiloba* but it appears lower in the section (34.1 m). *N. acostaensis* is present throughout the section, and its abundance increases above 34 m. A scattered abundance pattern is recorded of *Globigerinita glutinata*. Just below the ‘barre jaune’ *G. bulloides* is dominant in a few samples.

3.3.2. Benthic foraminifera

Benthic foraminifera are present throughout the section with the exception of two samples just below the ‘barre jaune’, and are generally reasonably well preserved. In several of the indurated levels above 34 m however, they could not be quantified. Common taxa in the Tortonian part of the section represent a fairly diverse open marine association of outer neritic to upper bathyal environments. An impoverishment (declining simple diversity and Shannon–Weaver index: Fig. 2) sets in just after the Tortonian–Messinian boundary and continues throughout the early Messinian. Selected relative frequency data are plotted in Fig. 5. A group of benthic species commonly found in open marine Mediterranean environments of late Miocene age disappears at 40.3 m (7.167 Ma: *Siphonina reticulata*, *Uvigerina proboscidea*: referred to as ‘group 1’ in Figs. 5 and 6; not included are scarce *Cibicides wuellerstorfi*, *C. bradyi*, and *Bolivina reticulata*). Between 37 and 34 m more taxa exit (*Bolivina scalprata miocenica*, *Uvigerina striatissima*, *Planorbolina mediterraneensis*) or show decreasing abundances (*Lenticulina* spp., *Bolivina tortuosa*: ‘group 2’ in Figs. 5 and 6). Around 27 m the *Cibicides ungerianus/pseudoungerianus* group disappears together with *Cassidulina laevigata* and *Astrononion stelligerum* (in benthos ‘group 3’ in Figs. 5 and 6). Above ~34 m the benthic assemblages show frequent shifts. Alternating with high abundances of shallow benthic taxa (e.g. *Elphidium* and *Discorbis* spp.), high dominance is recorded of *Bolivina spathulata* (70–90%). Typical late Messinian taxa such as *Bolivina dentellata* and *Bulimina echinata* are relatively abundant below the ‘barre jaune’.

4. Integrated microfossil data: successive stages of Messinian development of the Pissouri Basin

Already during the earliest Messinian indications are found for a development towards increasingly unfavourable paleoenvironments in the Pissouri Basin. Both the planktonic and benthic microfossil taxa have responded to this development in more or less discrete steps. Summarized data is shown in Fig. 6. Transitions in the compositions of microfossil assemblages occur at 40.3, 34 and 27 m and around the slumped interval, corresponding to ages of 7.167, 6.73, 6.41 Ma and approximately 6.1 Ma; these transitions are used to define the five successive intervals described below.

4.1. Interval 1 (51.2–40.3 m; 7.65–7.167 Ma)

The lowermost 9 m of section include the Tortonian–Messinian boundary at 41.5 m (7.24 Ma, as defined in Krijgsman et al., 1999a; Hilgen et al., 2000; Sierro et al., 2001). The calcareous nannofossil assemblage (Figs. 3 and 6) is dominated by *Reticulofenestra* spp., a placolith-bearing nannoplankton group thriving in high-productivity conditions (Young, 1994). *C. pelagicus* produces the largest common, diagenetically very robust and unmistakable coccoliths, and indicates cool waters (Raffi and Rio, 1981). Biogeographic data from Ziveri et al. (2004) documents a clear abundance maximum of *C. pelagicus* in the northern Atlantic, corresponding to areas with a mean annual temperature below 10 °C and a consistently high productivity.

Planktonic foraminifer assemblages (Figs. 4 and 6) are dominated by *Globigerinoides* spp., and include among others *Globorotalia* spp. and neogloboquadrinids. *G. scitula* is considered to be a (sub-) polar species (Bé, 1977; Itou et al., 2001). It is usually present in glacial-age sediments of the Mediterranean Sea (Thunell, 1978; Rohling et al., 1997; Capotondi et al., 1999) and rarely occurs in modern settings (Pujol and Vergnaud-Grazzini, 1995). Its habitat ranges from the surface to 1000 m depth (Schiebel and Hemleben, 2000). Itou et al. (2001) argued that abundance of *G. scitula* corresponds to intensified vertical mixing. Neogloboquadrinids are found in cold, stratified waters and are linked to the formation of a deep chlorophyll maximum, which enhances primary productivity (DCM; Fairbanks and Wiebe, 1980; Rohling and Gieskes, 1989; Kuroyanagi and Kawahata, 2004). The simultaneous presence of neogloboquadrinids, as well as surface-dwellers (*Globigerinoides* spp.) of oligotrophic stratified waters, and deep dwellers such as *Globorotalia* spp. indicating mixed waters could

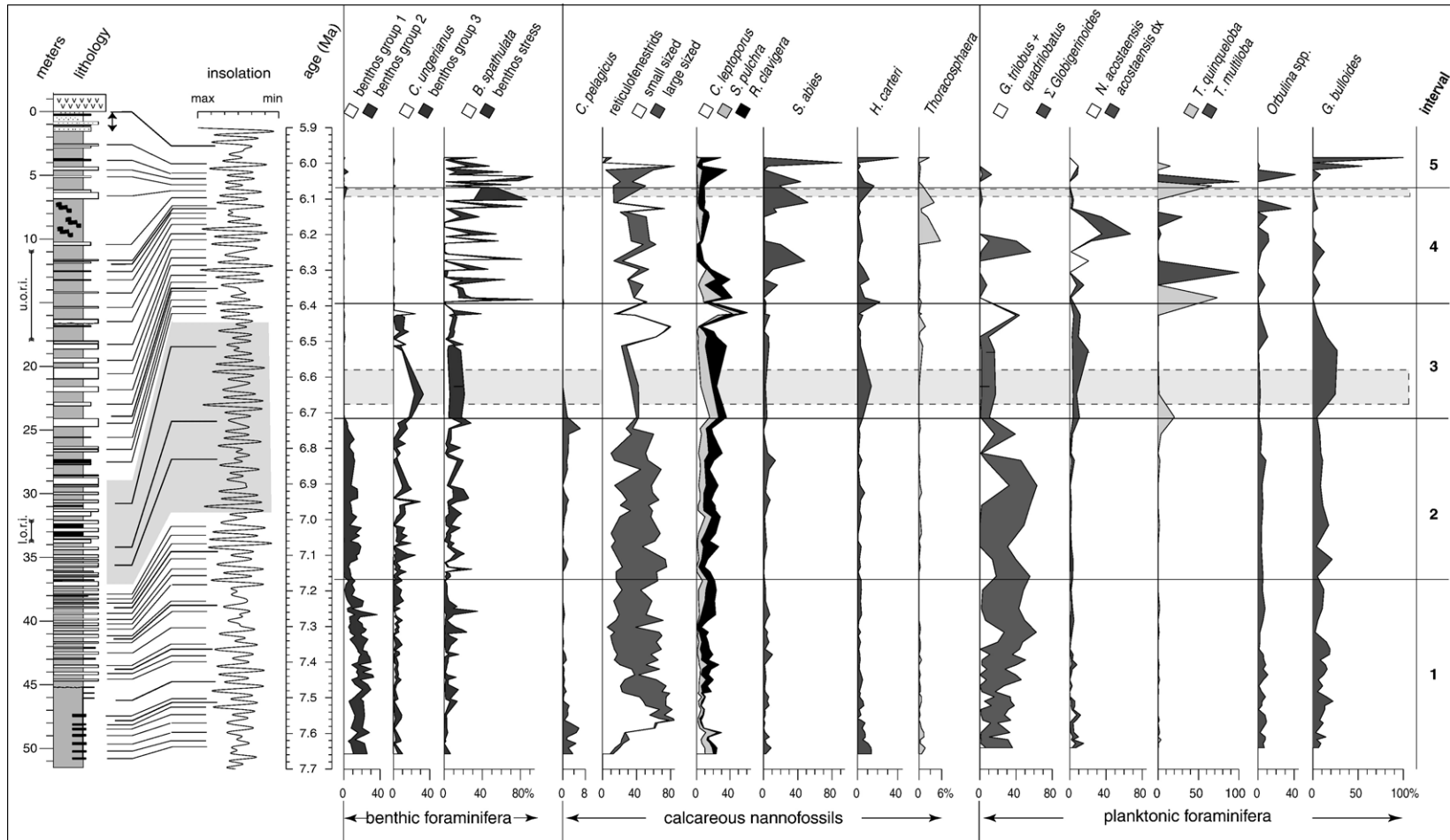


Fig. 6. Compilation of distribution patterns of selected nanoflora and foraminifera taxa and groups against geologic time. Benthos: Group 1 = *Siphonina reticulata* + *Cibicides italicus* + *Uvigerina proboscidea*; Group 2 = *Bolivina scalprata miocenica* + *B. tortuosa* + *U. striatissima* + *Planorbulina mediterranensis* + *Lenticulina* spp.; Group 3 = *Astrononion stelligerum* + *Cassidulina laevigata* + *Cibicides ungerianus* + *C. pseudoungerianus*; Stress = *Bolivina dilatata* + *B. spatulata* + *B. dentellata* + *Bulimina aculeata* + *B. subulata* + *B. elongata* + *B. echinata* + *Uvigerina cylindrica* + *Rectuvigerina bononiensis*.

indicate a high seasonal contrast (Hemleben et al., 1989; Pujol and Vergnaud-Grazzini, 1995). The plankton taxa in the lowermost 4 m of the section record relatively low sea surface temperatures (SST) and moderately high sea surface productivity (SSP).

The relatively diverse benthic foraminifer fauna is dominated by *Bolivina plicatella* and contains a subordinate number of taxa found in relatively deep open marine environments (*S. reticulata*, *C. italicus*, *C. wuellerstorfi*; Fig. 5), conform other upper bathyal locations, for instance Faneromeni (Crete; Kouwenhoven et al., 2003).

Around 7.5 Ma (~47 m; Fig. 2) the colour alternations within the marls of cycles PC I–VII are gradually replaced by alternations of marls and indurated, more calcareous sediments. Coinciding are gradual shifts in the microfossil assemblages. The planktonic taxa indicate a transition to lower SSP and higher SST. Among the nannoflora, *R. clavigera* shows an increase from < 100 to some 400 specimens per mm². Roth and Coulbourn (1982) considered *Rhabdosphaera* spp. able to survive in low nutrient conditions. Ziveri et al. (1995a) recorded *Rhabdosphaera* spp. in modern assemblages over a wide range of SST's (14–20 °C). The numbers of large-sized reticulofenestrads increase, whereas those of small-sized reticulofenestrads and *C. pelagicus* decrease simultaneously.

The abundances of Neogloboquadrinids and *Globorotalia* spp. decline and the interval between ~47 and 40.3 m (7.5–7.167 Ma) is dominated by *Globigerinoides* spp. that indicate subtropical surface waters. *G. obliquus* is extinct but is considered from an ecological point of view, by several authors as ancestral to *G. ruber* and hence a good indicator of oligotrophic waters (e.g. Hemleben et al., 1989; Pujol and Vergnaud-Grazzini, 1995; Blanc-Valleron et al., 2002; Peeters et al., 2002; Sierro et al., 2003).

Minor shifts in the benthic assemblage (decrease of *S. reticulata* and *U. striatissima*; increase of *U. proboscidea* and *B. tortuosa*; Fig. 5) seem to record decreasing oxygenation at the sea floor. Similar changes in benthic foraminifer assemblages were shown to coincide with a shift to lighter stable oxygen isotopes around 7.5 Ma, reported from both eastern and western Mediterranean sites (e.g. Salé (Morocco): Hodell et al., 1989, 2001; eastern Mediterranean: Kouwenhoven et al., 1999, 2003; Seidenkrantz et al., 2000).

The subsequent change in assemblage composition defining the transition to interval 2 is most clearly expressed in the benthic foraminifera. At 40.3 m the open marine, deeper-water taxa disappear altogether (among others *S. reticulata*, *C. italicus*, *U. proboscidea*;

group 1 in Fig. 5) and are not recorded again before the Pliocene (compare Wright, 1980; Sprovieri and Hasegawa, 1990). This event can be correlated throughout the central and eastern Mediterranean and occurs at 7.167 Ma (Kouwenhoven et al., 1999, 2003; Seidenkrantz et al., 2000).

4.2. Interval 2 (40.3–34 m; 7.167–6.73 Ma)

Some expression of environmental change at the transition to interval 2 is reflected in the planktonic taxa. The nannoflora (numbers/mm²; Fig. 2) shows minima in the overall abundance, and relatively low abundance of reticulofenestrads and *C. pelagicus*; which suggests that the event recorded by the benthic foraminifera is not primarily related to increased surface productivity. Except for the disappearance of *G. scitula*, the planktonic foraminifera do not clearly record the change at 7.167 Ma; however, the relatively high abundance of *Globigerinoides* spp., notably *G. obliquus* also indicates relatively low productivity levels.

The abundances of the planktonic taxa show shifts across interval 2. In the nannoflora, two maxima of reticulofenestrads numbers are associated with (minor) maxima of *C. pelagicus* (Fig. 3) and high overall numbers (Fig. 2), and indicate periods of elevated productivity. The declining abundance of reticulofenestrads at the top of interval 2 is associated with the disappearance of *C. pelagicus*.

In the planktonic foraminifera assemblages decreasing abundances are recorded for the *Globigerinoides* spp. Neogloboquadrinids, included in the 'cold-eutrophic' group by Sierro et al. (2003) and flourishing in spring when eutrophicated waters follow deep winter mixing (Hemleben et al., 1989; Pujol and Vergnaud-Grazzini, 1995) are more prominent around 34 m. Together with a first relative maximum of *T. quinqueloba* (20%), this indicates cold eutrophic waters (Tolderlund and Bé, 1971; Hemleben et al., 1989). *T. quinqueloba* was also inferred to tolerate hypersaline conditions (Kroon et al., 1988; Van de Poel, 1992). *G. glutinata* (10% at 34 m) is found in subarctic and subantarctic waters with low overall foraminiferal abundances (Tolderlund and Bé, 1971). Sierro et al. (1999; 2003) attribute abundance maxima of *G. glutinata* to stressed conditions, possibly due to eutrophy or high salinity, if they occur together with *T. quinqueloba* (and *T. multiloba*) and coincide with low total abundance and diversity (see also Pérez-Folgado et al., 2003).

Further impoverishment of the benthic assemblage occurs between 37 and 34 m when "group 2" (Fig. 5)

gradually disappears. Species showing a temporary or continuous increase in abundance indicate limited oxygenation and/or increased amounts of nutrients arriving at the sea floor (boliviniids; *Bulimina aculeata*). For several species salinity tolerance is inferred (*B. plicatella*, *B. spathulata*, *B. aculeata*, *Hanzawaia boueana*: e.g. Van der Zwaan, 1982; Jonkers, 1984; Reiss and Hottinger, 1984; Debenay et al., 1987; Van de Poel, 1992).

Towards the end of interval 2, the diversity of the three fauna groups gradually declines (Fig. 2). Together with the changes recorded at species level in both surface-water and sea-floor dwelling taxa, this suggests the development of more adverse conditions, of which stagnation of bottom waters is most pronounced, but possibly including intermittent stratification of surface waters. Indications exist for increasing salinity in the deep, and perhaps in the surface waters.

4.3. Interval 3 (34–27 m; 6.73–6.41 Ma)

The clayey sapropels deposited between ~34 and 32 m (l.o.r.i. in Figs. 2–7) contain bedding-parallel shear planes which reduce the stratigraphy and were avoided in the counts. Nannofossils are relatively scarce across this level (Fig. 2). *G. bulloides* reaches >25% of the planktonic foraminiferal assemblage. This species indicates cool, nutrient-rich waters and is often associated with upwelling (e.g. Pujol and Vergnaud-Grazzini, 1995; Northcote and Neil, 2005). Of the benthic foraminifera *C. ungerianus* and *B. aculeata* are relatively abundant, the latter species is commonly associated with some dysoxia and elevated organic flux to the sea floor (e.g. Mackensen et al., 1993; Altenbach et al., 1999).

From 32 m upwards the marls are commonly laminated and diatomaceous. The nannoflora shows maxima of *S. pulchra*, *R. clavigera*, small-sized reticulofenestrids and *C. leptoporus*. *Rhabdosphaera* spp. can survive in low-nutrient environments (Roth and Coulbourn, 1982) and a wide range of SST's (Ziveri et al., 1995a). Knappertbusch (1993) observed higher numbers of *R. clavigera* and *S. pulchra* in the oligotrophic Eastern, than in the western Mediterranean. Kleijne (1992) confirmed this for *R. clavigera*. According to Brand (1994) and Young (1994), *R. clavigera* is adapted to stable, extremely oligotrophic conditions and does not increase its population size in regions of high nutrient concentrations. Flores et al. (2005) include *R. clavigera* and *Syracosphaera* spp. in their 'warm-oligotrophic' group. At ~30 m *S. pulchra* and *R. clavigera* coincide with high numbers of small-sized

Reticulofenestra spp., which, in contrast, indicate elevated sea surface productivity. Reticulofenestrids remain by far the most abundant nannofloral taxa; moreover, the trophic level may not be the only decisive factor. Wade and Bown (in press, referring to *R. minuta*) describe small-sized *Reticulofenestra* from the contemporaneous and nearby Polemi Basin, and infer tolerance to hypereutrophic and schizohaline conditions, and extreme resistance to hypersalinity. *C. leptoporus*, a well established diagenetically robust and widely distributed species, shows maximum abundance near the top of interval 3. Present studies suggest that "intermediate" forms—according to Knappertbusch et al. (1997): those with coccolith sizes ranging from 5 to 8 μm —have an affinity for cool, nutrient poor waters (Ziveri et al., 2004), although reports are contradictory (see Flores et al., 2005). The abundance maximum of *C. leptoporus* at 28 m coincides with 40% abundance of the planktonic foraminifer *G. trilobus/quadrilobatus*, which suggests low trophic levels.

Above the organic-rich level *G. bulloides* declines. A first relative maximum of *Orbulina* spp. (~20%) is associated with the small-sized reticulofenestrids around 30 m. *Orbulina universa*, thriving in relatively warm and oligotrophic surface waters (e.g. Hemleben et al., 1989) was found to tolerate deviating salinity in lab culture ($23 < S < 46\text{‰}$: Bijma et al., 1990), and is a common, often dominant taxon in pre-MSC assemblages (e.g. Sprovieri et al., 1996a,b; Blanc-Valleron et al., 2002; Siero et al., 2003).

Conditions at the sea floor are reflected by *B. plicatella*, which dominates the benthic foraminiferal assemblage (20–60% relative frequency). This taxon is common to abundant in several Miocene Mediterranean sections where it seems to avoid sapropelitic strata. It has been associated with mild dysoxia (Van der Zwaan, 1982; Jonkers, 1984) and moderately elevated salinity (Van der Zwaan, 1982). From its occurrence pattern in the Carboneras–Nijar Basin (SE Spain) Van de Poel (1992) inferred it to be schizohaline. Jonkers (1984) found *B. plicatella* in low-diversity assemblages associated with diatomitic lithotypes of Pliocene sections on Crete. Eventually its numbers decline and around 30 m the benthic foraminifer assemblage is further impoverished and no longer dominated by *B. plicatella*. The relative frequencies of shallow-water benthic species (*Elphidium* spp.) and epiphytes (discorbids; *Rosalina* spp.) increase. Peak abundances are recorded of taxa indicating adverse conditions at the seafloor, which may include elevated salinity (*B. spathulata*, *B. aculeata*). *H. boueana* was inferred to tolerate elevated salinity but not oxygen deficiency (Van

der Zwaan, 1982). *B. dentellata* and *B. echinata* appear more regularly: these taxa are predominantly, if not exclusively recorded in the Messinian of the Mediterranean and are commonly associated with hypersaline environments (Van der Zwaan, 1982; Cita and Grignani, 1983; Poignant and Moissette, 1992; Violanti, 1996).

The dominance of successive taxa suggests rapid and profound changes in sea-surface as well as sea floor conditions. We find evidence for intermittent increase of surface-water salinity. The benthic foraminifera indicate stagnation and elevated salinity at the seafloor, where the conditions have changed such that fish scales and silica are preserved, and secondary gypsum is formed (Fig. 2). Radiolarians start to appear regularly in the wash residues. The transition to interval 4 is marked by a drop in the %P and the microfossil diversities.

4.4. Interval 4 (27–10 m; 6.41–~6.1 Ma)

The nannoflora numbers are low. Collapse of the nannoflora assemblage is evident around 20 m and precedes the upper organic-rich level (17.5–10.5 m). Large placoliths, which are quite resistant to dissolution, are not preferentially preserved. There is no relative increase in large reticulofenestrids, *C. pelagicus* and other robust forms; instead of selective, the decline is general. A sudden increase in abundance of the high-productive calcareous dinocyst *Thoracosphaera* coincides with the base of the organic-rich interval. *Thoracosphaera* remains present until the top of the section. It has been associated with stressful and unstable, but ameliorating conditions following the K/T boundary event (Melinte et al., 2003; Lamolda et al., 2005).

Levels with oligotypic planktonic foraminifera assemblages show 60–100% dominance of single species. At 21 m (6.3 Ma) the assemblage is monospecific, consisting of 100% *T. multiloba*. Several authors related *T. multiloba* to the progressive isolation of the Mediterranean Sea and it may well be tolerant to increased salinity (e.g. Violanti, 1996; Siero et al., 2003). Other planktonic taxa that may tolerate deviating salinity include *Orbulina* spp., and *G. obliquus*, based on its affinity with *G. ruber* (Pujol and Vergnaud-Grazzini, 1995; salinity limits of *G. ruber* in lab culture $22 < S < 49\%$: Bijma et al., 1990). *G. glutinata* was found at the base of sapropels in low-diversity Messinian assemblages from the eastern and western Mediterranean (Pérez-Folgado et al., 2003). Heavy stable oxygen isotope values made the authors infer increased salinity in these levels. Samples barren of planktonic foraminifera occur towards the top of interval 4.

The benthic foraminifera assemblages are intermittently dominated up to 90% by either stress tolerant or shallow-water taxa. *B. dentellata* and *B. echinata* occur more regularly; together with peak abundances of *B. aculeata*, *B. spathulata* and *B. plicatella* these taxa indicate elevated organic carbon levels, oxygen stress and deviating salinity. Throughout the upper organic-rich interval *B. plicatella* shows further demise and towards the top of interval 4 its numbers are insignificant. It appears that preservation of silica and phosphorus (fish scales) is favoured by stagnant bottom waters.

4.5. Interval 5 (~6 m–base of the “barre jaune”; ~6.1–6 Ma)

Upon re-entry the nannoflora assemblages show alternating maxima of reticulofenestrids, *S. abies*, *H. carteri*, and *R. clavigera*, all indicating rather different environments. An increase in abundance of species as *C. leptoporus* and *S. abies* was earlier noticed in several Messinian sections close to the evaporites, which suggests these taxa tolerate deviating salinity (Negri, unpublished data; Parisi, unpublished data). The genus *Sphenolithus* is long ranging, but extinct since the Pliocene and has uncertain taxonomic affinities. Moreover, its detailed ecology is not clear. Sphenoliths were documented as K-selected: adapted to low-latitude warm-water, stable oligotrophic environments (Haq and Lohmann, 1976; Haq, 1980; Lohmann and Carlson, 1981; Aubry, 1992), perhaps with a shallower water preference (Perch-Nielsen, 1985). Gibbs et al. (2004, 2005) noticed a covariance with Pliocene glacial cyclicity, essentially a preference for relatively oligotrophic, warm waters, which is in agreement with data of Flores et al. (2005) for the Messinian. Wade and Brown (in press), recording almost monospecific assemblages of sphenoliths in diatom rich samples from the Messinian of the Polemi Basin, inferred mesotrophic marine environments with normal salinity. Also in the Pissouri Basin sphenoliths are among the taxa successively dominating the assemblages up to nearly 100%. We suggest that sphenoliths were capable of inhabiting a wide range of environments, and were probably schizohaline. High abundance of *H. carteri* suggests elevated nutrient levels and marine environments. It is a key species increasing in abundance in sapropels (Negri et al., 1999a,b; Negri and Villa, 2000; Negri and Giunta, 2001). Flores et al. (2005) confirmed a correlation of *H. carteri* with elevated productivity and possibly with elevated salinity in the Messinian. Plankton studies suggest that *H. carteri* has affinity for warmer waters

(McIntire and Bé, 1967; Brand, 1994). Affinity for elevated nutrient conditions is confirmed by higher abundances in areas such as the mesotrophic parts of the S. Pedro basin (Ziveri et al., 1995b), the Arabian Sea (Andruleit and Rogalla, 2002) and the Australian sector of the Southern Ocean. Ziveri et al. (2004) reported *H. carteri* to be abundant in the upwelling area off NW Africa. In support of this, the oligotrophic (P limited) eastern Mediterranean Sea records very low abundances of this species (Knappertbusch, 1993; Ziveri et al., 2000; Malinverno et al., 2003). Wade and Brown (in press) describe *H. carteri* from the Polemi Basin and infer shallow, brackish, and hypereutrophic environments, which would suggest a tolerance to deviating salinity. *R. clavigera* increases again in the topmost part of the Pissouri section. Consequently, the nannoflora data record extreme environmental differences, suggesting that prior to the MSC the paleoenvironment shifted to considerably different states within relatively short time spans. In contrast with planktonic foraminifera however, all dominating nannofloral taxa seem to record relatively high sea surface temperatures. The neogloboquadrinids show demise in this interval, but the assemblages are dominated by *T. multiloba*, *T. quinqueloba* and *G. bulloides*, indicating mixed, nutrient rich and cold waters (Tolderlund and Bé, 1971; Mohiuddin et al., 2005; Northcote and Neil, 2005; see also Sierro et al., 2003).

The benthic fauna continuously shows rapid shifts in dominance and peaks of stress tolerant taxa as *B. spathulata* and *B. aculeata*. Towards the ‘barre jaune’ some species persist (*B. dentellata*, *B. echinata*) and some appear (*Glabratella* sp., *Pararotalia aculeata*; Van der Zwaan, 1982; Merle et al., 2002; Szczechura, 2004), which are rather typically recorded in restricted, hypersaline Miocene environments of the Tethyan and Paratethyan realm. Whereas elevated salinity may be intermittent at the sea surface, it appears to be permanent in the bottom waters some 100 ky before onset of the MSC.

5. Discussion: early Messinian events and possible causal mechanisms

Although local factors may have affected the basins on Cyprus, generalized events should be invoked to explain events that can be correlated to other parts of the Mediterranean. The successive intervals recording basin restriction in the Pissouri section are in agreement with results from other Mediterranean locations (e.g. Sprovieri et al., 1999; Sierro et al., 1999, 2001, 2003; Seidenkrantz et al., 2000; Blanc-Valleron et al., 2002;

Kouwenhoven et al., 2003), and are likewise reflected in the biotic record and the sedimentology. In the following sections we first discuss the paleobathymetry and then relate the local development recorded in the Pissouri Motorway section to regional (Mediterranean-wide) events.

5.1. The %P, paleodepth estimates, and α -planktonic levels

5.1.1. Paleodepth estimates in the Pissouri Basin

A first approximation of the paleodepth of the Pissouri Basin, calculated from the %P, arrived at 800 to 1000 m. However, a more or less straightforward relation between %P and depositional depth is found in undisturbed, open marine environments (Van der Zwaan et al., 1990), whereas in the Pissouri Basin restricted conditions existed during most of the studied interval. Moreover, the high %P values do not seem realistic when compared with the benthic assemblages, which suggest that the paleodepth of the Pissouri Basin was rather stable at around 300–500 m. The temporary shifts in the %P around 40 m (~7.16 Ma) and 34 m (~6.7 Ma) are probably an early expression of variations in sea-floor oxygenation rather than paleobathymetrical fluctuations (compare Van Hinsbergen et al., 2005). Shallowing is not commonly associated with these events (e.g. Kouwenhoven et al., 2003; Seidenkrantz et al., 2000).

Especially in deposits younger than ~6.4 Ma (27 m and up) the extreme shifts in %P cannot reflect sea-level fluctuations, as the %P would indicate sea-level movements as large as 1000 m, which would surpass the depth of the basin. By this time many depth-diagnostic benthic species have disappeared, which complicates attempts to arrive at a reliable depth estimate.

Merle et al. (2002) inferred shallowing of the Pissouri sub-basin to neritic depths long before onset of the salinity crisis. Several of the observed phenomena, for instance the collapse of the nannoflora around 20 m, could well be explained by shallowing. Coccolithophores are known to occupy shallow-water, near-shore environments (e.g. Cachao et al., 2002), but at depths less than 100 m the preservation of autochthonous nannoflora is rare and it essentially disappears due to dilution by clastic influx and dissolution in coarse-grained sediments. Arguments against consistent shallowing of the basin are, however, easily overlooked. The nannoflora remains present, albeit in low numbers and there is no relative increase in robust coccoliths, which would be a case for dissolution. Radiolarians are recorded throughout

the younger part of the section and indicate episodes of upwelling in an offshore environment (Kling, 1978). Radiolarians do occur in nearshore environments (e.g. Nishimura et al., 1997), but their preservation is rare in surface sediments at less than 200 m water depth (Chen and Tan, 1999; Itaki, 2003). Only in the top, just below the ‘barre jaune’, do the radiolarians disappear. The re-entry of nannoflora above the slump interval further suggests that the basin remained essentially marine throughout most of the section. With the exception of isolated barren levels planktonic foraminifera remain present throughout the section, with *G. bulloides* suggesting a water

depth of 200 m at minimum just below the ‘barre jaune’ (e.g. Sierro et al., 2003).

Superficially, the benthic assemblages seem to indicate a shallowing trend starting around 6.5 Ma (Figs. 5 and 7). However, at the paleodepth considered shallow benthics are always present in comparatively low numbers. The benthic species *B. aculeata* and *B. spathulata* adapt to different water depths, depending on prevailing environmental conditions but are most common in upper bathyal environments. More important here, however, is their stress tolerance. Fig. 7 visualizes the %P versus the abundances of shallow-water and stress-tolerant benthic groups, and *B.*

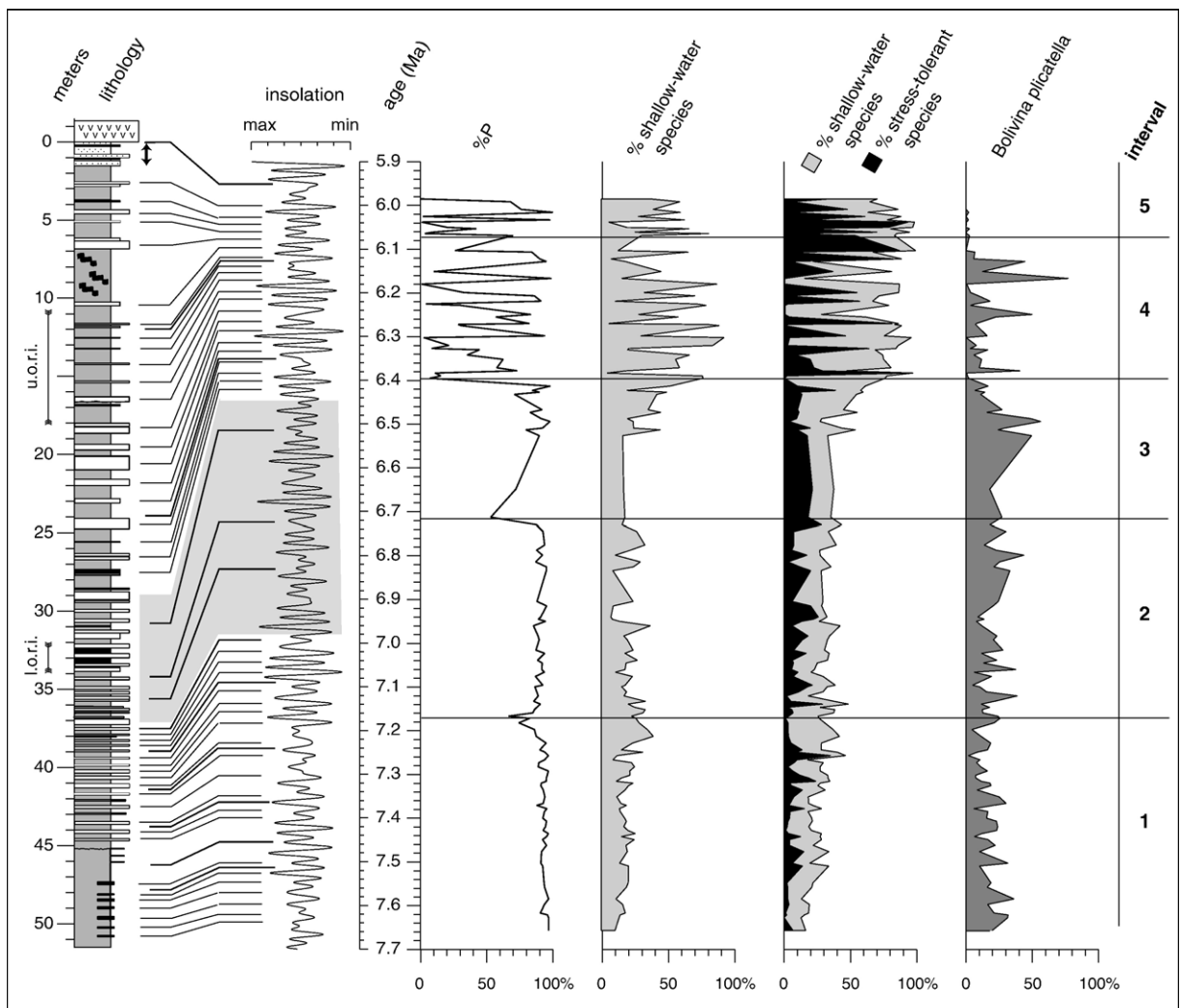


Fig. 7. Plots of the %P (= percentage of planktonic foraminifera in the foraminiferal association), the percentage of shallow-water benthic foraminifera, the summed percentages of shallow-water and stress-tolerant benthic foraminifera and the relative frequency pattern of *B. plicatella* (= *B. plicatella mera* + *B. cf. B. pseudoplicata*) against geologic time of the Pissouri section. Taxa included in the benthic foraminifera groups: Shallow-water taxa: *Discorbis* spp. + *Rosalina* spp. + *Elphidium* spp. + *Cibicides lobatulus*; stress tolerant taxa: *Bolivina dilatata* + *B. spathulata* + *B. dentellata* + *Bulimina aculeata* + *B. subulata* + *B. elongata* + *B. echinata* + *Uvigerina cylindrica* + *Rectuvigerina bononiensis*.

plicatella and shows repeated sequences of dominance of each of these groups. Rather than shallowing, the repetitive relative increase of shallow-water benthic taxa indicates intermittent periods of severe (oxygen and/or salinity) stress at the sea floor, completely suppressing autochthonous benthic assemblages.

For clarity we correlated the %P in the upper 35 m of the section with the distributions of the benthic groups of Fig. 7 (Fig. 8). There is no convincing correlation between %P and shallow-water taxa: $R = -.359$. Correlation of %P with the sum of the shallow-water and stress-resistant groups results in $R = -.692$ ($N = 59$; $p < 0.01$; Figs. 7 and 8). Together with the negative correlation between shallow-water and stress-resistant taxa ($R = -.627$) this suggests that stagnation rather than sea level caused variations in %P, and shallow-water taxa mainly dominated due to the virtual absence of autochthonous benthic fauna. This is substantiated by the high occurrences of *B. plicatella* in intervals with a high %P and low dominance of the summed shallow-

water and stress-resistant taxa ($R = -.857$; see Fig. 7). Consequently, the shallow-water taxa are considered allochthonous at the paleodepth we estimate for the Pissouri section, which is still 200 m at minimum just below the ‘barre jaune’. Hence, consistent shallowing to neritic depths long before the onset of the MSC as proposed by Merle et al. (2002) seems, in the light of our data, not realistic.

5.1.2. A-planktonic (foraminifera) levels

Notwithstanding consistent shallowing being unlikely, episodes of extremely low %P and a-planktonic levels could be due to minor sea level fluctuations operating on astronomical time scales. Assuming a silled configuration of the Pissouri basin and evaporation exceeding precipitation as is the present situation, a minor drop of sea level could either restrict or completely block inflow and/or outflow (depending on the local circulation) and result in evaporative draw down, thereby increasing the salinity. A-planktonic

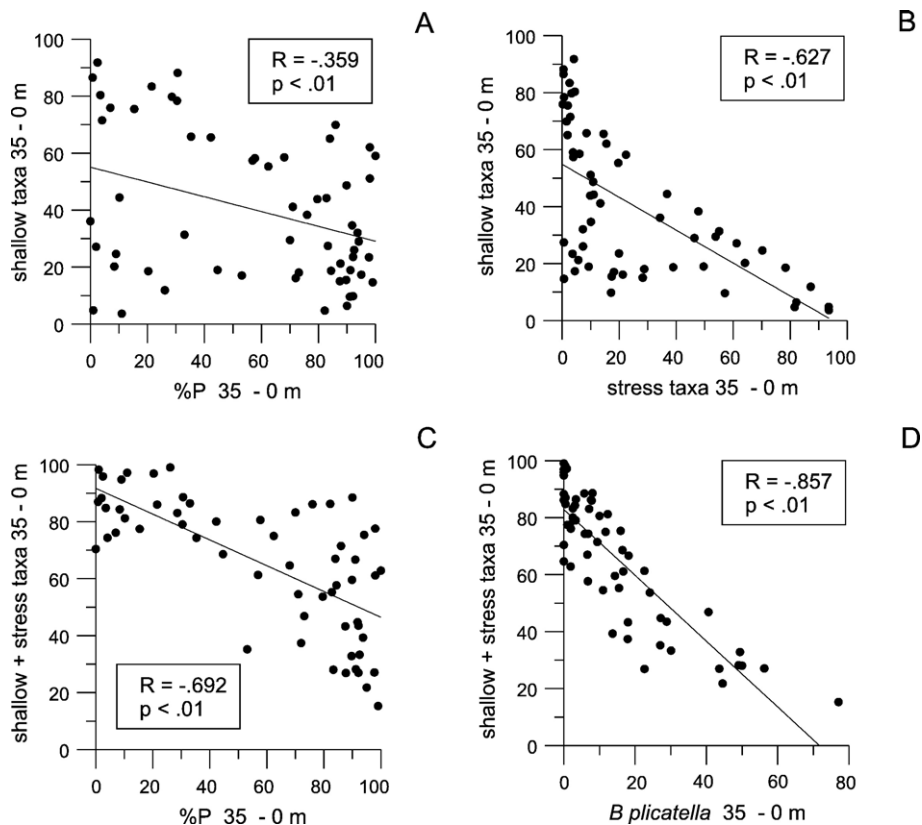


Fig. 8. Bivariate graphs and correlation coefficients (R) for the upper 35 m of the Pissouri section of: (A) relative frequencies of shallow-water taxa against the %P; (B) relative frequencies of shallow-water taxa against those of stress-tolerant taxa; (C) summed relative frequencies of shallow-water and stress-tolerant taxa against the %P; (D) summed relative frequencies of shallow-water and stress-tolerant taxa against the relative frequency of *B. plicatella* (= *B. plicatella* mera + *B. cf. B. pseudoplicata*). For explanation see text.

zones could be the result (compare Fenton et al., 2000 for the Red Sea during the Last Glacial Maximum). This would necessarily be a local phenomenon of a restricted, silled basin and most prominent on glacial time scales (obliquity, ~41 ky). Both appear not to be the case.

Cyclical fluctuations of %P are described by Sierro et al. (1999, 2003) in the Sorbas Basin in Spain, occurring in the Upper Abad marls from ~6.7 Ma onwards and a-planktonic levels occur after ~6.4 Ma. Similar shifts in the %P have been found at Falconara (Sicily) and Metochia (Gavdos; unpublished data). In the Sorbas Basin these a-planktonic levels predominantly occur in the transitions from marls to sapropels and correlate with precession, just as the majority of planktonic foraminiferal distribution patterns; moreover, they are not more outspoken on glacial (obliquity) time scales.

Data coverage and preservation do not allow such detailed time resolution in the Pissouri section, but we tentatively assume that also in this basin a potential correlation exists of %P with precessional cyclicity and specific lithotypes.

5.2. Events on a regional scale and possible causal mechanisms

Cause or causes of the MSC are commonly sought in gateway tectonics and its possible effects on Mediterranean circulation, draw down and salt budgets (e.g. Ryan, 1973; Blanc, 2000; Meijer and Krijgsman, 2005). In the Gibraltar arc, comprising the Rif Mountains and the Betic Cordillera seismic tomography has indicated active subduction (Gutscher et al., 2002) and Duggen et al. (2003) suggested uplift of the continental margins of southern Iberia and northwest Africa caused by slab rollback. Krijgsman and Garcés (2004) demonstrated that tectonic activity in the Gibraltar region has continued in the late Miocene.

The Betic Corridor towards the Atlantic was essentially closed in the late Tortonian (Soria et al., 1999; Garcés et al., 1998, 2001), rendering the Spanish basins marginal to the Mediterranean so that vertical movements in the Rif area, the southernmost of the connections of the Mediterranean with the Atlantic, must have been instrumental in restriction of the Mediterranean. Krijgsman et al. (1999b) inferred partial uplift around 7.2 Ma within the Taza–Quercif area of the Rif Corridor, which correlates with uplift in the Melilla basin (Van Assen et al., *in press*). Water mass exchange between the Mediterranean and the Atlantic became restricted. Assuming an anti-estuarine thermohaline circulation and evaporation exceeding precipitation as

today, surficial inflow of Atlantic waters into the Mediterranean will have continued, but outflow of deeper (and more saline) waters obstructed. Consequently, the Mediterranean circulation slowed down, leading to dysoxic deep water masses and increased preservation of organic material.

A common feature of the earliest Messinian is that lithological changes occur throughout the Mediterranean. The base of the Lower Abad marls for instance, is dated at 7.24 Ma (Sierro et al., 2001). In the Cretan sections Faneromeni (Hilgen et al., 1995) and Potamidha (Krijgsman et al., 1994) the first sapropels were deposited during the precession minimum dated at 7.167 Ma and correlate to cycle LA1 of the Lower Abad marls (Sierro et al., 2001). In the Pissouri basin the lithological cyclicity becomes more expressed around this time. Deep-water benthic foraminiferal faunas would be the first to respond to restriction, and uplift of the sill connecting the Mediterranean with the Atlantic would prevent deeper-water benthic faunas with an affinity for equilibrium marine conditions from re-entering the Mediterranean. This is essentially what appears to have happened, as the exit of selected benthic foraminifera recorded at 7.167 Ma in the Pissouri basin can be correlated throughout the Mediterranean (Kouwenhoven et al., 1999, 2003; Seidenkrantz et al., 2000). Additionally, deep-water locations record sediments barren of benthic foraminifera immediately after 7.167 Ma (Giblicemi/Falconara composite (Sicily): Sprovieri et al., 1996a,b; Blanc-Valleron et al., 2002; Kouwenhoven et al., 2003) or after a relatively short transitional period characterized by oligotypic benthic assemblages (Metochia (Gavdos): Seidenkrantz et al., 2000). Either the deep waters were most stagnant, or continuing evaporation had contributed to early brine formation. Although this can as yet not be confirmed by ocean circulation models (see for instance Meijer et al., 2004), stagnant waters and a dysoxic brine could rise from deeper to shallower levels and through time could affect shallower parts of the basin. Some faunal and isotope evidence for a salinity effect in the deep waters as early as 7.167 Ma has been found before, although stable isotope records are often hampered by poor preservation (Gavdos: Seidenkrantz et al., 2000; Sicily: unpublished data).

Basically, benthic fauna data are in line with a scenario like this: the assemblages in the deepest parts of the basin are most severely affected by the changing conditions at 7.167 Ma. The planktonic foraminifera and the nanoflora in the Pissouri section record relatively oligotrophic environments at 7.167 Ma, suggesting that

increased sea-surface productivity is not primary related to this event.

The subsequent phase in the restriction of the Mediterranean can be correlated to the emergence of the Taza–Guercif area in the Rif Corridor around 6.7 Ma (Krijgsman and Langereis, 2000). This is coeval with restriction of bottom-water circulation in the Melilla basin (Van Assen et al., *in press*) and the transition from the Lower to the Upper Abad marls in the Sorbas basin (6.699 Ma), which was attributed to increased tectonic activity in the internal Betics (Sierro et al., 2001) and associated with onset of sapropel formation and changes in planktonic microfauna. Around this time diatomites start appearing throughout the Mediterranean (e.g. Hilgen and Krijgsman, 1999).

In sections deposited at intermediate water depths, benthic foraminifera remain present and record the increasingly adverse conditions towards the MSC (e.g. Sorbas (Spain): Goubert et al., 2001; Sánchez-Almazo et al., 2001; Faneromeni (Crete): Kouwenhoven et al., 2003). Also the Pissouri basin reflects extra-restricted conditions, and instability in the faunal assemblages younger than ~ 6.7 Ma points to increasingly adverse conditions. Benthic and planktonic foraminifera and calcareous nannofossils record rapidly changing assemblages with peak occurrences of taxa, which have been associated in literature with deviating salinity. This would be in agreement with organic dinocyst data from the Faneromeni section (Crete), where indications were found for hypersaline surface-waters at 6.68 Ma (Santarelli et al., 1998), and with data from Sicily, where Blanc-Valleron et al. (2002) found salinity fluctuations of surface waters and increasingly stagnating bottom waters from 6.71 Ma onwards.

With the current state of knowledge, no specific tectonic event can be correlated with the increasing restriction of the basin around 6.4 Ma. Tectonic activity in the Gibraltar arc, however, was shown to have continued in the late Miocene (Krijgsman and Garcés, 2004) and continuing restriction in the Rif Corridor is reflected by sediments deposited in the Melilla basin, which record the last marine influence at 6.07 Ma (Van Assen et al., *in press*).

However, an alternative causal mechanism can be found in the 400 ky eccentricity component of astronomical forcing, which could play a role in the pre-Messinian development of the Mediterranean (e.g. Krijgsman et al., 1999a; Blanc-Valleron et al., 2002; Kouwenhoven et al., 2003; Sierro et al., 2003). A relation is observed between the successive time steps in basin restriction, and the particular interference configuration of astronomical cyclicity frequencies

expressed as increasing amplitude of the insolation curve. Astronomical forcing will be expressed in climate signals—including runoff—and sea level, although effects as extreme and disastrous as the MSC would basically require threshold geographical conditions like partial shut-off of the Mediterranean from oceanic basins.

Thermohaline circulation is influenced by climatic effects on runoff and the evaporation–precipitation balance. Regional climatic development is subject to discussion, as some proxy records indicate climatic instability (e.g. Andersen et al., 2001; Ivanov et al., 2002), whereas others infer stable climatic conditions throughout most of the Messinian (e.g. Suc and Bessais, 1990; Bertini et al., 1998; Warny et al., 2003). Like climate, sea level is influenced by astronomical forcing. Increasingly accurate dating led to the observation that a glacial sea level fall cannot be correlated with the actual onset of the MSC (e.g. Hodell et al., 2001; Krijgsman et al., 2004). It appears, however, that major steps in basin restriction can be correlated both to tectonic events and to the specific configuration of the insolation curve. It cannot be excluded that tectonic activity and astronomical cyclicity have acted in concert in affecting the Mediterranean basin, where climatic or sea level variations may have been highly amplified by the increasing isolation of the basin (e.g. Krijgsman, 2002; Sierro et al., 2003).

6. Conclusions

Integration of foraminifera and nannoflora data from the Pissouri Basin reaffirms that restricted conditions in the eastern Mediterranean have started just after the Tortonian–Messinian boundary at 7.167 Ma and are first expressed in the sedimentary cyclicity and the benthic foraminifera assemblages. Stagnancy of bottom waters has preceded clear effects of restricted circulation in the surface waters, which developed later. Increasingly adverse paleoenvironments developed more or less gradual. This gradual restriction of the basin was punctuated, however, by rather well defined transitions to a more adverse state around 6.7 and 6.4 Ma. Evidence for increasing surface-water salinity preceding the MSC is apparent as early as 6.7 Ma. We infer that rapidly changing surface-water paleoenvironments, leading to oligotypic assemblages, scarcity of calcareous nannofossils and eventually to the a-planktonic zones in the foraminiferal record may in part be explained by periodically enhanced salinity. Furthermore we infer regular increases of primary productivity, induced by periods of upwelling.

Significant shallowing of the Pissouri Basin prior to the Messinian salinity crisis is unlikely. An evaluation of all available data indicates that shallowing was minor or absent until the ‘barre jaune’, the level just below the first evaporites, and that the paleodepth was rather stable around 300–500 m, with a minimum of 200 m. The percentage of planktonic foraminifera (%P) is of minor value for depth reconstructions due to basin restriction, and controlled by factors other than paleodepth after ~6.4 Ma (27 m). Instead, the recorded shifts in the %P can be explained by rapid and repeated changes of environmental conditions on a precessional time scale, although no direct correlation can be established with high-amplitude astronomical cyclicity in the Pissouri Basin due to limitations of data coverage.

The development of the Pissouri Basin is not particularly deviating from other locations described from the Mediterranean. Restriction of the basin proceeded with discrete steps, which can be correlated with similar changes elsewhere in the Mediterranean. These basin-wide changes have a different expression at deep-water sites where benthic foraminifera disappeared at 7.16 Ma or shortly afterwards, and intermediate-water locations where benthic foraminifera remained present. The restricted nature of the Mediterranean during the Messinian will have caused an amplification of environmental changes in the Pissouri Basin that was also described from other Messinian sections. Causal mechanisms in the restriction history of the Mediterranean were tectonic movements in the Rif Corridor, of which the effects were possibly enhanced by astronomically induced sea level fluctuations concentrating around 400 ky eccentricity maxima. Perhaps the transitions around 6.4 Ma should be mostly accounted for by astronomical cyclicity.

Acknowledgements

Gerrit van't Veld and Geert Ittmann are acknowledged for preparation of wash residues for foraminiferal analyses. Discussions with Frits Hilgen, Erik Snel, Jan-Willem Zachariasse and Bert van der Zwaan were greatly appreciated. Kati Baldi is thanked for help with literature. Comments by the reviewers, M.-S. Seidenkrantz and J.-A. Flores, are much appreciated and were most helpful in improving the original manuscript. A.N. was funded by the Italian MIUR Progetti di Rilevanza Nazionale 2003. This is NSG (Netherlands School of Sedimentary Geology) contribution no. 2006.03.01.

Appendix A. Calcareous nannoplankton: taxa list and notes

Taxonomy in general follows that outlined in [Perch-Nielsen \(1985\)](#) and [Young \(1998\)](#).

- Amaurolithus delicatus* Gardtner and Bukry (1975)
Amaurolithus primus (Bukry and Percival, 1971) Gardtner and Bukry (1975)
Calcidiscus leptoporus (Murray and Blackman, 1898) Loeblich and Tappan, 1978
Coccolithus pelagicus (Wallich, 1871) Schiller, 1930
Discoaster asymmetricus Gartner (1969)
Discoaster brouweri Tan (1927) emend. Bramlette and Riedel (1954)
Discoaster challengerii Bramlette and Riedel (1954)
Discoaster icarus Stradner (1973)
Discoaster loeblichii Bukry (1971)
Discoaster intercalaris Bukry (1971)
Discoaster pentaradiatus Tan (1927) emend. Bramlette and Riedel (1954)
Discoaster tamalis Kamptner (1967)
Discoaster variabilis Martini and Bramlette (1963)
Helicosphaera carteri (Wallich, 1877) Kamptner, 1954
Helicosphaera intermedia Martini (1965)
Helicosphaera orientalis Black (1971)
H. sellii (Bukry and Bramlette, 1969b) Jafar and Martini, 1975
Helicosphaera stalis Theodoridis (1984)
Helicosphaera walbersdorffensis Muller (1974)
Reticulofenestra Hay et al., 1966. These are generally size-defined following the taxonomy outlined in [Young \(1998\)](#).
R. haqii [Backman, 1978/R.](#) sp. 3–5 µm
R. minuta Roth, 1970/R. sp. <3 µm (small retic.)
R. pseudoumbilicus (Gartner, 1967b) Gartner, 1969c. >7 µm
R. sp. 5–7 µm, noted by [Backman and Shackleton \(1983\)](#)
Reticulofenestra rotaria Theodoridis (1984)
Rhabdosphaera clavigera Murray and Blackman (1898)
Sphenolithus abies Deflandre in Deflandre and Fert, 1954.
Syracosphaera pulchra Lohmann, 1902
Thoracosphaera Kamptner, 1927

Appendix B. Selected planktonic foraminifera

Taxonomy in general follows that outlined in [Iaccarino \(1985\)](#) and [Perch-Nielsen \(1985\)](#).

- Globigerina bulloides* d'Orbigny
Globigerina obesa (Bolli)
Globigerina falconensis Blow
Globigerinita glutinata (Egger)

Globigerinoides bollii Blow
Globigerinoides bulloideus Crescenti
Globigerinoides obliquus Bolli
Globigerinoides trilobus (Reuss)
Globigerinoides quadrilobatus (d'Orbigny)
Globorotalia menardii form 5 Tjalsma
Globorotalia menardii form 4 Tjalsma
Globorotalia nicolae Catalano and Sprovieri
Globorotalia miotumida Jenkins
Globorotalia scitula (Brady)
Globorotalia suterae Catalano and Sprovieri
Globorotalia ventriosa Ogniben
Globorotaloides falconarae Giannelli and Salvatorini, 1976
Globoturborotalita decoraperta (Takayanagi and Saito)
Globoturborotalita nepenthes (Todd)
Globoturborotalita woodii (Jenkins)
Neogloboquadrina acostaensis (Blow)
Orbulina bilobata (d'Orbigny)
Orbulina suturalis Brönnimann
Orbulina universa d'Orbigny
Turborotalita multiloba (Romeo)
Turborotalita quinqueloba Natland

Appendix C. Selected benthic foraminifera

Abundant and representative taxa are listed. Taxonomy essentially follows concepts in van der Zwaan et al. (1986: Uvigerinids), Loeblich and Tappan (1988), and Jones (1994).
Astrononion stelligerum (d'Orbigny): *Nonionina stelligera* d'Orbigny, 1839
Bolivina dentellata Tavani.
Bolivina plicatella Cushman, 1930c, var. *mera* Cushman and Ponton, 1932.
Bolivina plicatella var. *pseudoplicata*: *Bolivina* cf. *B. pseudo-plicata* Heron-Allen and Earland, 1930.
Bolivina scalprata miocenica: *Bolivina scalprata* Schwager var. *miocenica* Macfadyen, 1930.
Bolivina dilatata Reuss, 1850.
Bolivina spathulata (Williamson): *Textularia variabilis* Williamson var. *spathulata* Williamson, 1858.
Bolivina tortuosa Brady, 1881.
Bulimina aculeata d'Orbigny, 1826.
Bulimina echinata d'Orbigny, 1852.
Bulimina elongata d'Orbigny, 1846.
Cassidulina obtusa Williamson, 1858.
Cibicides italicus Di Napoli Alliata, 1952.
Cibicides lobatulus (Walker and Jacob): *Nautilus lobatulus* Walker and Jacob, 1798.
Cibicides ungerianus (d'Orbigny): *Rotalina ungeriana* d'Orbigny, 1846.

Hanzawaia boueana (d'Orbigny): *Truncatulina boueana* d'Orbigny, 1846.
Pararotalia stellata (d'Orbigny), syn. *Pararotalia aculeata* (d'Orbigny): *Rotalina aculeata* d'Orbigny, 1846.
Planorbulina mediterranensis d'Orbigny, 1826.
Rectuvigerina bononiensis (Fornasini): *Uvigerina bononiensis* Fornasini, 1888.
Rosalina globularis d'Orbigny, 1826.
Siphonina reticulata (Czjzek): *Rotalina reticulata* Czjzek, 1848.
Uvigerina proboscidea Schwager, 1866.
Uvigerina striatissima Perconig, 1955.

References

- Altenbach, A.V., Pflaumann, U., Ralph, S., Thies, A., Timm, S., Trauth, M., 1999. Scaling and distributional patterns of benthic foraminifera with flux rates of organic carbon. *Journal of Foraminiferal Research* 29, 173–185.
- Andersen, N., Paul, H.A., Bernasconi, S.M., McKenzie, J.A., Behrens, A., Schaeffer, P., Albrecht, P., 2001. Large and rapid climate variability during the Messinian salinity crisis: evidence from deuterium concentrations of individual biomarkers. *Geology* 29, 799–802.
- Andrleit, H.A., Rogalla, U., 2002. Coccolithophores in surface sediments of the Arabian Sea in relation to environmental gradients in surface waters. *Marine Geology* 31, 1–22.
- Aubry, M.-P., 1992. Paleogene calcareous nannofossils from the Kerguelen Plateau, Leg 120. In: Wise, S.W., Schlich, R., et al. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Results*, vol. 120. College Station, TX, pp. 471–491.
- Backman, J., 1978. Late Miocene-Early Pliocene nannofossil biochronology and biogeography of the Vera Basin, SE Spain. *Stockholm Contributions in Geology* 32, 93–114.
- Baumann, K.H., Andrleit, H.A., Xin, Su, 1998. Comparison of different preparation techniques for quantitative nannofossil studies. *Journal of Nannoplankton Research* 20, 75–80.
- Bé, A.W.H., 1977. An ecological, zoogeographic and taxonomic review of recent planktonic foraminifera. In: Ramsay, A.T.S. (Ed.), *Oceanic Micropaleontology*, vol. 1. Academic Press, London, pp. 1–100.
- Bellanca, A., Caruso, A., Ferruzza, G., Neri, R., Rouchy, J.-M., Sprovieri, M., Blanc-Valleron, M.-M., 2001. Transition from marine to hypersaline conditions in the Messinian Tripoli Formation from the marginal areas of the central Sicilian Basin. *Sedimentary Geology* 140, 87–105.
- Bertini, A., Londeix, L., Maniscalco, R., Di Stefano, A., Suc, J.-P., Clauzon, G., Gautier, F., Grasso, M., 1998. Paleobiological evidence of depositional conditions in the Salt Member, Gessoso-Solfifera Formation (Messinian, Upper Miocene) of Sicily. *Micropaleontology* 44, 413–433.
- Bijma, J., Faber Jr., W.W., Hemleben, Ch., 1990. Temperature and salinity limits for growth and survival of some planktonic foraminifera in laboratory cultures. *Journal of Foraminiferal Research* 20, 95–116.
- Bizon, G., Muller, C., Vergnaud-Grazzini, C., 1979. Paleoenvironmental conditions during deposition of late Miocene diatomaceous sediments in Morocco and Cyprus. *Annales Géologiques du Pays Hellenique, Tôme Hors Série* 1, 113–128.

- Blanc, P.L., 2000. Of sills and straits: a quantitative assessment of the Messinian salinity crisis. *Deep-Sea Research I* 47, 1429–1460.
- Blanc-Valleron, M.-M., Pierre, C., Caullet, J.P., Caruso, A., Rouchy, J.-M., Cespuoglio, G., Sprovieri, R., Pestrea, S., Di Stefano, E., 2002. Sedimentary, stable isotope and micropaleontological records of paleoceanographic change in the Messinian Tripoli Formation (Sicily, Italy). *Palaeogeography, Palaeoclimatology, Palaeoecology* 185, 255–286.
- Brand, L., 1994. Physiological ecology of marine coccolithophores. In: Winter, A., Siesser, W.G. (Eds.), *Coccolithophores*. Cambridge University Press, pp. 39–48.
- Cachao, M., Drago, T., Silva, A.D., Moita, T., Oliveira, A., Naughton, F., 2002. The secret (estuarine?) life of *Helicosphaera carteri*: preliminary results. *Journal of Nannoplankton Research* 24, 76–77.
- Capotondi, L., Borsetti, A.M., Morigi, C., 1999. Foraminiferal ecozones: a high-resolution proxy for the Late Quaternary biochronology in the central Mediterranean Sea. *Marine Geology* 153, 253–274.
- Chen, M., Tan, Z., 1999. Radiolarian distribution in surface sediments of the northern and central South China Sea. *Marine Micropaleontology* 32, 173–194.
- Cita, M.B., 1976. Biodynamic effects of the Messinian Salinity Crisis on the evolution of planktonic foraminifers in the Mediterranean. *Palaeogeography, Palaeoclimatology, Palaeoecology* 20, 23–42.
- Cita, M.B., Grignani, D., 1983. Nature and origin of Late Neogene Mediterranean sapropels. In: Schlanger, S.O., Cita, M.B. (Eds.), *Nature and Origin of Cretaceous C-Rich Facies*, pp. 165–196.
- Debenay, J.-P., Ba, M., Ly, A., Sy, I., 1987. Les écosystèmes paraliques du Sénégal. Description, répartition du peuplement de foraminifères benthiques. *Revue de Paléobiologie* 6, 229–255.
- Di Stefano, E., Cita, M.B., Spezzaferri, S., Sprovieri, R., 1999. The Messinian–Zanclean Pissouri section (Cyprus, Eastern Mediterranean). *Memorie della Societa Geologica Italiana* 54, 133–144.
- Duggen, S., Hoernle, K., van den Bogaard, P., Rüpke, L., Morgan, J.P., 2003. Deep roots of the Messinian salinity crisis. *Nature* 422, 602–606.
- Fairbanks, R.G., Wiebe, P.H., 1980. Foraminifera and chlorophyll maximum: vertical distribution, seasonal succession, and paleoceanographic significance. *Science* 209, 1524–1526.
- Fenton, M., Geiselhart, S., Rohling, E.J., Hemleben, Ch., 2000. A planktonic zones in the Red Sea. *Marine Micropaleontology* 40, 277–294.
- Filippelli, G.M., Sierro, F.J., Flores, J.-A., Vázquez, A., Utrilla, R., Pérez-Folgado, M., Latimer, J.C., 2003. A sediment–nutrient–oxygen feedback responsible for productivity variations in late Miocene sapropel sequences of the western Mediterranean. *Palaeogeography, Palaeoclimatology, Palaeoecology* 190, 335–348.
- Flecker, R., Ellam, R.M., in press. Identifying Late Miocene episodes of connection and isolation in the Mediterranean–Paratethyan realm using Sr isotopes. *Sedimentary Geology*.
- Flores, J.-A., Sierro, F.J., Filippelli, G.M., Bárcena, M.A., Pérez-Folgado, M., Vázquez, A., Utrilla, R., 2005. Surface water dynamics and phytoplankton communities during deposition of cyclic late Messinian sapropel sequences in the western Mediterranean. *Marine Micropaleontology* 56, 50–79.
- Garcés, M., Krijgsman, W., J. Agustí, J., 1998. Chronology of the late Turolian deposits of the Fortuna basin (SE Spain): implications for the Messinian evolution of the eastern Betics. *Earth and Planetary Science Letters* 163, 69–81.
- Garcés, M., Krijgsman, W., Agustí, J., 2001. Chronostratigraphic framework and evolution of the Fortuna Basin (Eastern Betics) since the Late Miocene. *Basin Research* 13, 199–217.
- Gibbs, S.J., Shackleton, N.J., Young, J.R., 2004. Orbitally forced climate signals in mid-Pliocene nannofossil assemblages. *Marine Micropaleontology* 51, 39–56.
- Gibbs, S.J., Young, J.R., Bralower, T.J., Shackleton, N.J., 2005. Nannofossil evolutionary events in the mid-Pliocene: an assessment of the degree of synchrony in the extinctions of *Reticulofenestra pseudoumbilicus* and *Sphenolithus abies*. *Palaeogeography, Palaeoclimatology, Palaeoecology* 217, 155–172.
- Giunta, S., Negri, A., Maffioli, P., Sangiorgi, F., Capotondi, L., Morigi, C., Principato, M.S., Corselli, C., in press. Phytoplankton Dynamics in the Eastern Mediterranean Sea during Marine Isotope Stage 5e. *Palaeogeography, Palaeoclimatology, Palaeoecology*.
- Glaçon, G., Vergnaud-Grazzini, C., Iaccarino, S., Rehault, J.P., Randrianasolo, A., Sierro, F.J., Weaver, P., 1990. Planktonic foraminiferal events and stable isotopic record in the Upper Miocene of the Tyrrhenian Sea, ODP Site 654, Leg 107. In: Kastens, K.A., Mascle, J., et al. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Results*, vol. 107. College Station, TX, pp. 415–427.
- Goubert, E., Néraudeau, D., Rouchy, J.-M., Lacour, D., 2001. Foraminiferal record of environmental changes: Messinian of the Los Yesos area (Sorbas Basin, SE Spain). *Palaeogeography, Palaeoclimatology, Palaeoecology* 175, 61–78.
- Gutscher, M.-A., Malod, J., Rehault, J.-P., Contrucci, I., Klingelhoefer, F., Mendes-Victor, L., Spakman, W., 2002. Evidence for active subduction beneath Gibraltar. *Geology* 30, 1071–1074.
- Haq, B.U., 1980. Biogeographic history of Miocene calcareous nannoplankton and paleoceanography of the Atlantic Ocean. *Micro-paleontology* 25, 414–443.
- Haq, B.U., Lohmann, G.P., 1976. Early Cenozoic calcareous nannoplankton biogeography of the Atlantic Ocean. *Marine Micropaleontology* 1, 119–194.
- Hemleben, C., Spindler, M., Anderson, O.R., 1989. *Modern Planktonic Foraminifera*. Springer, New York, pp. 1–363.
- Hilgen, F.J., Krijgsman, W., 1999. Cyclostratigraphy and astrochronology of the Tripoli diatomite formation (pre-evaporite Messinian, Sicily, Italy). *Terra Nova* 11, 16–22.
- Hilgen, F.J., Krijgsman, W., Langereis, C.G., Lourens, L.J., Santarelli, A., Zachariasse, W.J., 1995. Extending the astronomical (polarity) time scale into the Miocene. *Earth and Planetary Science Letters* 136, 495–510.
- Hilgen, F.J., Bissoli, L., Iaccarino, S., Krijgsman, W., Meijer, R., Negri, A., Villa, G., 2000. Integrated stratigraphy and astrochronology of the Messinian GSSP at Oued Akrech (Atlantic Morocco). *Earth and Planetary Science Letters* 182, 237–251.
- Hodell, D.A., Benson, R.H., Kennett, J.P., Rakic-El Bied, K., 1989. Stable isotope stratigraphy of latest Miocene sequences in northwest Morocco: the Bou Regreg section. *Paleoceanography* 4, 467–482.
- Hodell, D.A., Curtis, J.H., Sierro, F.J., Raymo, M., 2001. Correlation of late Miocene to early Pliocene sequences between the Mediterranean and North Atlantic. *Paleoceanography* 16, 164–178.
- Hsü, K.J., Cita, M.B., Ryan, W.B.F., 1973a. The origin of the Mediterranean evaporites. Initial Reports of the Deep Sea Drilling Project, XIII, vol. 13. US Government Printing Office, Washington, DC, pp. 1203–1231.
- Hsü, K.J., Ryan, W.B.F., Cita, M.B., 1973b. Late Miocene desiccation of the Mediterranean. *Nature* 242, 240–244.
- Iaccarino, S., 1985. Mediterranean Miocene and Pliocene planktic foraminifera. In: Bolli, H.M., et al. (Ed.), *Plankton Stratigraphy*. Cambridge University Press, pp. 283–314.
- Itaki, T., 2003. Depth-related radiolarian assemblage in the water-column and surface sediments of the Japan Sea. *Marine Micropaleontology* 47, 253–270.

- Ito, M., Ono, T., Oba, T., Noriki, S., 2001. Isotopic composition and morphology of living *Globorotalia scitula*: a new proxy of sub-intermediate ocean carbonate chemistry? *Marine Micropaleontology* 42, 189–210.
- Ivanov, D., Ashraf, A.R., Mosbrugger, V., Palamarev, E., 2002. Palynological evidence for Miocene climate change in the Forecarpathian Basin (Central Paratethys, NW Bulgaria). *Palaeogeography, Palaeoclimatology, Palaeoecology* 178, 19–37.
- Jones, R.W., 1994. *The Challenger Foraminifera*. Oxford University Press. 149 pp.
- Jonkers, H.A., 1984. Pliocene benthonic foraminifera from homogeneous and laminated marls on Crete. *Utrecht Micropaleontological Bulletin* 31. 179 pp.
- Kidd, R.B., Cita, M.B., Ryan, W.B.F., 1978. Stratigraphy of eastern Mediterranean sapropel sequences recovered during DSDP Leg 42A and their paleoenvironmental significance. In: Hsü, K.J., Montadert, L., et al. (Eds.), *Init. Repts. DSDP*, vol. 42A. U.S. Govt. Printing Office, Washington, pp. 412–443.
- Kleijne, A., 1992. Extant Rhabdosphaeraeae (coccolithophorids, class Primmiosiphyceae) from the Indian Ocean, Red Sea, Mediterranean Sea and North Atlantic Ocean. *Scripta Geologica* 100, 1–63.
- Kling, S., 1978. Radiolaria. In: Haq, B.U., Boersma, A. (Eds.), *Introduction to Marine Micropaleontology*. Elsevier, pp. 203–244.
- Knappertbusch, M., 1993. Geographic distribution of living and Holocene coccolithophores in the Mediterranean Sea. *Marine Micropaleontology* 21, 219–247.
- Knappertbusch, M., Cortes, M., Thierstein, H.R., 1997. Morphologic variability of the coccolithophorid *C. leptoporus* in the plankton surface sediments and from the early Pleistocene. *Marine Micropaleontology* 30, 293–317.
- Kouwenhoven, T.J., Seidenkrantz, M.-S., van der Zwaan, G.J., 1999. Deep-water changes: the near-synchronous disappearance of a group of benthic foraminifera from the late Miocene Mediterranean. *Palaeogeography, Palaeoclimatology, Palaeoecology* 152, 259–281.
- Kouwenhoven, T.J., Hilgen, F.J., van der Zwaan, G.J., 2003. Late Tortonian–early Messinian stepwise disruption of the Mediterranean–Atlantic connections: constraints from benthic foraminiferal and geochemical data. *Palaeogeography, Palaeoclimatology, Palaeoecology* 198, 303–319.
- Krijgsman, W., 2002. The Mediterranean: *Mare Nostrum* of earth sciences. *Earth and Planetary Science Letters* 205, 1–12.
- Krijgsman, W., Garcés, M., 2004. Paleomagnetic constraints on the geodynamic evolution of the Gibraltar Arc. *Terra Nova* 16, 281–287.
- Krijgsman, W., Langereis, C.G., 2000. Magnetostratigraphy of the Zobzit and Koudiat Zarga sections (Taza–Guercif basin, Morocco): implications for the evolution of the Rifian Corridor. *Marine and Petroleum Geology* 17, 359–371.
- Krijgsman, W., Hilgen, F.J., Langereis, C.G., Zachariasse, W.J., 1994. The age of the Tortonian/Messinian boundary. *Earth and Planetary Science Letters* 121, 533–547.
- Krijgsman, W., Hilgen, F.J., Raffi, I., Sierro, F.J., Wilson, D.S., 1999a. Chronology, causes and progression of the Messinian salinity crisis. *Nature* 400, 652–655.
- Krijgsman, W., Langereis, C.G., Zachariasse, W.J., Bocaletti, M., Moratti, G., Gelati, R., Iaccarino, S., Papani, G., Villa, G., 1999b. Late Neogene evolution of the Taza–Guercif Basin (Rifian Corridor, Morocco) and implications for the Messinian salinity crisis. *Marine Geology* 153, 147–160.
- Krijgsman, W., Blanc-Valleron, M.-M., Flecker, F., Hilgen, F.J., Kouwenhoven, T.J., Merle, D., Orszag-Sperber, F., Rouchy, J.-M., 2002. The onset of the Messinian salinity crisis in the Eastern Mediterranean (Pissouri Basin, Cyprus). *Earth and Planetary Science Letters* 194, 299–310.
- Krijgsman, W., Gaboardi, S., Hilgen, F.J., Iaccarino, S., de Kaenel, E., van der Laan, E., 2004. Revised astrochronology for the Ain el Beida section (Atlantic Morocco): no glacio-eustatic control for the onset of the Messinian Salinity Crisis. *Stratigraphy* 1, 87–101.
- Kroon, D., Wouters, P.F., Moodley, L., Ganssen, G., Troelstra, S.R., 1988. Phenotypic variation of *Turborotalita quinqueloba* (Nataland) tests in living populations and in the Pleistocene of an eastern Mediterranean piston core. In: Brummer, G.J.A., Kroon, D. (Eds.), *Planktonic Foraminifera as Tracers of Ocean–Climate History*. Free University Press, Amsterdam, pp. 131–147.
- Kuroyanagi, A., Kawahata, H., 2004. Vertical distribution of living planktonic foraminifera in the seas around Japan. *Marine Micropaleontology* 53, 173–196.
- Lamolda, M.A., Melinte, M.C., Kaiho, K., 2005. Nannofloral extinction and survivorship across the K/T boundary at Caravaca, southeastern Spain. *Palaeogeography, Palaeoclimatology, Palaeoecology* 224, 27–52.
- Loeblich Jr., A.R., Tappan, H., 1988. *Foraminiferal Genera and their Classification*. Van Nostrand Reinhold, NY. 869 pp.
- Lohmann, G.P., Carlson, J.J., 1981. Oceanographic significance of Pacific late Miocene calcareous nannoplankton. *Marine Micropaleontology* 6, 553–579.
- Mackensen, A., Fütterer, D.K., Grobe, H., Schmiedl, G., 1993. Benthic foraminiferal assemblages from the eastern South Atlantic Polar Front region between 35 and 57 degrees S: distribution, ecology and fossilization potential. *Marine Micropaleontology* 22, 33–69.
- Malinverno, E., Ziveri, P., Corselli, C., 2003. Coccolithophorid distribution in the Ionian Sea and its relationship to eastern Mediterranean circulation during late fall–early winter 1997. *Journal of Geophysical Research* 108, 8115.
- Mayer-Eymar, C., 1867. *Catalogue systématique et descriptif de fossils des terrains tertiaires qui se trouvent au Musée Federal de Zürich*. 1, 37 pp., 2, 65 pp.
- McIntire, A., Bé, A.W.H., 1967. Modern coccolithophoridae of the Atlantic Ocean—I: Placoliths and Cyrtholiths. *Deep-Sea Research* 14, 561–597.
- Meijer, P., Krijgsman, W., 2005. A quantitative analysis of the desiccation and refilling of the Mediterranean during the Messinian Salinity Crisis. *Earth and Planetary Science Letters* 240, 510–520.
- Meijer, P., Slingerland, L., Wortel, M.J.R., 2004. Tectonic control on past circulation of the Mediterranean Sea: a model study of the Late Miocene. *Paleoceanography* 19, PA1026. doi:10.1029/2003PA000956.
- Melinte, M.C., Lamolda, M.A., Kaiho, K., 2003. Nannofloral extinction and survivorship around the K/T boundary event at Caravaca, SE Spain. “Bioevents: their stratigraphic records, patterns and causes”, Caravaca de la Cruz, Spain, June 2003.
- Merle, D., Pestrea, S., Courme-Rault, M.-D., Zorn, L., Blanc-Valleron, M.-M., Orszag-Sperber, F., Krijgsman, W., 2002. Les paléopeuplements marins du Messinien pré-évaporitique de Pissouri (Chypre, Méditerranée orientale): aspects paléocéologiques précédant la crise de salinité messinienne. *Geodiversitas* 24, 669–689.
- Mohiuddin, M.M., Nishimura, A., Tanaka, Y., 2005. Seasonal succession, vertical distribution, and dissolution of planktonic foraminifera along the Subarctic Front: implications for paleoceanographic reconstruction in the northwestern Pacific. *Marine Micropaleontology* 55, 129–156.
- Murray, J.W., 1991. *Ecology and Palaeoecology of Benthic Foraminifera*. Longman Scientific and Technical. 397 pp.

- Negri, A., Giunta, S., 2001. Calcareous nannofossil paleoecology in the sapropel S1 of the eastern Ionian sea: paleoceanographic implications. *Palaeogeography, Palaeoclimatology, Palaeoecology* 169, 101–112.
- Negri, A., Villa, G., 2000. Calcareous nannofossil biostratigraphy, biochronology and paleoecology at the Tortonian/Messinian boundary of the Faneromeni section (Crete). *Palaeogeography, Palaeoclimatology, Palaeoecology* 156, 195–209.
- Negri, A., Giunta, S., Hilgen, F.J., Krijgsman, W., Vai, G.B., 1999a. Calcareous nannofossil biostratigraphy of the M. del Casino section (northern Apennines, Italy) and paleoceanographic conditions at times of late Miocene sapropel formation. *Marine Micropaleontology* 36, 13–30.
- Negri, A., Capotondi, L., Keller, J., 1999b. Calcareous nannofossils, planktic foraminifers and oxygen isotopes in the late Quaternary sapropels of the Ionian Sea. *Marine Geology* 157, 84–99.
- Nesteroff, W.D., 1973. Mineralogy, petrography, distribution, and origin of the Messinian Mediterranean evaporites. Initial Reports of the Deep Sea Drilling Project, XIII, vol. 13. US Government Printing Office, Washington, DC, pp. 673–693.
- Nishimura, A., Nakaseko, K., Okuda, Y., 1997. A new coastal water radiolarian assemblage recovered from sediment samples from the Antarctic Ocean. *Marine Micropaleontology* 30, 29–44.
- Northcote, L.C., Neil, H.L., 2005. Seasonal variations in foraminiferal flux in the Southern Ocean, Campbell Plateau, New Zealand. *Marine Micropaleontology* 56, 122–137.
- Orszag-Sperber, F., Rouchy, J.-M., Bizon, G., Bizon, J.J., Cravatte, J., Muller, G., 1980. La sédimentation messinienne dans le bassin de Polemi (Chypre). *Géologie Méditerranéenne* 7, 91–102.
- Orszag-Sperber, F., Rouchy, J.-M., Blanc-Valleron, M.-M., 2000. La transition Messinien–Pliocène en Méditerranée orientale (Chypre): La période du Lago Mare et sa signification. *Comptes Rendus de l'Académie des Sciences, Série, II* 331, 483–490.
- Peeters, F.J.C., Brummer, G.J.A., Ganssen, G., 2002. The effect of upwelling on the distribution and stable isotope composition of *Globigerina bulloides* and *Globigerinoides ruber* (planktic foraminifera) in modern surface waters of the NW Arabian Sea. *Global and Planetary Change* 34, 269–291.
- Perch-Nielsen, K., 1985. Cenozoic calcareous nannofossils. In: Bolli, H.M., Saunders, J.B., Perch-Nielsen, K. (Eds.), *Plankton Stratigraphy*. Cambridge University Press, Cambridge, pp. 427–554.
- Pérez-Folgado, M., Sierro, F.J., Barcena, M.A., Flores, J.A., Vazquez, A., Utrilla, R., Hilgen, F.J., Krijgsman, W., Filippelli, G.M., 2003. Western versus eastern Mediterranean paleoceanographic response to astronomical forcing: a high-resolution microplankton study of precession-controlled sedimentary cycles during the Messinian. *Palaeogeography, Palaeoclimatology, Palaeoecology* 190, 317–334.
- Poignant, A., Moissette, P., 1992. Foraminifères benthiques des intercalations marneuses d'une série diatomitique du Messinien d'Algérie. *Neues Jahrbuch für Geologie und Paläontologie, Monatshefte* 11, 657–674.
- Pujol, C., Vergnaud-Grazzini, C., 1995. Distribution patterns of live planktic foraminifers as related to regional hydrography and productive systems of the Mediterranean Sea. *Marine Micropaleontology* 25, 187–217.
- Raffi, I., Rio, D., 1981. *Coccolithus pelagicus* (Wallich): a paleotemperature indicator in the late Pliocene Mediterranean deep sea record. In: Wezel, F.C. (Ed.), *Sedimentary Basins of Mediterranean Margins*. Pitagora, Bologna, pp. 187–190.
- Reiss, Z., Hottinger, L., 1984. *The Gulf of Aqaba*. Springer Verlag, Berlin. 354 pp.
- Rohling, E.J., Gieskes, W.W.C., 1989. Late Quaternary changes in Mediterranean Intermediate Water density and formation rate. *Palaeogeography* 6, 531–545.
- Rohling, E.J., Jorissen, F.J., De Stigter, H.C., 1997. 200 year interruption of Holocene sapropel formation in the Adriatic Sea. *Journal of Micropaleontology* 16, 97–108.
- Roth, P.H., Coulbourn, W.T., 1982. Floral and solution patterns of coccoliths in surface sediments of the North Pacific. *Marine Micropaleontology* 7, 1–52.
- Rouchy, J.-M., Orszag-Sperber, F., Blanc-Valleron, M.-M., Pierre, C., Riviere, M., Combourieu-Nebout, N., Panayides, I., 2001. Paleoenvironmental changes at the Messinian–Pliocene boundary in the eastern Mediterranean (southern Cyprus basins): significance of the Messinian Lago-Mare. *Sedimentary Geology* 145, 93–117.
- Ryan, W.B.F., 1973. Geodynamic implications of the Messinian crisis of salinity. In: Drooger, C.W. (Ed.), *Messinian Events in the Mediterranean*. North Holland, NY, pp. 26–38.
- Sánchez-Almazo, I.M., Spiro, B., Braga, J.C., Martin, J.M., 2001. Constraints of stable isotope signatures on the depositional palaeoenvironments of upper Miocene reef and temperate carbonates in the Sorbas Basin, SE Spain. *Palaeogeography, Palaeoclimatology, Palaeoecology* 175, 153–172.
- Santarelli, A., Brinkhuis, H., Hilgen, F.J., Lourens, L.J., Versteegh, G.J.M., Visser, H., 1998. Orbital signatures in a Late Miocene dinoflagellate record from Crete (Greece). *Marine Micropaleontology* 33, 273–297.
- Schiebel, R., Hemleben, C., 2000. Interannual variability of planktic foraminiferal populations and test flux in the eastern North Atlantic Ocean (JGOFS). *Deep-Sea Research I* 47, 1809–1852.
- Seidenkrantz, M.-S., Kouwenhoven, T.J., Jorissen, F.J., Shackleton, N.J., van der Zwaan, G.J., 2000. Benthic foraminifera as indicators of changing Mediterranean–Atlantic water exchange in the late Miocene. *Marine Geology* 163, 387–407.
- Sierro, F.J., Flores, J.A., Zamarreño, I., Vazquez, A., Utrilla, R., Frances, G., Hilgen, F.J., Krijgsman, W., 1999. Messinian pre-evaporite sapropels and precession-induced oscillations in western Mediterranean climate. *Marine Geology* 153, 137–146.
- Sierro, F.J., Hilgen, F.J., Krijgsman, W., Flores, J.A., 2001. The Abad composite (SE Spain): a Messinian reference section for the Mediterranean and the APTS. *Palaeogeography, Palaeoclimatology, Palaeoecology* 168, 141–169.
- Sierro, F.J., Flores, J.A., Francés, G., Vazquez, A., Utrilla, R., Zamarreño, I., Erlenkeuser, H., Barcena, M.A., 2003. Orbitaly-controlled oscillations in planktic communities and cyclic changes in western Mediterranean hydrography during the Messinian. *Palaeogeography, Palaeoclimatology, Palaeoecology* 190, 289–316.
- Soria, J.M., Fernandez, J., Viseras, C., 1999. Late Miocene stratigraphy and paleogeographic evolution of the intramontane Guadix Basin (Central Betic Cordillera, Spain): implications for an Atlantic–Mediterranean connection. *Palaeogeography, Palaeoclimatology, Palaeoecology* 151, 255–266.
- Sprovieri, R., Hasegawa, S., 1990. Plio–Pleistocene benthic foraminifer stratigraphic distribution in the deep-sea record of the Tyrrhenian Sea (ODP Leg 107). In: Kastens, K.A., Mascle, J., et al. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Results*, vol. 107. College Station, TX, pp. 429–459.
- Sprovieri, R., Di Stefano, E., Sprovieri, M., 1996a. High resolution chronology for late Miocene Mediterranean stratigraphic events. *Rivista Italiana di Paleontologia e Stratigrafia* 102, 77–104.
- Sprovieri, R., Di Stefano, E., Caruso, A., Bonomo, S., 1996b. High resolution stratigraphy in the Messinian Tripoli Formation in Sicily. *Paleopelagos* 6, 415–435.

- Sprovieri, M., Bellanca, A., Neri, R., Mazzola, S., Bonanno, A., Patti, B., Sorgente, R., 1999. Astronomical calibration of late Miocene stratigraphic events and analysis of precessionally driven paleoceanographic changes in the Mediterranean basin. *Memorie della Societa Geologica Italiana* 54, 7–24.
- Suc, J.-P., Bessais, E., 1990. Pérennité d'un climat thermo-xérique en Sicile avant, pendant, après la crise de salinité messinienne. *Comptes Rendus de l' Académie des Sciences, Serie II* 310, 1701–1707.
- Szczechura, J., 2004. *Pararotalia aculeata* (d'Orbigny, 1846) from the Middle Miocene of the Central Paratethys. *Przeglad Geologiczny (Polish Geological Review)* 52, 76–79 (http://www.pgi.gov.pl/pdf/pg_2004_01_09a.pdf; in Polish, with English abstract).
- Tolderlund, D.S., Bé, A.W.H., 1971. Seasonal distribution of planktonic foraminifera in the western North Atlantic. *Micropaleontology* 17, 297–329.
- Thunell, R.C., 1978. Distribution of recent planktonic foraminifera in surface sediments of the Mediterranean Sea. *Marine Micropaleontology* 3, 147–173.
- Van Assen, E., Kuiper, K.F., Krijgsman, W., Sierro, F.J., Barhoun, N., in press. Messinian astrochronology of the Melilla basin: stepwise restriction of the Mediterranean–Atlantic connection through Morocco. *Palaeogeography, Palaeoclimatology, Palaeoecology*.
- Van de Poel, H.M., 1992. Foraminiferal biostratigraphy and paleoenvironments of the Miocene–Pliocene Carboneras–Nijar Basin (SE Spain). *Scripta Geologica* 102, 1–32.
- Van Hinsbergen, D.J.J., Kouwenhoven, T.J., van der Zwaan, G.J., 2005. Paleobathymetry in the backstripping procedure: correction for oxygenation effects on depth estimates. *Palaeogeography, Palaeoclimatology, Palaeoecology* 221, 245–265.
- Van der Zwaan, G.J., 1982. Paleocology of late Miocene Mediterranean foraminifera. *Utrecht Micropaleontological Bulletin* 25, 201 pp.
- Van der Zwaan, G.J., Gudjonsson, L., 1986. Middle Miocene–Pliocene stable isotope stratigraphy and paleoceanography of the Mediterranean. *Marine Micropaleontology* 10, 71–90.
- Van der Zwaan, G.J., Jorissen, F.J., de Stigter, H.C., 1990. The depth dependency of planktonic/benthic foraminiferal ratios: constraints and applications. *Marine Geology* 95, 1–16.
- Van der Zwaan, G.J., Jorissen, F.J., Verhallen, P.J.J.M., Von Daniels, C.H. 1986. Atlantic-European Oligocene to recent *Uvigerina*-taxonomy, paleoecology and paleobiogeography. *Utrecht Micropaleontology Bulletin* 35, 240 pp.
- Vazquez, A., Utrilla, R., Zamarreño, I., Sierro, F.J., Flores, J.-A., Francés, G., 2000. Precession-related sapropels of the Messinian Sorbas Basin (south Spain): paleoenvironmental significance. *Palaeogeography, Palaeoclimatology, Palaeoecology* 158, 353–370.
- Vergnaud-Grazzini, C., Ryan, W.B.F., Cita, M.B., 1977. Stable isotope fractionation, climate change and episodic stagnation in the eastern Mediterranean Sea. *Sedimentary Geology* 28, 81–93.
- Violanti, D., 1996. Paleoautecological analysis of *Bulimina echinata* (Messinian, Mediterranean area). In: Cherchi, A. (Ed.), *Autecology of Selected Fossil Organisms* Bolletino della Societa Paleontologica Italiana, vol. 3, pp. 243–253.
- Wade, B.S., Bown, P., in press. Calcareous nannofossils in extreme environments: the Messinian Salinity Crisis, Polemi Basin, Cyprus. *Palaeogeography, Palaeoclimatology, Palaeoecology*.
- Warny, S.A., Bart, P.J., Suc, J.-P., 2003. Timing and progression of climatic, tectonic and glacio-eustatic influences on the Messinian Salinity Crisis. *Palaeogeography, Palaeoclimatology, Palaeoecology* 202, 59–66.
- Wright, R., 1978. Neogene paleobathymetry of the Mediterranean based on benthic foraminifers from DSDP Leg 42A. In: Hsü, K.J., Montadert, L., et al. (Eds.), *Initial Reports DSDP*, vol. 42. U.S. Government Printing Office, pp. 837–847.
- Wright, R., 1980. Benthic foraminiferal repopulation of the Mediterranean after the Messinian (Late Miocene) event. *Palaeogeography, Palaeoclimatology, Palaeoecology* 29, 189–214.
- Young, J.R., 1994. The functions of coccoliths. In: Winter, A., Siesser, W.G. (Eds.), *Coccolithophores*. Cambridge University Press, pp. 63–82.
- Young, J.R., 1998. Chapter 9: neogene. In: Bown, P.R. (Ed.), *Calcareous Nannofossil Biostratigraphy*. Kluwer Academic Publishing, Dordrecht, pp. 225–265.
- Ziveri, P., Thunell, R.C., Rio, D., 1995a. Seasonal changes in coccolithophore densities in the Southern California Bight during 1991–1992. *Deep-Sea Research I* 42, 1881–1903.
- Ziveri, P., Thunell, R.C., Rio, D., 1995b. Export production of coccolithophores in an upwelling region: results from San Pedro Basin, Southern California Borderlands. *Marine Micropaleontology* 24, 335–358.
- Ziveri, P., Rutten, A., De Lange, G.J., Thomson, J., Corselli, C., 2000. Present-day coccolith fluxes recorded in central eastern Mediterranean sediment traps and surface sediments. *Palaeogeography, Palaeoclimatology, Palaeoecology* 158, 175–195.
- Ziveri, P., Baumann, K.-H., Böckel, B., Bollmann, J., Young, J.R., 2004. Present day coccolithophore biogeography of the Atlantic Ocean. In: Thierstein, H.R., Young, J.R. (Eds.), *Coccolithophores—from Molecular Processes to Global Impact*. Springer Verlag, pp. 529–562.