Foraminiferal response to the deposition of insolation cycle 90 sapropel in different Mediterranean areas

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ABSTRACT – Foraminifera were investigated across the sapropel unit corresponding to insolation cycle 90 deposited in three different oceanographic and depositional settings of the Mediterranean Sea (Alboran Sea, South Adriatic Sea and Ionian Sea). The constant presence of benthic foraminifera throughout the sapropels at <2000 m water depth and their absence within the sapropel at greater depth (>3000 m) indicate that the severity of oxygen depletion at the time of sapropel onset increases with increasing water depth.

Planktonic and benthic foraminiferal patterns also document an interruption during sapropel deposition, which allows for the recognition of two sapropel phases. In all basins, the short interruption appears to be related to climatic deterioration, which led to the break in stratification and, hence, to the re-oxygenation of bottom waters. Since the interruption of the time-equivalent sapropel intervals has been documented previously in other Mediterranean areas, these data support the recent theory that this interruption must have been a trans-Mediterranean phenomenon and that the interruption records a short excursion out of the periods of wet climate associated with precessional minima. *J. Micropalaeontol.* **27**(1): 45–61, May 2008.

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INTRODUCTION

In the Mediterranean Sea, numerous dark-coloured layers, termed sapropels (Cita & Grignani, 1982; Thunell *et al.*, 1983; Hilgen, 1991), have been found in marine and land sequences (summary in Rohling & Hilgen, 1991 and references therein). Sapropel formation has been shown to be astronomically time-controlled, occurring around minima in the precessional cycle (Rossignol-Strick, 1985; Hilgen, 1991). The precessional minima with which sapropels coincide were periods of wetter climate in the Mediterranean Basin (Rossignol-Strick, 1983; Rohling & Hilgen, 1991).

The debate over the mechanisms that led to the formation of sapropels still remains unresolved. Two models have been proposed to explain the enrichment in organic carbon during their formation: the productivity model and the stagnation model. The productivity model postulates that the formation of sapropel correlates with periods of enhanced marine productivity and consequent increased flux of organic matter to the seafloor (Calvert & Pedersen, 1992; Lourens *et al.*, 1992; Castradori, 1993; Sancetta, 1994). In the stagnation model, anoxia is proposed as the dominant mechanism, enhancing organic matter preservation by increasing density stratification in the water column (Rossignol-Strick *et al.*, 1982; Thunell & Williams, 1989; Bethoux, 1993; Tang & Stott, 1993).

It is now widely accepted that primary productivity and restricted bottom water ventilation are not mutually exclusive as mechanisms leading to sapropel formation (Cramp & O'Sullivan, 1999; Sancetta, 1999).

Although the occurrence of same-age sapropel layers (Legs 160 and 161) extends across the entire Mediterranean (Comas *et al.*, 1996; Emeis *et al.*, 1996; de Kaenel *et al.*, 1999; Murat, 1999), marked differences have been observed in organic carbon content and geochemical properties between the western and the

eastern areas (Nijenhuis et al., 2001; Meyers & Arnaboldi, 2005; Meyers & Bernasconi, 2005). This can mean either that the western and eastern basins responded differently to the same regional/global forcing factors, or that the dominant mechanisms triggering sapropel formation were not operating to the same extent within the two basins. These hypotheses may find foundation in one of the major questions argued by Emeis et al. (2000) and are still open. They hypothesized that the 3000-year lag assumed for sapropel deposition in response to the minima in the astronomical procession index could have had implications for the processes acting in the Mediterranean Sea during the transition from non-sapropel to sapropel stage. This observation suggests that local climatic conditions during insolation maxima may have differently influenced the reduction in ventilation of the water mass and/or the increase in primary productivity in the photic layer.

In this context, it would be interesting to assess whether the oxygen content in the water masses and productivity enhancement were distributed uniformly across the Mediterranean Sea during the deposition of coeval sapropels. Foraminiferal patterns across synchronous sapropel intervals could then provide a good investigative tool. As demonstrated widely, planktonic foraminiferal associations within sapropels reflect periods of enhanced primary productivity in the water column (Rohling & Gieskes, 1989), whilst benthic foraminiferal faunas from sapropels reflect changes in bottom-water ventilation (Cita & Podenzani, 1980; Mullineaux & Lohmann, 1981; Ross & Kennett, 1983/84; Vismara-Schilling, 1984; Oggioni & Zandini, 1987; Nolet & Corliss, 1990; Jorissen, 1999; Schmiedl *et al.*, 2003).

This paper discusses a micropalaeontological study across the sediments from mid-Pleistocene insolation cycle 90 (955 Ka) deposited in different basins and at different water depth and

recovered at ODP drill-holes 977A (Alboran Basin, western Mediterranean) and 964D (Ionian Sea, eastern Mediterranean). A further purpose is to compare the sapropel recorded in the marine sediments (cores) with the time-equivalent sapropel layer found in the IM/Fosso 5 Agosto land section (Stefanelli et al., 2005). The high sedimentation rate of the Montalbano Jonico section (estimated to be about 50 cm ka⁻¹) offers an opportunity to examine an expanded stratigraphical interval (about 6 m thick). A high-resolution distributional pattern of benthic and planktonic foraminifera within the sapropel interval documents an ecosystem variability related to the unstable nature of bottom-water oxygen content (Stefanelli et al., 2005). The main aim is to assess differences/similarities in the i-cycle 90 sapropel expression and, thereby, to respond to the following question: how did the differences in hydrographic regime and in depth of depositional basin affect the formation of coeval sapropel?

Mediterranean circulation

The Mediterranean Sea is a semi-enclosed basin surrounded almost entirely by continents. Therefore, hydrography and sedimentation processes are controlled by the regional climate and topography of the adjacent land masses. The Mediterranean's physical circulation is driven by a surface wind that creates a pronounced eddy circulation in the surface layer, and by thermohaline gradients that drive intermediate and deep-water circulation (Emeis et al., 1996). The circulation pattern is anti-estuarine and is characterized by four major water masses (Wust, 1961; Rohling, 1991; Bethoux et al., 1999; Lascaratos et al., 1999; Send et al., 1999; Béranger et al., 2005): Atlantic Water (AW), Levantine Intermediate Water (LIW), Eastern Mediterranean Deep Water and Western Mediterranean Deep Water. Among them, in terms of sapropel formation, LIW plays the principal role, as reported by Rohling & Gieskes (1989) and Rohling (1991). The intermediate water mass was more rich in nutrients with respect to the overlying surface water. The nutricline is found in association with the halocline, between the surface and intermediate waters. As a consequence, at the time of sapropel formation, the shoaling of the halocline within the euphotic layer, due to a change in the circulation pattern, gave rise to the development of the deep chlorophyll maximum (DCM) below the halocline. The consequence was an increase in the downward flux of organic matter from the euphotic layer, which caused oxygen consumption at greater depth.

SAMPLING AND METHODS

The sapropel interval associated with insolation cycle 90 and MIS 25, dated at 955 Ka (de Kaenel *et al.*, 1999; Emeis *et al.*, 2000) from ODP Hole 977A (Leg 161) and Hole 964D (Leg 160) was investigated (Fig. 1).

In this study the age model provided by Howell *et al.* (1998) and von Grafenstein *et al.*, (1999) is adopted. The stratigraphical depth of sapropel boundaries (base and top) are those indicated by Murat (1999) and Emeis *et al.* (2000).

Site 977 is located in the Eastern Alboran Basin to the south of Cabo de Gata, halfway between the Spanish and Algerian coasts, at a water depth of 1984 m. Core 18X-1 was sampled in the stratigraphical interval between 156.68 and 156.0 revised metres composite depth (rmcd) (25 samples in total). The investigated interval corresponds to the termination of MIS 26 and the beginning of MIS 25 (von Grafenstein *et al.*, 1999). The sapropel layer does not show an evident change in colour and is documented between 156.34 and 156.24 rmcd (Murat, 1999).

Site 964 is located in the Ionian Basin at the foot of the Calabrian Ridge on a small bathymetric high, the Pisano Plateau, at a water depth of 3666 m. Core 4H-4 was sampled in the interval between 34.53 rmcd and 33.85 rmcd (35 samples). The investigated stratigraphic interval is enclosed entirely in MIS 25 (Howell *et al.*, 1998). The 12 cm thick sapropel (34.30–34.18 rmcd) exhibits sharp lower and upper boundaries. It is a composite sapropel with two dark-coloured beds. The lower dark-coloured bed is at 34.295–34. 285 rmcd depth, the uppermost one is at 34.235–34.205 rmcd depth.

Samples were also collected at the Bremen ODP Core Repository. The targeted cores were sampled at 2 cm spacing on average. Samples are 2 cm in diameter and the sample depths refer to midpoints of samples. Sediment samples were dried, weighed and washed through a 63 μ m screen. Subsequently, the coarse fraction was dry sieved at 125 μ m and 250 μ m. The analysis of benthic foraminifera was carried out on the split size fractions > 63 μ m. All the benthic foraminifera were counted and identified specifically whenever possible, or at generic level. Finally, all the counts were corrected for splits and the concentration of the benthic foraminifera was calculated as number of specimens per gram of dry sediment as well as percentages of frequency.

The diversity index H(S) and the dominance of the taxa (D) were also determined by means of the PAST (PALeontology STatistic) Program (Hammer *et al.*, 2001). They were performed on a raw data matrix of columns, each containing the count of individuals of different benthic taxa (per sample) down the row. The diversity index varies from 0 for associations with a single taxon, to high values for associations with many taxa, each with few individuals. Dominance varies from 0, when all the taxa are equally present in the association, to 1 when only one taxon dominates the association.

The planktonic foraminiferal analysis examined the same samples used for benthic foraminifer's counts. The planktonic foraminiferal counts were made on splits of 250–400 specimens from the >63 μ m fraction, and then their percentages of frequency were calculated. Successively, the percentage values were used for the application of a statistical method, Hierarchical Cluster Analysis (HCA), performed by means of SPSS program version 9.0, in order to demonstrate the linkage between taxa distribution and palaeoenvironmental gradients. For the analysis, those benthic and planktonic taxa with frequency values greater than 2% – as well as those of particular environmental significance – were selected.

The outcome of the HCA is a dendrogram in which foraminifera, with (palaeo)ecological similarity, are grouped into clusters. Each of these clusters can represent a distinct community from which it is possible to draw palaeoecological interpretations.

A raw data matrix, comprising *n* number of samples (in rows) \times *n* number of taxa (in columns), was used and the clustering was performed in R-mode. The most significant dendrograms were obtained using the Average-Linkage Within Group, Pearson correlation.



Fig. 1. Mediterranean basin with location of the investigated sites. The grey side-bars indicate the stratigraphic intervals studied for this work. The black side-bars indicate the stratigraphic interval of the sapropel layer associated with i-cycle 90.

The last step of HCA involves performing cumulative plots (the sum of the percentages of frequency of the taxa present in each cluster) in order to observe the stratigraphic distribution of the identified assemblages.

IM/Fosso 5 Agosto section

The IM/Fosso 5 Agosto land section represents the uppermost part of Interval A in the Montalbano Jonico composite section (Ciaranfi *et al.*, 2001). Nannofossil biostratigraphical analysis refers the section to the 'small' *Gephyrocapsa* Zone and to the lowermost part of the *Pseudoemiliania lacunosa* Zone (Maiorano *et al.*, 2004). The section is 55 m thick and consists entirely of dark and light muddy sediments (Fig. 1).

Figure 2 displays the palaeoenvironmental conditions in which it was deposited (from Stefanelli *et al.*, 2005, modified). Foraminiferal distribution suggests deposition of the pre- and post-sapropel stratigraphical intervals in a deep sedimentary basin, consistent with the upper bathyal zone (200–500 m water depth), under relatively 'cold' climate conditions (Stefanelli, 2004; Stefanelli *et al.*, 2005).

The sapropel layer is enclosed in MIS 25. It is associated with i-cycle 90 and consists of a 6 m thick interval of dark mud



Fig. 2. (a) Palaeoclimate curve based on planktonic foraminifera; (b) oxygen stable isotope record performed on the planktonic foraminiferid species *Globigerina bulloides*; (c) changes in palaeodepth recorded by benthic foraminifera. Sapropel occurred during deepening phase. Grey-shaded intervals indicate dysoxic sapropel phases A and B. FO, first occurrence; LCO, last common occurrence. Modified from Stefanelli *et al.* (2005).

(Stefanelli *et al.*, 2005). The continuous presence of benthic foraminifera across the sapropel suggests that the bottom was not totally anoxic. However, this layer exhibits two low oxygen phases, A and B. Both phases are characterized by warm climatic conditions together with freshwater input at the base, whereas, at the top, colder climatic conditions and a gradual mixing of the surficial water layers are documented. The identified phases are separated by a short re-oxygenation interval produced by a drop in temperature (Stefanelli *et al.*, 2005).

RESULTS

Foraminiferal fauna in Site 977A Core 18X-1, eastern Alboran Basin

Benthic foraminifera (Fig. 3). The benthic foraminiferal microfaunas are well preserved with no barren samples. Sixty-four taxa were counted and identified; the maximum number of taxa identified per sample was 45. For HCA, a raw data matrix made up of 25 samples \times 32 taxa was used.

Figure 4 records the outcome of HCA. The resulting dendrogram can be divided into the following clusters: Cluster A, Cluster B (divisible into subclusters B1 and B2), Cluster C and Cluster D. Figure 5 illustrates the cumulative plots of the benthic foraminiferal clustering. In the pre-sapropel interval (156.68–156.34 rmcd), benthic foraminifera numbers (BFN) range between 38 ind. g^{-1} and 120 ind. g^{-1} . Pre-sapropel diversities are rather high, with *H*(*S*) values around 2.5. This interval is characterized by several taxa, principally grouped into Cluster A. *Eponides pusillus* is the dominant species, with a frequency of up to 50%. *Cassidulina crassa* is also abundant, up to 20% of frequency. The associated taxa *Globocassidulina subglobosa*, *Bulimina striata mexicana*, *B. marginata*, *Bolivina pseudoplicata*, *Cibicidoides* group, *Pullenia* group and *Sphaeroidina bulloides* are present with low percentages of frequency (less than 4%).

At approximately 156.36 rmcd, BFN decreases. The assemblages become more specialized and reach the minimum diversity and the maximum dominance values in the two intervals, 156.32–156.28 rmcd and 156.26–156.24 rmcd, respectively. From 156.28–156.26 rmcd, BFN slightly increases and is associated with an increase in benthic faunal diversity, with H(S)=2.

In the sapropel interval, *Bolivina catanensis* (with a frequency up to 47%), *Globobulimina affinis* (80%), *Articulina tubulosa* and *Cassidulina carinata* (both 30%) are the dominant taxa. The associated taxa *Gyroidinoides* group and *Uvigerina peregrina* (both with frequencies up to 10%), *Bolivina* group, *Buliminella elegantissima*, *Bulimina exilis*, *Chilostomella mediterranensis*, *Fissurina* group, *Lagena* group and *Trifarina anguolsa* are rather scattered. These species are grouped in Clusters B and D (Fig. 4).

Bolivina catanensis, Globobulimina affinis, Articulina tubulosa and Cassidulina carinata never co-occur together. B. catanensis, which dominates the Cluster D assemblage, characterizes the



Fig. 3. Benthic patterns in Site 977A: (a) benthic foraminifera number (BFN) per gram of dry sediment; (b) number of counted taxa per sample; (c) number of total individuals counted per sample; (d) dominance (D); (e) species diversity (H(S)). All the graphs are plotted versus depth. Grey-shaded intervals indicate the sapropel phases A and B.

basal layer of the sapropel, from 156.34 rmcd to 156.32 rmcd. *G. affinis*, which dominates the subcluster B2 assemblage, characterizes two layers, 156.32–156.28 rmcd and 156.26–156.24 rmcd, which are separated by a short layer (156.28–156.26 rmcd) in which *A. tubulosa* and *C. carinata* are the most abundant benthic species belonging to the subcluster B1 assemblage.

From 156.24 rmcd depth, in the post-sapropel stratigraphical interval, the fauna returns to being well diversified, with values similar to those observed in the pre-sapropel interval (H(S)=2.5). The benthic foraminifera numbers are lower when compared with the pre-sapropel numbers. The assemblages are characterized by *Anomalinoides minimus*, *Quinqueloculina* group, *Melonis* group, *Nonionella turgida*, *Bolivina variabilis*, *Epistominella exigua*, *Fursenkoina schreibersiana* and *Globocassidulina brady*, all taxa grouped in Cluster C.

E. pusillus and the associated taxa of Cluster A are also present, with minor percentages of frequency with respect to the pre-sapropel interval (Fig. 5).

Planktonic foraminifera. Planktonic foraminiferal assemblages are abundant and diverse, some specimens are filled with pyrite and/or CaCO₃. For HCA, a raw data matrix made up of 25 samples \times 12 taxa was used.

Figure 6 reports the resulting HCA dendrogram in which two clusters are recognizable: Cluster I and Cluster II. Cluster I groups *Globigerinoides ruber alba*, *Globorotalia inflata*, *Globigerina rubescens*, *Globigerinoides tenellus* and *Orbulina universa*. Cluster II groups *Globigerina bulloides*, *Turborotalia quinqueloba*, *Globigerinita glutinata*, *Neogloboquadrina dutertrei*, *Neogloboquadrina pachyderma* (dextral and sinestral), *Globorotalia truncatulinoides* and *G. scitula*.

Figure 7 displays the cumulative plots of the planktonic foraminifera clustering. In the pre- and post-sapropel stratigraphic intervals, the Cluster II assemblage is dominant, whereas the Cluster I assemblage characterizes the sapropel samples.

In the pre-sapropel stratigraphical interval, among the species grouped in Cluster I, *Globigerina rubescens* and *Globigerinoides tenellus* show their maximum peak in abundance. Between 156.68 rmcd and 156.5 rmcd, *Globigerina bulloides* and *Neo-globoquadrina pachyderma* dex are the most representative specimens, then they decrease in percentages (from 15–20% to 5–10%, respectively) within the sapropel interval. Generally, *G. ruber alba*, *T. quinqueloba* and *G. inflata* are well represented. In detail, *G. ruber alba* displays its maximum peak in abundance at 156.32 rmcd core depth, then it gradually decreases in the upper part of the sapropel; *G. inflata* increases towards the top of the sapropel and reaches its maximum abundance at 156.27 rmcd and *T. quinqueloba* occurs with percentages around 20%.

The peak in frequency of *N. pachyderma* sin, *N. dutertrei*, *O. universa* and *G. glutinata* is significant between 156.30 rmcd and 156.28 rmcd. In this short interval, these species increase in abundance, whereas *G. inflata*, *T. quinqueloba* and *G. bulloides* decrease. In the samples immediately above, between 156.279 rmcd and 156.26 rmcd, *G. inflata* and *N. pachyderma* dex increase in abundance, while *N. pachyderma* sin, *N. dutertrei*, *O. universa* and *G. glutinata* decrease.

In the post-sapropel interval the assemblages are characterized by *G. inflata* (frequency >20%), *G. bulloides* (>10%) and *N. pachyderma* (dex and sin) (10–30%).

Foraminiferal assemblages at Site 964 Core 4H-4, Ionian Sea

Benthic foraminifera. Fifteen benthic taxa were counted and identified. The maximum number of taxa identified per sample is eight. The samples associated with the dark-coloured beds are barren of benthic foraminifera. The benthic foraminiferal faunal pattern is shown in Figure 8.

Cases Valid Missing Total Percent Ν Ν Percent Ν Percent 32 100.0% 0 100.0% 0% 32

Case Processing Summary a.

^{a.} Correlation between vectors of Values used

Dendrogram using Average Linkage (Within Group)

Rescaled Distance Cluster Combine



Fig. 4. Dendrogram based on R-mode cluster analysis by means of SPSS. Four clusters are identified: Cluster A, Cluster B, Cluster C and Cluster D. Cluster B is subdivided into two subclusters, B1 and B2.



Fig. 5. Cumulative plots of clusters at Site 977A plotted versus depth. Grey-shaded intervals indicate the sapropel phases A and B.

| | | Са | ises | | |
|-------|---------|---------|---------|-------|---------|
| Valid | | Missing | | Total | |
| Ν | Percent | Ν | Percent | Ν | Percent |
| 12 | 100.0% | 0 | 0% | 12 | 100.0% |

Case Processing Summary a.

^{a.} Correlation between vectors of Values used

Dendrogram using Average Linkage (Within Group)

Rescaled Distance Cluster Combine



Fig. 6. Dendrogram based on R-mode cluster analysis by means of SPSS. Two clusters are identified: Cluster I and Cluster II.

Two species dominate the assemblages: *Articulina tubulosa* and *Anomalinoides minimus*, although they never co-occur in the same samples, with the exception of the last sample at the top of sapropel at 34.19 rmcd depth (Fig. 9). Consequently, the dominance of only two species and the very low presence of associated taxa did not permit statistical analyses.

In the pre-sapropel interval, BFN average is 15 ind. g^{-1} on, except in the interval between 34.44 rmcd and 34.38 rmcd, where the values increase up to 50 ind. g^{-1} . Diversity is low and shows an increasing trend towards the sapropels, reaching the maximum value in the sample just below the sapropel, with H(S)=1, at 34. 31 rmcd. *A. tubulosa* dominates the pre-sapropel interval



Fig. 7. Cumulative plots of clusters at Site 977A plotted versus depth. Grey-shaded intervals indicate the sapropel phases A and B.



Fig. 8. Benthic patterns at Site 964D: (a) benthic foraminifera number (BFN) per gram of dry sediment; (b) number of counted taxa per sample; (c) dominance (D); (d) species diversity (H(S)). All the graphs are plotted versus depth. Grey-shaded interval indicates the sapropel unit. Black colour indicates benthic sterile intervals (phases A and B).

exclusively. Towards the sapropel, this species co-occurs with the genus *Pyrgo*, which has a frequency of 30%. *Quinqueloculina* group is also present with very low frequencies (<2%).

Within the sapropel interval, the samples associated with the two dark-coloured beds are barren of benthic foraminifera.

Between the dark-coloured beds, in the short interval 34.286-34.245 rmcd, BFN strongly increases, reaching its maximum values (138 ind. g⁻¹ on average). In this short interval *Anomalinoides minimus* is the dominant species. Just before sapropel termination, (34.20–34.18 rmcd), above the second and uppermost dark-coloured bed, *A. tubulosa* and *A. minimus* co-occur, both with a frequency of 50%.

In the immediately subsequent post-sapropel interval, *Articulina tubulosa* again dominates the assemblages.

Planktonic foraminifera. The dendrogram obtained by HCA cannot be interpreted as the clustering of the planktonic taxa did not allow palaeoecological interpretation. Opinion is that, probably, the low number of samples analysed for this stratigraphical interval did not give rise to a significative raw data matrix. Consequently, the quantitative distributional patterns of each taxon are discussed for Site 964D.

The distribution versus depth of the most abundant planktonic foraminifera and the palaeoclimate curve is shown in Figure 10.

Globigerinoides ruber, Globigerina bulloides, Globorotalia scitula, Globigerinita glutinata are the most typical species in the pre-sapropel interval.



Fig. 9. Stratigraphic distribution of the dominant species Articulina tubulosa and Anomalinoides minimus at Site 964D plotted versus depth. The associated genera *Pyrgo* and *Quinqueloculina* are also displayed. Grey-shaded interval indicates the sapropel unit. Black colour indicates benthic sterile intervals (phases A and B).

The first dark-coloured layer is characterized by an increase in values of *N. dutertrei*, *G. bulloides*, *N. pachyderma* dex, *T. quinqueloba* and *O. universa*. The assemblage identified between the two dark-coloured intervals documents the strong decrease in *T. quinqueloba*, the near absence of *G. glutinata* and *G. scitula*, and an increase in *N. pachyderma* dex, *G. inflata* and *G. bulloides*. The second dark level contains a microfauna dominated by *G. bulloides*, *G. ruber* gr., *G. glutinata* and *T. quinqueloba*.

G. glutinata and *G. bulloides* dominate the post-sapropel assemblages. *G. trilobus*, generally absent in the investigated core section, occurred from 34.17 rmcd and 33.9 rmcd. A peak in frequency of *N. pachyderma* dex and *G. inflata* is also observed.

DISCUSSION

The life strategies of most benthic foraminiferal species are well known from studies on their distribution pattern and the microhabitat of recent benthic foraminifera from the Mediterranean (Mullineaux & Lohmann, 1981; Nolet & Corliss, 1990; Jorissen et al., 1992, 1995; De Stigter et al., 1998; De Rijk et al., 1999; Jorissen, 1999; Schmiedl et al., 2000; 2003; Sgarrella & Moncharmont Zei, 1993) and from other areas (Corliss, 1985; Mackensen & Douglas, 1989; Corliss & Emerson, 1990; Sen Gupta & Machain-Castillo, 1993; Gooday, 1994; Loubere, 1997). Similarly well documented is the geographical and depth distribution of living planktonic foraminifera in the Mediterranean Sea (Pujol & Vergnaud-Grazzini, 1995; Reiss et al., 1999). Information about the life strategies of the major benthic and planktonic species that characterize the assemblages in Holes 977A and 964D is reported in Appendix A and they are illustrated in Plate 1.

Foraminiferal number, diversity and distribution in the western and eastern Mediterranean: ecosystem variability prior to, during and after the sapropel deposition

Across the Mediterranean Sea, benthic foraminifera frequency decreases from the high values encountered at Hole 977A

(60 ind. g^{-1} on average) to very low values at Hole 964D (15 ind. g^{-1} on average). This trend can be explained in terms of food availability, which decreases with increasing water depth (from 1984 m at 977A to 3666 m at 964D), as previously documented by several authors (Cita & Zocchi, 1978; Parisi, 1981; Parisi & Cita, 1982; De Rijk et al., 1999). Similarly, diversity decreases strongly with increasing depth, from H(S)=3in the middle bathyal 977A, towards H(S) < 1 in the deepest 964D. These observations corroborate previous studies carried out in the Mediterranean Sea, which reported unusually lowdiversity faunas in the lower bathyal and abyssal ecosystems (Cita & Zocchi, 1978; Mullineaux & Lohmann, 1981) under oligotrophic and well-oxygenated conditions (Pickard & Emery, 1990; Antoine et al., 1995) and high-diversity faunas in the middle/upper bathyal and shelf ecosystems (Schmiedl et al., 2000; 2003) under meso- to eutrophic conditions.

In western Site 977A, before the sapropel deposition, the stability of the deep-sea ecosystem favoured the development of the highly diverse Cluster A assemblage under meso- to eutrophic conditions. The distinct vertical microhabitat preferences, from epifauna to shallow infauna observed in the presapropel assemblage also reflect a (palaeo)environmental setting with high oxygen content at the bottom–water interface that can reach deep layers within the sediment column (Loubere, 1997). Accordingly, the occurrence of *G. inflata* and, in some levels, of *G. truncatulinoides* documents the presence of a water column with deep convective mixing.

The cumulative plots of Clusters I and II performed on planktonic microfauna mirror the palaeoclimate curve *sensu* Lourens *et al.* (1992) (see Fig. 6), based on selected warm-water (*Globigerinoides tenellus*, *G. ruber*, *Globigerina rubescens*, *Orbulina universa* – Cluster I) and cold-water species (*Globigerina bulloides*, *Globorotalia scitula*, *Neogloboquadrina pachyderma* dex and sin, *Globigerinita glutinata* and *Turborotalia quinqueloba* – Cluster II). This suggests that the temperature and/or seasonality are two important factors influencing the



Fig. 10. Stratigraphical distribution of selected planktonic foraminifera species at Site 964D plotted versus depth. Palaeoclimate record is also shown. Grey-shaded interval indicates the sapropel unit. Black colour indicates benthic sterile intervals (phases A and B).

planktonic assemblage composition and distribution in this time interval. Focusing in detail, the palaeoclimate curve shows an increase in temperature of the water masses beginning several samples prior to sapropel deposition, at 156.5 rmcd (see Fig. 7).

Just before sapropel deposition, the observed increase in numbers of *G. ruber* and *G. tenellus/G. rubescens*, which culminates within the sapropel, as well as the simultaneous slight decrease of *G. bulloides* and *N. pachyderma*, suggest the presence of warm, low surficial water density with consequent increase in stratification. However, the environmental deterioration was not drastic enough to stop seasonal vertical mixing, as evidenced by the presence of *G. inflata*. Also, no persistent anoxia developed at the bottom, as documented by the persistent presence of benthic foraminifera throughout the sapropel interval.

The rhythmical succession in benthic foraminifera sapropel assemblages can be interpreted as a response to the continuous changes in oxygen content of the bottom water, allowing identification of distinct sapropel phases. The dominance of *B. catanensis* in the lower part of the sapropel interval, later replaced by *G. affinis*, implies the gradual thinning of the oxygenated top layer of the sediments during the development of the first sapropel phase (phase A). The replacement of *A. tubulosa* and *C. carinata* by the dysoxic species *G. affinis* documents short oxygenation pulses under unstable environmental conditions (Schmiedl *et al.*, 1998; Jorissen, 1999). Finally, the replacement of *G. affinis* in the upper part of the sapropel interval by *A. tubulosa* and *C. carinata* suggests the re-establishment of the sapropel condition still under a dysoxic regime (phase B).

The presence of the genera Articulina and Cassidulina throughout the sapropel documents a short interval characterized by oxygen replenishment at the seafloor. In these samples, the peak in frequency of the cool taxon *G. inflata* and the increase in abundance of *G. bulloides* and *N. pachyderma* dex document the drop in temperature that probably drove a vertical water mixing and, hence, the oxygen increase at the bottom-water interface.

During the onset of the second sapropel subunit, the lower abundance of *G. affinis* (from 80% in the first subunit to 60% detected in the second subunit) and the increase in frequency of *C. carinata* and *A. tubulosa* (from 2% in the first subunit to 20% detected in the second subunit) clearly suggest an improved



Explanation of Plate 1.

The most (palaeo)ecologically significant benthic species encountered in this work (scale bar 100 micron). fig. 1. Articulina tubulosa (Seguenza, 1862). fig. 2. Bolivina catanensis Seguenza, 1862. figs 3–4. Cassidulina crassa d'Orbigny, 1839. figs 5–6. Cassidulina carinata (Silvestri, 1896). fig. 7. Globobulimina affinis d'Orbigny, 1839. fig. 8. Uvigerina mediterranea Hofker, 1932. fig. 9. Uvigerina peregrina Cushman, 1923. figs 10–11. Eponides pusillus Parr, 1950. fig. 12. Anomalinoides minimus Vismara-Schilling & Parisi, 1981. fig. 13. Pyrgo lucernola (Schwager, 1866). figs 14–15. Cibicidoides pachyderma (Rzeahk, 1886).

oxygen concentration at the bottom. The increase in frequency of *G. scitula* and *T. quinqueloba* and the decreasing of *G. ruber alba* suggest an ameliorate ventilation in the water column and an increased superficial water productivity.

G. inflata is absent in many Late Quaternary sapropel layers due to the lack of mixing in the water column, with year-round stratification (Capotondi *et al.*, 2000). In 977A, the continuous presence of *G. inflata* within the sapropel could indicate a seasonal contrast, concluding that sapropel deposition occurred strictly in the summer period.

Immediately after deposition of the sapropel, benthic foraminiferal diversity is similar to the pre-sapropel value. This observation suggests a high recovery potential of benthic species as soon as the (palaeo)environmental conditions improve. Thus, the relative increase in *N. pachyderma* and *G. bulloides*, the presence of *G. scitula* and the minor values of *G. ruber* are evidence of cooling of the water masses. This led to the break in water-mass stratification that characterizes the end of the sapropel, thus facilitating vertical mixing in the water column, with consequent oxygen renewal in the deepest bottom layers.

The lower BFN recorded in the post-sapropel interval, with respect to the pre-sapropel values, probably reflects different trophic conditions, related to the transition from glacial sediments (termination of MIS 26 prior to the sapropel) to interglacial (beginning of MIS 25 after the sapropel). This theory is based on the observations of Schmiedl *et al.* (1998) from the study of benthic foraminifera distribution in a long core from the Ionian Sea. They observed that the glacial sediments are characterized by enhanced productivity and organic matter fluxes to the seafloor that led to an increase in the number of foraminifera. By contrast, in interglacial sediments, productivity and organic matter fluxes are low, determining a decrease in the number of benthic foraminifera.

In the eastern Mediterranean Site 964D, the pre- and postsapropel intervals are dominated by the normal oligotrophic deep-assemblage – of which *A. tubulosa* is the most representative species – indicating a stable deep-sea ecosystem (Mullineaux & Lohmann, 1981; Jorissen, 1999; De Rijk *et al.*, 1999). The similar benthic foraminiferal diversity and number observed in pre- and post-sapropel intervals means that at the greatest depths foraminifera showed a high potential for recovery when the sapropel ended.

At the time of sapropel deposition, the whole fauna disappears because the oxygen content at the bottom-water interface and in the sediment column is too low to support benthic life.

During the onset of the first sapropel subunit (phase A), the palaeoclimate curve reveals cold conditions. The peak in frequency of *N. dutertrei* and *T. quinqueloba* documents the presence of a low density water mass and a highly stratified column, with high nutrients and terrestrial organic material input. As is well known, *N. dutertrei* characterizes the sapropel assemblages in colder climate conditions (Capotondi & Vigliotti, 1999; Negri *et al.*, 1999). This species is observed commonly with a relatively high percentage of abundance in Late Quaternary sapropels, together with *N. pachyderma*. Their presence has been interpreted as the seasonally shallowing of the thermocline within the photic zone, indicating the presence of the deep chlorophyll

maximum and stratified conditions in the euphotic layer (Rohling *et al.*, 1997).

During the onset of the second sapropel subunit (phase B), the co-occurrence of *G. ruber* and *G. scitula* could testify a strong seasonal contrast and/or thermal and density stratification in the water column. This reconstruction is also suggested by the palaeoclimate curve characterized by the dominance of *G. ruber*, which usually occurs in sapropels associated with a strong reduction in ventilation and a low salinity surface water layer (Bè & Tolderlund, 1971; Thunell, 1978).

In a similarly hostile scenario, the occurrence of A. minimus restricted between the two distinct anoxic phases can be interpreted as an interruption in sapropel deposition. Subsequently, these data document that also at greatest depth sapropel results interrupt. A. minimus was able to colonize the deep basin rapidly during short intervals of improved oxygenation and seasonal food pulses, as observed also by Jorissen (1999), Oggioni & Zandini (1987) and Schmiedl et al. (2003). The absence of the classical infaunal taxa (Fursenkoina, Globobulimina, Bulimina), which one would have expected here, suggests that food fluxes were too low to support their existence. The maximum frequency reached by G. inflata implies that sapropel interruption was driven by a short-term climate change, as previously hypothesized for Site 977A, producing vertical water mixing with consequent oxygen replenishment at the bottom-water surface.

By the termination of sapropel, the planktic assemblage is characterized by an increase in *G. trilobus*, suggesting the presence of a shallow pycnocline. The occurrence of *G. inflata* and *G. scitula* documents a break in water-mass stratification. Finally, the dominance of *G. bulloides* and *G. glutinata* and *T. quinquelobalhumilis* suggests a nutrient enrichment in the photic zone, probably related to continental input.

Foraminiferal investigation carried out in the IM/Fosso 5 Agosto section documents a gradual decrease in bottom-water oxygenation prior to the onset of sapropel deposition and a rapid return to stable environmental conditions at the end of the stagnation event (for details, see Stefanelli et al., 2005). The distribution pattern of planktonic and benthic foraminifera within the sapropel suggests a surface-water cooling, with consequent rapid re-oxygenation of bottom waters, which subdivides the sapropel into two phases (A and B). Both phases are characterized by an early subphase with warm climate conditions, a decrease in salinity in surficial water layers and are dominated by the low oxygen-tolerant benthic species Globobulimina affinis. The late subphase shows thermal stratification during summer and a relatively deep and oxygenated mixed layer during winter. In this subphase the contemporaneous replacement of the 'less opportunistic, but more resistant to low oxygen conditions' species Globobulimina affinis by Bolivina alata, B. dilatata and Brizalina spathulata, all 'less resistant to low oxygen conditions' species indicates a relative oxygen improvement in sediment pore-water.

I-cycle 90 coeval sapropels from different Mediterranean locations and its palaeoceanographic scenario

Figure 11 shows the benthic foraminifera distribution across the i-cycle 90 sapropel intervals recorded at the ODP Sites and at the IM/Fosso 5 Agosto land section.



Fig. 11. Species-key distribution across the pre-sapropel, sapropel and post-sapropel intervals in the investigated Mediterranean areas.

Transition from non-sapropel to sapropel stage. Focusing on non-sapropel to sapropel transition, benthic foraminifera suggest that the transition occurs differently in the different marine ecosystems.

At 400 m and 1984 m water depths, when an extreme oxygen deficiency occurred up to the sediment surface, deep infauna and low-oxygen-tolerant taxa, such as *Bolivina* group and *G. affinis*, replace the shallow infaunal and the epifaunal species, which disappear from the assemblage because they are less tolerant of low oxygen conditions. This biological substitution implies a regular transition from oxic to dysoxic conditions over a relatively long period of time, which allowed the deep infaunal species to take over the foraminiferal assemblages gradually. This reconstruction is in accordance with the observations of Jorissen (1999) about the faunal development associated with the deposition of S1 at shallow depth (<1250 m water depth).

The absence of deep infaunal species at 3666 m water depth in the sediments prior to i-cycle 90 sapropel formation is interpreted as a consequence of the low trophic conditions that did not allow the downward expansion of the bathymetrical range of the deep infaunal species to this water depth. At the time of sapropel formation, when primary productivity increases, deep infaunal species are absent, although the enrichment in organic matter at the dysoxic/anoxic boundary would be sufficient for the downward expansion of their bathymetric range. According to Jorissen (1999), this is interpreted as the response to a very rapid anoxic condition onset that does not allow deep infaunal species to colonize the bottom at 3666 m.

Sapropel interruption. During sapropel deposition, the benthic foraminifera distribution documents brief oxygen replenishment at the seafloor, which divides the layer into two phases (A and B). The study of planktonic foraminifera indicates that this feature is linked to the cold climatic phase and to vertical mixing of the surficial and intermediate water masses.

The consequent oxygen replenishment at the seafloor is testified by the presence of different taxa in the investigated sites. Infaunal and epifaunal species, such as *C. carinata* and *B. marginata*, were found in the IM/Fosso 5 Agosto land section, *C. carinata* and *A. tubulosa* in Site 977A and *A. minimus* in Site 964. All these species are described as opportunistic, suggesting that the improvement in marine ventilation was very rapid, nearly instantaneous.

The interruption of the time-equivalent sapropel interval has already been documented in other ODP sites from different water depths and hydrographic settings (Bernasconi & Pika-Biolzi, 2000; Hassold *et al.*, 2003; Meyers & Arnaboldi, 2005; Meyers & Bernasconi, 2005). This means that the synchronous water cooling observed in this study corroborates well the hypothesis of Meyers & Arnaboldi (2005). They argued that the interruption must have been a trans-Mediterranean phenomenon and that the interruptions record brief excursions out of the periods of wet climate associated with precessional minima.

Transition from sapropel to non-sapropel stage. The history of the re-colonization of the seafloor at the end of the sapropel deposition is observed to be similar at the three studied sites. The major frequency in abundance of the opportunistic shallow infaunal species *U. peregrina/U. mediterranea* in the IM/Fosso 5 Agosto land section, and of the opportunistic epifaunal species *A. minimus* in Site 977A and *A. tubulosa* in Site 964D, suggests that the re-oxygenation was very rapid, almost instantaneous (Jorissen, 1999).

Benthic and planktonic foraminiferal patterns indicate that the process of re-oxygenation, modulated by the gradual cooling of the water, was not synchronous in all places. In Site 977A and in the land section, the re-oxygenation was coincident with the end of i-cycle 90 sapropel formation, but at greater depth, it occurred just before the end of sapropel deposition. In the deepest ecosystem, as soon as the stagnant conditions begin to dissipate, *A. minimus* and *A. tubulosa* were able to colonize the re-oxygenated habitats very quickly, before the return to normal oligotrophic conditions characterized by the dominance of *A. tubulosa*. This environmental reconstruction is in agreement with the observations reported by Jorissen (1999), Schmiedl *et al.* (2003) and Capotondi *et al.* (2006) concerning the re-oxygenation of the seafloor at the end of sapropel S5, deposited in the eastern deep ecosystems.

The results here partially support the assumptions of the above-mentioned authors about the effect of water depth on the severity of sapropel expression. The severity in oxygen depletion during i-cycle 90 sapropel deposition increases with increasing water depth (from 400 m at the IM/Fosso 5 Agosto land section and 1984 m at Site 977A, to 3666 m at 964D).

Using the palaeocirculation model of Myers & Rohling (2000) for the timing of sapropel formation, it is hypothesized that the lowering of surface salinity - which would decrease the density of the surface waters and, hence, reduce the potential for convective overturning and deep-water formation - was mitigated in the Alboran Basin and in the northern part of the Ionian Basin nearest the Adriatic Sea. Irrespective of the massive change in climatic conditions associated with the precessional minima, the constant inflow of Atlantic Water and of the water mass coming from the North Adriatic Sea may have reduced the dilution of the surface/intermediate water by the continental runoff. This implies that, in the Alboran Basin, the anti-estuarine circulation was weak and, since water-column ventilation remained feasible during the period of i-cycle 90 deposition, the deep-water formation did not completely cease and intermittent oxygen pulses arrived at the bottom.

In the Ionian Basin, at shallow water depth, the seafloor was overlain directly by the less diluted intermediate water; therefore, stagnant conditions never occurred. By contrast, at greatest depth the intermittent oxygen pulses did not arrive at the bottom, producing an anoxic deep-water layer.

CONCLUSIONS

High resolution analysis of benthic and planktonic foraminifera throughout a sapropel corresponding to insolation cycle 90 was performed in three different oceanographic and depositional settings (Alboran Basin, South Adriatic Sea and Ionian Sea) of the Mediterranean Sea.

The faunal successions provide information about the conditions leading to sapropel deposition and evidence some differences related principally to the different water depths of the basins and to the local oceanographic regime. In all investigated basins sapropel 90 is interrupted and two subphases (phase A and phase B) are identifiable.

At depths >3000 m the absence of benthic microfauna documents stagnant conditions. The mechanism that led to the onset of the first sapropel phase A is linked to the increase in primary productivity, whereas the second sapropel phase B results are associated with the different density of the water masses.

During the onset of the sapropels at depths <2000 m (in Site 977A and in the IM/Fosso 5 Agosto section) the water-mass stratification was not sufficiently strong to determine anoxia at the bottom and hence to stop benthic life. In both sites, the

upper half of the sapropel layer records less severity with respect to the lower half. It is hypothesized that the surface water was cooler and that the increase in primary productivity was the mechanism that caused the onset of the second sapropel phase. However, this should not preclude the minor water depths of deposition that could favour the bottom ventilation present in later phase B of i-cycle 90 sapropel formation.

Foraminiferal content and distribution document that in all the investigated sites the short interruption was related to climatic deterioration, to a break in stratification and to a re-oxygenation of the bottom waters. This event appears to be correlated with the short-term climate variability already documented by Schmiedl *et al.* (2003 and references therein), thus confirming that i-cycle 90 sapropel interruption is a trans-Mediterranean phenomenon.

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| APPENDIX A: (| (Palaeo)ecological | meanings of the | foraminifera s | pecies encoun | tered in this | study |
|----------------------|--------------------|-----------------|----------------|---------------|---------------|-------|
|----------------------|--------------------|-----------------|----------------|---------------|---------------|-------|

Benthic foraminifera

| Articulina tubulosa | The most prominent representative species in the group of the miliolid taxa, indicative of |
|--|---|
| Anomalinoides minimus and Eponides pusillus | oligotrophic and well-ventilated Mediterranean deep-sea environments (Jorissen, 1999). Small, epifaunal, opportunistic species, indicative of a high trophic level in combination with sufficiently high oxygen concentrations. These species, together with <i>Epistominella exigua</i> , co-occur in the bathyal and abyseal assemblages of the eastern Mediterranean |
| Bolivina catanensis. | Opportunistic species with a shallow to intermediate infaunal microhabitat, common in |
| <i>Cassidulina carinata</i> and | mesotrophic to eutrophic environments with moderate oxygen depletions in the bottom and in |
| C. crassa | pore-water. Bulimina marginata, B. striata mexicana, Gyroidinoides soldanii, Hyalinea balthica and |
| | Melonis barleanum are also reported in this group. |
| Cibicidoides pachydermus | Epifaunal species more or less opportunistic, adapted to high oxygen conditions and reported to |
| Globobulimina affinis | be intolerant of environmental stress, in particular oxygen deficiency at the bottom (van der Zwaan, 1983). In the western Mediterranean Sea, its distribution is associated with oligotrophic and well-ventilated conditions. Schmiedl <i>et al.</i> (2000) observed a decrease in its number in favour of infaunal taxa at higher trophic level. <i>Gyroidinoides orbicularis</i> shows a similar life strategy, although it also occurs in significant numbers at higher trophic levels of the bathyal continental slope (Schmiedl <i>et al.</i> , 2000). Species with a deep infaunal microhabitat, especially resistant to very low oxygen conditions (Jorissen, 1999). It is common in low-oxygen habitats or eutrophic continental margins where it feeds from degraded organic matter at the dysoxic/anoxic boundary (Corliss, 1985; Mackensen & Douglas, 1989; Schmiedl <i>et al.</i> , 2000). In the case of a 'normal' situation, with a well-oxygenated sediment–water interface, <i>G. affinis</i> lives at considerable depth (several centimetres) in the sediment, often in completely anoxic conditions (Jorissen, 1999). Together with <i>G. affinis</i> , also reported as associated species are <i>Bulimina exilis, Chilostomella</i> spp. and <i>Fursenkoina</i> spp. |
| Planktonic foraminifera | |
| Globigerinoides ruber | Oligotrophic shallow-dwelling species (0–50 m) that prefers tropical and warm subtropical water masses (Bè & Tolderlund, 1971). In the Mediterranean Sea, this species proliferates at the end of the summer when the surface waters are well stratified (Pujol & Vergnaud-Grazzini, 1995). It is |

also related to the low surficial salinity (Bè & Tolderlund, 1971; Thunell, 1978).

| Orbulina universa | Prolific at the end of the summer, when the frequency peaks lie below the thermocline, thus suggesting an adjustment between light intensity and temperature requirements (Pujol & Vergnaud-Grazzni, 1995) |
|---|--|
| Globigerina rubescensl Globigerinoides tenellus Globigerina bulloides | Tropical species living in surface waters. Both species are most frequent in the western Mediterranean Sea (Thunell, 1978). Opportunistic species thriving in any eutrophic setting and living in subpolar waters; abundant in the Mediterranean Sea in winter and in periods of high fertility (Pujol & Vergnaud-Grazzni, |
| Globorotalia scitula | summer in other western Mediterranean basins (Rohling <i>et al.</i> , 1997). A cool to cold-water species occurring at great depth (Rohling <i>et al.</i> , 1997). |
| Globorotalia inflata | A cool species occurring in well-mixed waters with intermediate to high nutrient levels. It indicates cooling and/or increased seasonal contrast, with vertical mixing during winter |
| Globigerina quinqueloba | Eurythermal species that increases production during diatom blooms (in spring) (Sautter & Thunnell, 1991). It is prolific in regions where no DCM is developed (Pujol & |
| Globigerinita glutinata | Vergnaud-Grazzni, 1995) and it is tolerant of fairly low temperatures (Rohling <i>et al.</i> , 1993). Cosmopolitan species. In the North Atlantic it increases with the presence of a deep mixed layer and with a decrease in surface water temperature. The species displays a first reaction of the planktonic foraminiferal fauna to phytoplankton development during the spring (Thunell & |
| Neogloboquadrina pachyderma | Reynolds, 1984; Schiebel & Hemleben, 2000). A deep dwelling species (>100 m) living close to, or below, the thermocline (Fairbanks & Wiebe, 1980) and preferring depths where water temperatures are colder. |
| Neogloboquadrina dutertrei | A deep dwelling species $(c. 100 \text{ m})$ living near the base of the local thermocline and associated with the presence of the DCM (Rohling & Gieskes, 1989). The species is linked closely to shallowing of the thermocline to within the photic zone, which enhances productivity of N . <i>dutertrei</i> . High percentages of the species characterize sapropel assemblages in colder climate intervals (e.g. sapropel 6). |

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