Paleoenvironmental conditions preceding the Messinian Salinity Crisis in the Central Mediterranean: Integrated data from the Upper Miocene Trave section (Italy)

Agata Di Stefano a,⁎, Marina Verducci b, Fabrizio Lirer c, Luciana Ferraro c, Silvia M. Iaccarino d, Silja K. Hüsing e, Frits J. Hilgen f

a Dipartimento di Scienze Geologiche, University of Catania, Corso Italia 55, 95129 Catania, Italy
b Dipartimento di Scienze della Terra, University of Siena, Via Laterina 8, 53100 Siena, Italy
c Istituto per l’Ambiente Marino Costiero (IAMC) CNR, Calata Porta di Massa, 80133 Napoli, Italy
d Dipartimento di Scienze della Terra, University of Parma, Viale G.P. Usberti 157a, 43100 Parma, Italy
e Dipartimento di Scienze della Terra, University of Siena, Via Laterina 8, 53100 Siena, Italy
f Stratigraphy/Palaeontology, Department of Earth Sciences, University of Utrecht, Budapestlaan 4, 3584 CD Utrecht, The Netherlands

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A B S T R A C T

Integrated data of calcareous plankton and benthic foraminifers from the pre-evaporitic interval of Trave section (Central Italy) allowed the reconstruction of surface and bottom-water conditions in the Central Mediterranean during the interval from 7.61 to 6.33 Ma, preceding the Messinian Salinity Crisis. Our data point out a three-step paleoenvironmental evolution. During the first stage (7.61–7.02 Ma) benthic foraminiferal assemblages depict stable, well-oxygenated and ventilated bottom-water conditions, while the surface water records variable temperature and high nutrient conditions, probably associated with strong seasonality. The second stage (7.02–6.70 Ma) points to unfavourable bottom-water condition, triggered by deep-sea stagnation. This is witnessed by a significant decrease in oxygen concentration and biotic diversity, and by the presence of stress-tolerant taxa. A general warming of the surface water and a strongly stratified water column, characterized by an expanded mixed layer, are also recorded. From 6.70 Ma onwards (third stage), a prominent change to more restricted, low-oxygenated, hypersaline conditions at the sea floor is testified by the total disappearance of deep-dwelling planktonic foraminifers and the increasing abundance of stress-tolerant species. Calcareous plankton reflects high instability of the surface water in terms of nutrients, temperature and salinity. During this stage the environmental deterioration reaches intermediate depths in the water column. The initial change toward a step-wise isolation of the Central Mediterranean bottom-waters is probably related to a general warming, responsible for a first slowing-down of the vertical circulation, favouring stratification of surface and intermediate waters and stagnation of bottom-waters. This warming is related to the restricted connection between the Mediterranean Sea and the Atlantic Ocean, which occurred since 7.146 Ma. In the Trave section, the isolation of bottom-waters most likely occurred at the same time as in other Mediterranean sections. However, due to the presence of a hiatus it cannot be excluded that it occurred with a delay of ~100 kyr, probably related to the shallower paleodepth of the basin.

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1. Introduction

The Mediterranean Sea underwent dramatic changes during the Messinian (Late Miocene), when it became isolated from the Atlantic and evaporation led to the so-called Messinian Salinity Crisis (MSC, Hsiu et al., 1973a,b, 1977). Since the discovery of deep basin evaporites (DSDP Leg 13, Hsiu et al., 1973a), this particular event, caused by a combination of tectonic and paleoclimatic processes, has been the subject of numerous multidisciplinary studies (see Rouby and Caruso, 2006, Hilgen et al., 2007; Roveri et al., 2008 for updated revisions), and at present the MSC is adequately known and understood in terms of general stratigraphy and chronology, although several doubts still remain about its paleoenvironmental evolution.

Concerning the pre-evaporitic interval, many results were obtained from studies in the Eastern (e.g. Negri and Villa, 2000; Krijgsman et al., 2002; Merle et al., 2002; Kouwenhoven et al., 2006; Wade and Bown, 2006; Drinia et al., 2007; Morigi et al., 2007) and/or Western Mediterranean (e.g. Van der Zwaan, 1979; Van der Zwaan and den Hartog Jager, 1983; Flores et al., 1992; Negri et al., 1999;
Sierro et al., 1999; Goubert et al., 2001; Blanc-Valleron et al., 2002; Kouwenhoven et al., 2003; Pérez-Folgado et al., 2003; Flores et al., 2005; Van Assen et al., 2006), but only few depict the complete paleoenvironmental evolution, from the seafloor conditions up to the surface waters during the pre-evaporitic stage. Here we present integrated micro-fossil data from the pre-evaporitic interval of the Trave section located in the Central Mediterranean (Adriatic Sea, Italy). This study follows upon the stratigraphic/paleontological study carried out on the Trave section by Iaccarino et al. (2008). The previous paper dealt with a more general description of the micro- and macro-fossil content of both the pre-evaporitic and post-evaporitic units, and quantitative distribution patterns of selected nannofossils and foraminifers were discussed exclusively for biostratigraphic purposes.

In this study we processed the available data from benthic and planktonic foraminifers (Iaccarino et al., 2008) through statistical analysis, combining them with new data from calcareous nannofossil assemblages, in the attempt to reconstruct paleoenvironmental conditions both at the seafloor and in the water column, starting from below the Tortonian/Messinian boundary up to the interval that directly precedes the evaporitic phase. Our paleoceanographic reconstruction is compared with the general paleoceanographic picture derived from other Mediterranean sections in order to obtain a more complete framework of the pre-evaporitic conditions for the whole Mediterranean Basin.

2. Geological setting

The Trave section crops out in Central Italy along the coastal cliffs between Monte dei Corvi and Mezzavalle, south of Ancona (Fig. 1). The area belongs to the central sector of the present-day foredeep basin and foreland ramp of the Outer Northern Apennine fold and thrust belt (Barchi et al., 2001). This external element of the Apennine chain started to develop since the Oligocene and progressively propagated towards the ENE, involving stratigraphic successions of three Mesozoic paleogeographic domains (Ligurian, Tuscan and Umbria–Marche–Adriatic) (Iaccarino and Papani, 1980; Ricci Lucchi, 1986; Barchi et al., 2001). The reader is referred to Roveri et al. (1998, 2001, 2005, 2006) and Manzi et al. (2007) for an exhaustive discussion concerning the geological aspects of the region.

In the study area, the Messinian succession is subdivided into a pre-evaporitic, an evaporitic and a post-evaporitic part. The latter is

Fig. 1. Simplified geological sketch map and location of the Trave section (after Iaccarino et al., 2008; modified by us).
further subdivided into a lower (p-ev1) and an upper (p-ev2) unit (Roveri et al., 2001, 2005; Manzi et al., 2007; Iaccarino et al., 2008). The pre-evaporitic succession consists of 4.9 m of grey/light bioturbated marls and indurated carbonates organized in 8 lithological cycles, and 11.30 m of alternating indurated marly limestones and organic-rich layers passing into sapropels, organized in 26 cycles (Iaccarino et al., 2008) (Fig. 2). It is followed by about 20 m of laminated microcrystalline (re-sedimented) gypsum, covered by a recent land-slide that marks the base of the post-evaporitic sequences (Iaccarino et al., 2008).

3. Material and methods

Quantitative data from foraminiferal assemblages derives from Iaccarino et al. (2008) to which the reader is referred for details about sample preparation and analytical methodologies.

Benthic foraminiferal species were grouped according to their similar environmental requirements (Appendix A.1). Planktonic foraminiferal species were grouped (Appendix B.1) following Sierro et al. (1993, 2001, 2003), and according to the criteria used also by Hilgen et al. (2000), Kouwenhoven et al. (2006), Drinia et al. (2007) and Morigi et al. (2007).

Statistical analyses were performed on benthic foraminiferal assemblages. The original 51 variable dataset (benthic foraminiferal species and variants) was reduced to 20 by omitting species or groups of species with a percentage abundance below 2% and/or scattered presence in the samples and using the categories listed in Appendix A.1. Principal Component Analysis (PCA) and R-mode cluster analysis (Davis, 1986) were run through SPSS 10.0. In order to homogenize the contribution of all taxa avoiding to overweight the most abundant ones, in the cluster analysis we used the between-group linkage method and the Pearson correlation coefficient as similarity measure. The species diversity of planktonic and benthic foraminiferal assemblages was calculated using the Shannon index (PAST ver. 1.72; Hammer et al., 2001).

Quantitative analysis of the total nannofossils assemblage was carried out on standard “smear-slides” from 81 samples, with a light microscope at ×1000 magnification, estimating percentages of the main components within a minimum of 350 specimens larger than 3 μm. Frequencies are shown in distribution graphs, where taxa with an average percentage higher than 1% are plotted. The “medium-sized reticulofenestrids” groups Reticulofenestra specimens, 3–7 μm in length, both with a closed (e.g. Reticulofenestra antarctica) and open central area (e.g. Reticulofenestra haquii).

4. Cyclostratigraphy and age model

A detailed comparison of the litho- and biostratigraphic features between the pre-evaporitic interval of our Trave section and an equivalent section by Hüsing et al. (2009; labeled Monte dei Corvi...
The revision is mainly based on a different position for the First Common Occurrence (FCO) of the *Globorotalia miotumida* gr., detected in cycle 7 (4.25 m) instead of cycle 9, through the analysis of additional samples. This biostratigraphic tie-point allowed the correlation of our cycle 7 with cycle 231 of Hüsing et al. (2009) (Fig. 2, Table 1). An additional constrain is represented by the Last Common Occurrence of left coiling *Globorotalia scitula* gr., detected in cycle 13, corresponding to the Paracme Base of the species recognized by Hüsing et al. (2009) in their cycle 233.

The strict correspondence between the two logs is further supported by characteristic cycle patterns and a distinct lithological change to dark sapropels from Hüsing et al.'s (2009) cycle 237, which corresponds to a similar change from Iaccarino et al.'s (2008) cycle 16.

The age–depth model for the pre-evaporitic interval of the Trave section is based on the astronomical ages of sapropel mid-points, following the tuning presented in Fig. 2. No further attempt has been made to extend the cyclostratigraphic correlation above cycle 32, as major differences between the two logs resulted from the identification of additional faint limestone beds by Hüsing et al. (2009).

According to the revised tuning, slight different ages were assigned to the biohorizons detected in the Trave section. In Table 1 a synthesis of the biostratigraphic results of both Iaccarino et al. (2008) and Hüsing et al. (2009) is reported, and the new astronomical ages are compared with those previously proposed by Iaccarino et al. (2008) and with the ages of the corresponding bioevents identified by Hüsing et al. (2009).

As a consequence of the new tuning, two aspects must be stressed: i) the position of the hiatus previously reported in Iaccarino et al. (2008) between 7.2 and 7.28 Ma shifts to 7.1 and 7.2 Ma; ii) the influx of *Globorotalia nicolae*, detected at 9.5 m in cycle 24, cannot be referred to the First Occurrence of the species, as reported in Iaccarino et al. (2008); in fact Hüsing et al. (2009) locate this event at a lower stratigraphic interval (cycle 240 corresponding to cycle 19); the position of this event at Trave section is closer to the Top Acme of the species reported by Hüsing et al. (2009) in cycle 246, but not exactly a coincident (the influx at Trave is slight below). For this reason we used two different numbers, 15 and 16 (Fig. 2, Table 1), to indicate the influx of *G. nicolae* at Trave and the Top Acme of the same species at Monte dei Corvi Beach, respectively.

Further clarifications concern: i) the nannofossil event reported as *Helicosphaera sellii* FCO in Iaccarino et al. (2008), that is here re-defined as “*H. sellii* influx” (Table 1); we believe in fact, that the *H. sellii* FCO is an exclusively Early Pliocene event (see Di Stefano and Sturiale, 2010 for further explanation) and the presence of this species in the Upper Miocene should represent temporary influxes; ii) the Paracme of *Reticulofenestra pseudoumbilicus*, that is here marked with the letter “m” (Table 1), to distinguish it from another paracme of this species occurring in the basal Pliocene, reported as Paracme “p” by Di Stefano and Sturiale (2010).

### 5. Distribution of benthic foraminiferal assemblages: implications for bottom-water conditions

Benthic foraminifers are present throughout the section with the exception of 14 samples, from 7.6 m (ca. 6.86 Ma) upwards that are completely barren. Carcassene taxa are dominant, whereas agglutinated foraminifers are extremely rare, as is often the case in Messinian sediments (Drinia et al., 2007).

On the basis of the bathymetric preferences of selected benthic foraminifers and from malacological data, Iaccarino et al. (2008) estimated a depth of about 300–400 m (outer shelf/upper slope, upper bathyal environment) for the Trave section. The distribution of benthic foraminifers along the section (Fig. 3) identifies four main intervals, highlighted by the R-mode cluster analysis (Figs. 4, 5), each characterized by peculiar assemblages, depicting well defined bottom-water conditions.

From the base up to 5.7 m (7.02 Ma), assemblages are dominated by the Cibicidoides group 1, *Siphonina reticulata* and the *Bigerinera* group, while Anomalolinoides spp., *Gyroidina* spp., *Oridorsalis* spp. and *Vulvulina pennatula* represent minor components. These taxa (Cluster I, Figs. 4, 5) are commonly found in open-sea Late Miocene Mediterranean environments (Kouwenhoven et al., 2006), and are characterized by their mutual preference for well-oxygenated environments with normal salinities (Lutze, 1977; Van der Zwaan, 1982; Lutze and Thiél, 1989; Verhallen, 1991; Sjöreda and Van der Zwaan, 1992; Kalho, 1994; Sgarrella et al., 1999; Kouwenhoven and van der Zwaan, 2006). The *Bigerinera* group and *Anomalolinoides* spp. are mesotrophic species that tolerate high flux of organic matter and...
Fig. 3. Quantitative distribution patterns of selected benthic taxa, grouped according to Appendix A1 (after Iaccarino et al., 2008; modified by us). Shaded bands and asterisks indicate barren samples. Dashed lines indicate the major changes in assemblage composition.
high productivity (Jorissen, 1988; Miao and Thunnell, 1993), while *Oridorsalis* spp. has been related to high oxygen content and low flux of organic carbon (Mackensen et al., 1985; Miao and Thunnell, 1993). High abundances of *S. reticulata* seem to coincide with periods of relatively cooler and more dense surface waters and thus enhanced deep-water mixing and circulation (Sgarrella et al., 1999). *V. penatula* is an index species of strong bottom current activity (Murray, 2006) as well. At 5.7 m (7.02 Ma), coincident with the top of the hiatus, the taxa characterizing the previous interval abruptly decrease and almost disappear. They are substituted by abundant *Bolivina scalpatra miocenica*, *Uvigerina* group 1, *Planulina ariminensis* and *Lenticulina* spp., and subordinate *Cibicidoides bradyi*. These assemblages (Cluster II, Figs. 4, 5) comprise both oxyphilic taxa, such as *P. ariminensis* (Linke and Lutze, 1993), and taxa tolerant of suboxic environments, such as *B. scalpatra miocenica*, the *Uvigerina* group 1, *Lenticulina* spp. and *C. bradyi* (Kaiho, 1994; Sgarrella et al., 1999; Kouwenhoven and van der Zwaan, 2006). Yet, *P. ariminensis* tolerates oxygen deficiency, since it has been found in modern dysoxic environments (Bernhard and Sen Gupta, 1999). It is able to feed on particles that originate from lateral advection and that are not related to high vertical flux rate and superficial productivity (Linke and Lutze, 1993). High abundances of this species have been related to periods of enhanced preservation of organic matter at the bottom (favoured by dysoxic conditions) caused by stratification of the water column and consequently sluggish deep-water circulation (Sgarrella et al., 1999). *C. bradyi* is an opportunistic species tolerant of low oxygen conditions (Miao and Thunnell, 1993), and able to use limited or alternate food resources (Rathburn and Corliss, 1994).

From 7.6 m (6.86 Ma) the assemblages are dominated by the *Uvigerina* group 1, the *Cibicidoides* group 2 and the *Melonis* group, while *Sigmillopsis schlumbergeri* is a minor component (Cluster III, Figs. 4, 5). *Uvigerina peregrina* prefers fine-grained sediments rich in organic carbon (Seiglie, 1968) and proliferates under sustained organic flux to the seafloor. It tolerates decreased oxygen content and increased salinity (Van der Zwaan, 1982; Lutze and Coulbourn, 1984; Verhallen, 1991; Sjoerdsmma and Van der Zwaan, 1992; Loubère, 1994,1996). *Cibicidoides pseudoungerianus*, in association with *Uvigerina* species, implies the adaptation to seasonally high fluxes of marine phytodetritus and tolerance to low quality organic matter from marine or terrestrial origin (Licari and Mackensen, 2005; Drinia et al., 2008). The genus *Melonis* and *S. schlumbergeri* are usually related to high fluxes of organic matter (Pflum and Frerichs, 1976; Jorissen, 1987; Caralp, 1989). Food quality resulting from changes in the oxygen content of bottom-waters seems to be the main factor determining this assemblage. This may have a profound effect when the involved foraminifers have specific dietetic requirements (Van der Zwaan, 1982).

The assemblages of this interval mark a transitional environment characterized by decreased oxygen content and increased salinity, indicating a further deterioration of the bottom-water conditions.

The last significant change takes place at 9.6 m (6.70 Ma), where the species diversity strongly decreases and assemblages become dominated by the *Bolivina* and *Bulimina* groups and the *Uvigerina* group 2 (Cluster IV, Figs. 4, 5). Sporadic *Hanzawaia boueana* and scattered peaks of *Cassisidula laevigata* also occur.

The *Bolivina* and *Bulimina* groups are considered to have opportunistic behaviour and tolerance to dyoxia, but also to high bottom-water salinity (*Bolivina dilatata, Van der Zwaan, 1982, 1983; Verhallen, 1991; Jorissen et al., 1992; *Bulimina subulata, Verhallen, 1991*). The genus *Bolivina* can be related to relative prolonged periods of dyoxia at the sea bottom (Bernhard and Sen Gupta, 1999), periodically following the strong input of organic matter to the sea floor.

The *Uvigerina* group 2 is mainly dependent on high fluxes of organic carbon to the seafloor, usually related to periods of high productivity and increased upwelling (Thomas, 1980; Gupta and Srinivasan, 1990, 1992; Loubère, 1996, 1997). *H. boueana* can tolerate stressed environments characterized by varying degrees of oxygen and salinity (Van der Zwaan, 1982). *C. laevigata* is a stress-tolerant species, thriving under unstable conditions (Conradsen et al., 1994). According to Gupta (1997) it correlates with high fluxes of organic matter due to high productivity in the surface waters and low oxygen levels.

The deterioration of the environment is complete, with the development of highly saline, dysoxic bottom-water conditions, and high preservation of organic matter.

![Fig. 4. Dendrogram resulting from R-mode cluster analysis (Pearson correlation coefficient) of benthic foraminiferal assemblages.](image-url)
Fig. 5. Cumulative plot of the four clusters in the pre-evaporitic sequence of the Trave section, PCA-1, PCA-2 and PCA-3 scores, faunal diversity of benthic foraminiferal assemblages (Shannon index), percentage of stress-tolerant taxa on the total assemblage, bottom-water oxygen content (Oxygen Index, OI) following Kouwenhoven and van der Zwaan (2006); Oxygen Transfer Function (OTF) following Drinia et al. (2007) and percentage of infaunal species on the total assemblage. Shaded bands and asterisks correspond to barren samples.
5.1. Principal Component Analysis (PCA) and Shannon index

PCA was applied to the benthic foraminiferal assemblages, to better highlight the environmental parameters that drove the main changes of the bottom-water conditions. Three factors were considered that account for 45% of the total variance (Fig. 5).

Factor 1 (PCA-1) describes 20% of the variance (Table 2). Taxa with large positive loadings are Cibicidoides group 1, S. reticulata, V. pennatula, the Bigenerina group and Lenticulina spp. Taxa with large negative loadings are the Bolivina and Bulimina groups, H. boueana and the Uvigerina group 2 (Table 2). PCA-1 discriminates between a high-diversity assemblage (positively correlated with PCA-1) composed of both epifaunal and shallow infaunal species, indicating an ecosystem suitable for many benthic species, and a low-diversity assemblage (negatively correlated with PCA-1) composed mainly of deep infaunal taxa, which indicate a specific restricted environment with stressed conditions (oxygen depletion, high salinity, high food supply). Therefore, we interpret PCA-1 as related to the oxygenation at the sea floor, or more generally, to the degree of environmental stress. The PCA-1 trend strengthens the environmental bottom-water conditions, as reconstructed from the distribution patterns of benthic foraminifers and the cluster analysis. In fact, from 7.61 to 7.02 Ma PCA-1 reveals positive scores, indicating the presence of a stable, normal marine, stenohaline, oxic environment. From 7.02 to 6.86 Ma PCA-1 scores decrease, crossing the zero line, highlighting a period of increasing environmental deterioration, and decreasing oxygenation at the sea floor. From that point onwards PCA-1 scores maintain negative values, pointing to the establishment of permanent stressed and unstable environmental conditions.

Factor 2 (PCA-2, Fig. 5) describes 14% of the variance. Taxa with large positive loadings are P. ariminensis, B. scalpatra miocenica, Melonis spp., the Melonis group, the Uvigerina group 1 and S. schlumbergeri. Taxa with large negative loadings are the Bolivina and Bulimina groups, the Uvigerina group 2, Oridorsalis spp., Anomalinoidea spp., V. pennatula and S. reticulata (Table 2). Positive loading taxa prefer environments with high organic matter supply, not necessarily related to surficial productivity. The main factor influencing the accumulation of organic matter at depth seems to be an enhanced density stratification favouring low oxygenation.

Negative loading taxa consist of both oxyphilic and dysoxic species without particular dietetic requirements. Thus, PCA-2 may be related to the development of density stratification and the accumulation of organic matter at the sea floor.

Factor 3 (PCA-3, Fig. 5) describes 11% of the variance. Taxa with large positive loadings are the Bigenerina group, V. pennatula, Oridorsalis spp., Uvigerina group 1 and Cibicidoides group 2. Taxa with large negative loadings are the Cibicidoides group 1, Gyroidina spp., C. bradyi and B. scalpatra miocenica (Table 2). The PCA-3 loadings constantly fluctuate across the zero line along the section. The only interval showing positive loadings is the second part of interval 2 (6.86–7.0 Ma). The positive correlation of Cibicidoides group 2 and Uvigerina group 1 with Factor 3 suggests a possible relation of PCA-3 with the quality of available food at the sea floor.

Species diversity index (Shannon index) provides further information concerning the environmental stability. It is considered a gross measure of the effect of environmental stress on benthic communities (Bolovskoy and Wright, 1976; Murray, 1991a). According to Murray (1991a,b), Shannon index diversity is around 3 in the open marine outer shelf to the slope environment. When stability conditions are disturbed, species diversity immediately reduces, and certain species become dominant (Kouwenhoven, 2000). If the Shannon diversity falls below 2, the balance in the assemblages is distorted by high dominance of few stress-tolerant taxa. In our record, the Shannon index of benthic foraminiferal assemblages (Fig. 5) changes significantly throughout the studied interval. From 7.61 to 7.02 Ma diversity is always above 2, with values around 3 in the older part of this interval. According to Murray (1991a,b), this indicates normal open marine conditions. From 7.02 to 6.86 Ma, the Shannon index decreases and fluctuates around the critical value of 2, indicating the development of a stressed environment, characterized by suboxic conditions. From 6.86 Ma onwards, diversity is constantly below 2 and continues to decrease, pointing to severe dysoxic conditions, probably caused by sustained organic carbon flux (Hermelin and Shimmield, 1990; Sen Gupta and Machain-Castillo, 1993). This environmental reconstruction is also supported by the trend in stress-tolerant species (percentage of Bolivina + Bulimina + Uvigerina on the total assemblage, Kouwenhoven et al., 2006; Fig 5 and Appendix A.2). Except for 14 samples, younger than 6.86 Ma and completely barren of benthic foraminifers, an increase of bolvindic, buliminid and uvigerinid abundance is evident from 7.02 Ma onwards. The highest values are reached after 6.70 Ma, when benthic foraminiferal assemblages consist almost exclusively of few stress-tolerant species.

5.2. Reconstruction of the paleo-oxygenation at depth

Variations in the oxygen content at the sea floor were obtained through two different approaches (Fig. 5). The first is based on the Oxygen Index (OI) (Kouwenhoven and van der Zwaan, 2006), and provides a relative and qualitative estimate of the oxygenation state at depth. It is based on the recognition of five groups of benthic foraminiferal species (see Appendix A.3), each considered to represent a certain level of oxygenation going from low oxygenation (comparable to the deep infauna of modern assemblages) to normal and well-oxygenated conditions (comparable to epifaunal, oxyphilic taxa in modern assemblages). The second approach is based on the Oxygen Transfer Function (OTF; see Appendix A.3) proposed by Drinia et al. (2007), in the attempt to estimate quantitatively the oxygen content at the sea floor.

Both approaches are consistent with each other and confirm a three-stage evolution of bottom-water oxygenation during the pre-evaporitic phase recorded at the Trave Basin. From 7.61 to 7.02 Ma, both indices reveal quite high oxygen contents. OI values are around 4, as reported in many similar Mediterranean sections (e.g., Scardilli, Potamidha and Faneromeni, Kouwenhoven and van der Zwaan, 2006), while OTF values range between 200 and 500 µmol/L, indicating normal and well-oxygenated environments. From 7.02 to 6.70 Ma, both indices show a decreasing trend, and the OTF drops below 200 µmol/L. From 6.70 Ma onwards OTF values are constantly

### Table 2

<table>
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<tr>
<th>Variables</th>
<th>PCA-1 loadings</th>
<th>PCA-2 loadings</th>
<th>PCA-3 loadings</th>
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<tr>
<td>Uvigerina group 2</td>
<td>-0.318</td>
<td>-0.410</td>
<td>-0.164</td>
</tr>
</tbody>
</table>

| Variance | 20.1% | 13.8% | 11.4% |
below 40 μMol/L, indicating dysoxic conditions (environments with 0.1–1.0 ml O2/l = ca. 5–45 μMol/L, are defined “dysoxic” by Bernhard and Sen Gupta, 1999).

Critical oxygen levels and nutrient supply are strongly related to each other, and constitute the two most important factors controlling the microhabitat distribution of benthic foraminifers (Jorissen, 1999). In modern environments, increasing food availability and decreasing oxygen concentration lead to an increase of shallow-dwelling and deep-dwelling infauna, until the benthic foraminiferal assemblages are exclusively composed of deep-dwelling infauna in eutrophic, dysoxic/anoxic environments. In the Trave section, the percentage abundance of infaunal versus epifaunal taxa (Fig. 5 and Appendix A.4) is around 30% of the total assemblage up to 7.02 Ma. A further evidence of decreasing oxygenation at the seabed is the gradual and continuous increase of the infaunal taxa reaching almost 100% of the total assemblage after 6.70 Ma.

6. Distribution of calcareous plankton: implications for water column conditions

6.1. Planktonic foraminifers

Planktonic foraminifers are continuously present throughout the section and were found in all the studied samples. The assemblages are rich and well-preserved, showing an improved preservation in the sapropel layers from about 7 m upwards. Trends of representative species or groups (Appendix B.1) are plotted in Fig. 6. In the lower part of the section up to 5.7 m (7.02 Ma), planktonic foraminiferal assemblages are dominated by the Globigerinoides group, and include also the Globorotaliids and G. scitula groups and the neogloboquadrinids. The Globigerinoides and Globoturborotalita groups are surface-dwellers usually thriving in warm, oligotrophic waters of the mixed layer, well above the thermocline and the nutricline (Hemleben et al., 1989). These species reach their highest abundances where there is a permanent vertical stratification of the water column. G. scitula is considered a subpolar species (Bé, 1977; Itou et al., 2001) preferring deep-waters up to 1000 m depth (Schiebel and Hemleben, 2000). It is found in glacial-age sediments in the Mediterranean Sea (Thunell, 1978; Rohling et al., 1997; Capotondi et al., 1999), and proliferates during intervals of intensified vertical mixing (Itou et al., 2001). Globorotaliids are abundant only during the winter months when phytoplankton blooms develop (Tolderlund and Bé, 1971; Hemleben et al., 1989). Neogloboquadrinids are usually associated with cold, nutrient-rich, and stratified waters and with the presence of a strong deep chlorophyll maximum (DCM) layer, whose resources constitute the basis of their diet (Fairbanks and Wiebe, 1980; Rohling and Gieskes, 1989; Sierro et al., 2003; Kuroyanagi and Kawahata, 2004).

At 5.7 m (7.02 Ma), the G. scitula group decreases and the G. miotumida group and Globorotalia menardii slightly increase. The assemblage is still dominated by the Globigerinoides and G. groups, while Orbulina spp. and the Globigerinella obesa group increase significantly. G. miotumida group and Globorotalia menardii are deep-water dwellers living in warm, oligotrophic waters (Tolderlund and Bé, 1971; Schneider and Kennett, 1996, 1999). Orbulina universa, thriving in relatively warm and oligotrophic surface waters (Bé and Tolderlund, 1971; Hemleben et al., 1989), was found to tolerate deviating salinity in laboratory culture (up to 46‰; Bijma et al., 1990), and is a common, often dominant taxon in pre-MSC assemblages (e.g., Sprovieri et al., 1996; Blanc-Valleron et al., 2002; Sierro et al., 2003). G. obesa is an intermediate dweller, abundant in tropical/subtropical waters, and adaptable to a wide range of temperature, salinity and nutrient concentrations (Bé and Tolderlund, 1971; Bé and Hutson, 1977).

At 9.6 m (6.70 Ma) Globorotaliids disappear and the Globigerinoides group becomes rare. Assemblages almost exclusively consist of Orbulina spp., Turborotalita quinqueloba, Globigerinella glutinata, Globigerina bulloides, the Globoturborotalita group and neogloboquadrinids. Species characterizing this interval show strong abundance fluctuation suggesting rapid changes in the near-surface waters, characterized by

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Fig. 6. Quantitative distribution patterns of the main components of the planktonic foraminiferal assemblages, grouped according to Appendix B.1 (after Iaccarino et al., 2008; modified by us). Dashed lines indicate the major changes in assemblage composition.
Fig. 7. Quantitative distribution patterns of the main components of calcareous nannofossil assemblages. Dashed lines indicate the major changes in assemblage composition.
alternating extreme and opposite environmental conditions. *Orbulina* spp. and *T. quinqueloba* tolerate hypersaline conditions (Kroon et al., 1988; Bijma et al., 1990; Van de Poel, 1992). Sierro et al. (1999; 2003) and Pérez-Folgado et al. (2003) report abundance maxima of *G. glutinata* as related to stressed conditions, possibly due to eutrophy or high salinity, when they occur together with *T. quinqueloba*, usually coinciding with low total abundance and diversity. According to these authors, in the Metochia section, on Gavdos, and in the sections of the Abad marls, in the Sorbas basin, these conditions occur at the onset of sapropel deposition.

6.2. Calcareous nannofossils

Calcareous nannofossils are found in all samples, showing variations in abundance, degree of preservation (generally better within the organic-rich layers and sapropels) and composition. In the lower part of the section (up to 5.7 m, 7.02 Ma), characterized by the worse degree of preservation, nannofossil assemblages show low diversity, being dominated by medium-sized *Reticulofenestra* spp., while *Coccolithus pelagicus* is a minor component that shows a decreasing trend (Fig. 7). The assemblage includes low percentages of *Sphenolithus* spp., *Helicosphaera* spp. (10–15%) and *Calcisiscus* spp. (less than 5%) as well. Medium-sized reticulofenestrids are usually associated with normal salinity and high productivity (Aubry, 1992, Young, 1994; Flores et al., 1995, Ziveri et al., 2004; Flores et al., 2005). Low diversity is generally related to low temperatures. Indeed modern *C. pelagicus*, occurring in significant percentages at the very base of the section but decreasing upwards, is traditionally interpreted as a cold-water proxy (e.g. McIntyre et al., 1970; Okada and McIntyre, 1979; Winter et al., 1994). Yet, *C. pelagicus* was also used as an indicator of nutrient enrichment in near-surface waters (McIntyre and Bé, 1967; Rahman and Roth, 1990; Roth, 1994; Cachão and Moita, 2000) and it can be used to trace the boundaries of areas with enhanced productivity.

The middle part of the section (5.7 to 9.6 m, 7.02–6.70 Ma) is characterized by the best preserved nannofossil assemblages and by an increased diversity. The assemblage is still dominated by medium-sized reticulofenestrids, while *C. pelagicus* shows lower frequencies (less than 10%). The presence of *Discocysta* spp. reaching frequencies of 10% is noteworthy. Other components are *Helicosphaera* spp. (highest frequency of 15%), *Sphenolithus*, *Calciscicus*, *Geminiithella rotula* and *Rhabdosphaera* spp. (percentages lower than 10%). Spotwise occurrences are recorded for *Umbilicosphaera* spp., *Pontosphaera* spp., *Holodiscocystus macroporus*, *Syracosphaera* spp., *Calciococcolithus murray* and *Scyphosphaera* spp. In this interval, a higher diversity is observed in spite of the predominance of medium-sized reticulofenestrids. In addition, the presence of typical warm-water taxa, such as *Discocysta* spp. (e.g. Bukry, 1973; Aubry, 1984; Siesser and Haq, 1987) in combination with lower frequencies of the “cool” species *C. pelagicus*, points to higher temperatures, especially in the upper part of this interval, where *Rhabdosphaera* spp. and *Syracosphaera* spp. start to be present. In fact, the genus *Syracosphaera* does not tolerate temperatures below 10 °C, while *Rhabdosphaera* spp. reaches its optimum between 14 and 20 °C (Santlïeben et al., 1995; Ziveri et al., 1995; Flores et al., 1999; Findlay and Flores, 2000).

From 9.6 m upward (6.70 Ma on) medium-sized reticulofenestrids show a sudden drop in abundance, followed by a strongly fluctuating distribution pattern. The assemblage is well diversified, and all taxa characterizing the middle part of the section are present. The highest frequencies are reached by *Helicosphaera* spp., *Calcisiscus* spp. and *Umbilicosphaera* spp. while *Discocysta* spp. and *C. pelagicus* are secondary components. All these taxa, most of which are considered typical of warm-water conditions, show large abundance fluctuations, reflecting frequent and sudden changes in temperature (note the opposite trends of the “cool” *C. pelagicus* versus the “warm” *Discocysta* + *Calcisiscus* spp., Fig. 8) and in other environmental parameters, such as salinity. *Umbilicosphaera* spp., though indicative of relatively high temperatures, are also able to flourish in shallow-water, hypersaline environments (Wade and Bown, 2006). On the contrary, *Helicosphaera* spp., here mainly represented by *H. carteri*, shows an opposite behaviour (Fig. 8). This taxon is documented from eutrophic, hypersaline waters (Giraudeau, 1992), although it is able to withstand salinity fluctuations.

6.3. Evolution of the water column

A reconstruction of the main changes that occurred in the water column, from the surface waters, according to the calcareous nannofossils, down to the greater depths where some of the planktonic foraminiferal species live, is here proposed (Fig. 9). Planktonic foraminiferal taxa were divided into three groups on the basis of their depth habitat (shallow-, intermediate- and deep-water dwellers), and into two groups according to their ecologic requirements (warm/oligotrophic and cold/eutrophic taxa; see Appendix B.2 and B.3).

From 7.61 to 7.02 Ma, nannofossil assemblages suggest normal salinity, open-ocean and high nutrient conditions of the surface waters. The low species diversity, together with significant percentages of *C. pelagicus* at the base of the section, indicates initially cool temperature conditions, while the upward decrease in *C. pelagicus* reflects a temperature increase. Planktonic foraminiferal data agree with this reconstruction. The presence of neogloboquadrinids, associated to both warm surface/intermediate dwellers and cold deep ones, indicates a variable Sea Surface Temperature (SST) and high Sea Surface Productivity (SSP), and might be associated with high seasonal contrast (Hemleben et al., 1989; Pujol and Vergnaud-Grazzini, 1995; Kouwenhoven et al., 2006). The abundance of shallow- and intermediate-dwelling planktonic foraminifers is well-balanced, while deep-water taxa constitute between 10 and 20% of the total assemblage. The same holds for the balance between warm/oligotrophic and cold/eutrophic taxa, indicating the presence of a mesotrophic, probably temperate, environment. From 7.02 to 6.70 Ma, nannofossil data are consistent with a normal salinity, open-ocean environment that is warmer than before but still characterized by high-nutrient conditions, apparently in contrast with the trophic conditions deduced by planktonic foraminiferal data. Within the planktonic foraminifers, surface-dwellers are dominant together with warm/oligotrophic species, while deep-dwelling taxa show a significant decrease. The predominance of shallow-dwelling species may be related to an expanded mixed layer, and a deeper thermocline, located below the photic zone (Ravelo et al., 1990). The strong predominance of warm-water oligotrophic taxa and/or taxa preferring stratified waters points towards an increase in SST and possibly a decrease in SSP, and the development of a strongly
stratified water column. This is probably responsible for the different (eu) trophic conditions in the shallower part of the surface waters, where a higher amount of nutrient is available.

From 6.70 Ma, the most significant feature of both surface and deep waters is the strong instability, as indicated by large and rapid fluctuations in the abundance of taxa with opposite paleoecological requirements. The strong variations in the abundance of medium-sized reticulofenestrids indicate intense fluctuations in nutrient availability. Sudden salinity (Umbilicosphaera spp. versus Helicosphaera spp.) and temperature (C. pelagicus versus Discoaster +Calcidiscus spp.) variations are recorded as well (Fig. 8). Within the planktonic foraminifers, the deep-dwellers disappear completely. The assemblage is now exclusively composed of surface- and intermediate-dwelling species that show strong fluctuations and alternating abundance peaks. Cold/eutrophic taxa return to dominate the assemblages, even if alternations between cold/eutrophic and warm/oligotrophic taxa sometimes occur. In the Trave section, planktonic foraminiferal species diversity (Fig. 9) is always lower than that recorded in oceanic sediments of the same age. A slight decreasing trend in species diversity begins at 7.02 Ma, reaching very low values (around 1.5 or less) from 6.70 Ma onwards. The dominance of Orbulina spp. and T. quinqueloba throughout this interval (their sum is above 50% in samples younger than 6.70 Ma), in association with high abundances of G. glutinata, provides evidence for the development of hypersaline conditions also in the near-surface waters. We think that the “classical” interpretation of the water column structure (based on habitat depths of planktonic foraminiferal species and on the ratio of warm/oligotrophic versus cold/eutrophic indices) is not applicable to the Trave section from 6.70 Ma onwards, when the assemblages become strongly influenced by the superimposition of stressful factors, such as changes in salinity and oxygenation, stagnation, strong water column stratification, etc. When this situation occurs, classical oceanographic features (e.g., thermocline, nutricline) are difficult to recognize and may not be present any more, and a picture of a highly unstable and frequently changing environment is what remains.

7. Isolation of the Mediterranean Sea: tectonic or climatic control?

Our evidence from Trave section indicates a step-wise isolation of the Central Mediterranean bottom-waters during the early Messinian, leading to an increase in salinity and a decrease in oxygenation in upper bathyal environments. Apparently the Mediterranean was predominantly influenced by climatic factors before the Tortonian/Messinian boundary (Kouwenhoven et al., 1999), while tectonically-driven gateway dynamics seem to be the dominating factor influencing the paleoenvironment afterwards. From 7.02 Ma a warming is witnessed in the Central Mediterranean by the increase in abundance of the warm/oligotrophic component both in the planktonic foraminiferal and in the calcareous nannofossil assemblages of the Trave section. It may have caused a first slowing-down of the vertical circulation of Mediterranean water masses, favouring stratification of surface and intermediate waters and stagnation at depth. This caused the disappearance of benthic foraminiferal taxa.

Fig. 9. Cumulative plot of faunal diversity of planktonic foraminiferal assemblages (Shannon index), the percentage of warm/oligotrophic and cold/eutrophic planktonic foraminifers and the percentages of shallow-, intermediate- and deep-dwelling species.
Fig. 10. Three-step paleoenvironmental model of the Trave Basin during the pre-evaporitic phase of the Messinian Salinity Crisis.

1. **7.61 - 7.02 Ma**
   - High seasonality
   - Increased nutrient input from continental sources
   - Well-oxygenated, normal marine conditions
   - Trave Basin
   - Variable SST, high SSP
   - Deep-water mixing
   - Stagnation of bottom waters from 7.167 Ma
   - Deepest Mediterranean basins

2. **7.02 - 6.70 Ma**
   - Enhanced evaporation
   - Sicily - Malta sill
   - Nanoplankton
   - Shallow-dwelling planktonic foraminifers
   - High SST, low SSP
   - Stratification in the water column
   - Sluggish circulation
   - Stagnations of bottom waters
   - Deepest Mediterranean basins

3. **6.70 - 6.33 Ma**
   - Alternate periods of enhanced evaporation and enhanced runoff
   - Sicily - Malta sill
   - Nanoplankton
   - Shallow-dwelling planktonic foraminifers
   - Intermediate-dwelling planktonic foraminifers
   - Stagnations of bottom and deep waters
   - Dysoxic environment
   - Deepest Mediterranean basins
typical of well-oxygenated environments, which were replaced by taxa thriving at suboxic conditions. There may be a relation with the progressive restriction of the connection between the Mediterranean Sea and the Atlantic Ocean, beginning at 7.146 Ma (Krijgsman et al., 1999; Hüsing et al., 2009). Oceanic circulation models indicate that shallowing of the sill depth at the Mediterranean–Atlantic connection could obstruct outflow of deeper waters (Kouwenhoven and van der Zwaan, 2006; Wade and Bown, 2006). As a consequence, circulation would slow down, water masses would age and the oxygen content of deep water masses would decrease. The isolation of Mediterranean bottom-waters determined the synchronous exit of a number of stress-intolerant deep water benthic species at 7.167 Ma, as recorded in several sections throughout the Mediterranean basin (Kouwenhoven et al., 1999; Seidenkraitz et al., 2000; Kouwenhoven et al., 2003,2006; Kouwenhoven and van der Zwaan, 2006). This benthic event thus seems to have occurred synchronously throughout the deeper Mediterranean basins. Sites at shallower paleodepths, located in the intermediate water masses, were affected less and/or at a later stage (van der Zwaan, 1982; Kouwenhoven and van der Zwaan, 2006), implying that initially some surface inflow, and the formation of intermediate waters, remained more or less intact.

In the Trave section, the presence of a hiatus makes it impossible to discriminate whether this event occurred at the same time as in other Mediterranean sections or was delayed by –100 kyr.

The absence of deep-dwelling planktonic foraminifers in some samples from 7.02 Ma onwards, and their complete disappearance after 6.70 Ma are indicative of enhanced stratification of water mass at intermediate depth, with sluggish (if not ceased) circulation, and ageing of water masses. At the same time, the overall decrease in planktonic foraminiferal species diversity, recorded contemporaneously in the Sorbas basin (Sierra et al., 2003), points towards stressful conditions in surface and intermediate waters. From 6.70 Ma onwards, the deterioration of the environment is thus no longer restricted to the seafloor, but reached also intermediate depths. This second phase may be related to an important tectonic event, namely the increase of tectonic activity in the Rifian Corridor dated at 6.8–6.7 Ma (Krijgsman and Langereis, 2000).

8. Conclusions

Changes in the calcareous plankton and benthic foraminiferal assemblages of the upper bathyal Trave section (Central Mediterranean) point to a three-step evolution of the basin, in the preamble of the MSC. The most important transitions occurred at 7.02 and 6.70 Ma, and are used to define three successive stages, summarized below (Fig. 10).

8.1. Stage 1 (7.61–7.02 Ma)

Benthic foraminiferal assemblages indicate well-ventilated and highly oxygenated bottom-water conditions, whilst calcareous plankton associations suggest normal salinity, open-ocean, eutrophic condition, associated to strong seasonality.

8.2. Stage 2 (7.02–6.70 Ma)

The point at 7.02 Ma represents a major pivotal change both in bottom-water environment and in the water column, although it is difficult to point out when the change exactly happened, since this point marks the top of the hiatus, about 100 kyr long.

Benthic assemblages record the incoming deterioration of seafloor condition, stated by a significant decrease of the oxygen content, due to deep-water stagnation, and high supply of organic matter (even higher from 6.86 Ma on). Planktonic foraminiferal associations point to the presence of a strongly stratified water column, characterized by higher SST and lower productivity, associated to an expanded mixed layer and a deeper thermocline, located below the photic zone. Calcareous nanofossil assemblages still indicate normal salinities and high nutrient condition for surficial waters, and also support the hypothesis of a warming during this stage, recognized almost synchronously within the entire Mediterranean basin. The temperature increase is probably responsible for the enhanced stratification of the water mass, that confines nutrients to the uppermost layers on one hand, and favour water stagnation at depth on the other.

8.3. Stage 3 (6.70–6.33 Ma)

Dominance of stress-tolerant benthic species and the presence of barren intervals testify seafloor conditions characterized by dysoxia, high salinity and high fertility. Deep-water stagnation, associated to oxygen depletion and salinity increase, reaches intermediate depth, resulting in the disappearance of intermediate-dweller planktonic foraminifers. Nanofossil assemblages point to hypersaline, unstable and stressed conditions in the near-surface waters, characterized by strongly fluctuating environmental parameters (temperature, salinity and trophism).

This last stage, probably related to the increase of tectonic activity in the Rifian Corridor, represents the first step towards the “true” development of the MSC.

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Appendix A. Benthic foraminifers

A.1. Benthic foraminiferal categories used in the statistical analysis, listed in alphabetical order

- Anomalinoïdes spp.
- Anomalinoïdes spp.
- Bigenerina group: B. nodosaria d’Orbigny, B. cylindrica Cushman
- Bolivina group: B. dilatata Reuss, B. spathulata (Williamson), B. catanensis Seguenza, B. scalpatra Schwager var. miocenica Macfadyen
- Bulimina group: B. subulata Cushman and Parker, B. aculeata marginata d’Orbigny
- C. laevigata d’Orbigny
- C. bradyi (Trauth)
- Cibicidoides group 1: C. wuellerstorfi (Schwager), C. italicus Napoli Alliata
- Gyroidina spp.
- H. boueana (d’Orbigny)
- Cibicidoides group 2: C. pseudoungerianus (Cushman), C. ungerianus (d’Orbigny), C. kullenbergi Parker
- Lenticulina spp.
- Melonis group: M. affinis (Reuss), M. soldanii (d’Orbigny)
- Oridorsalis spp.
- P. ariminensis d’Orbigny
- S. schlumbergeri (Silvestri)
- S. reticulata (Czjzek)
- U. peregrina Cushman, U. proboscidea (Schwager), U. rutile Cushman and Todd, U. gaudryinoides Fornasini
- V. pennatula (Batsch)
A.2. Stress-tolerant taxa


A.3. Benthic foraminiferal species used in the calculation of the Oxygen Index (according to Kouwenhoven and van der Zwaan, 2006) and the Oxygen Transfer Function (according to Drinia et al., 2007)

B.2. Shallow-, intermediate- and deep-water dwellers

Shallow-water dwellers: G. glutinata, Globigerinoides group, Orbulina spp., Dentoglobigerina spp.

Intermediate-water dwellers: neogloboquadrinids, G. bulloides, Globoturborotalita group, T. quinquela, G. obesa group


B.3. Warm/oligotrophic taxa and cold/eutrophic taxa (following Sierro et al., 1999, 2003)

Warm/oligotrophic species: Globigerinoides group, Orbulina spp., G. obesa group.

Globoturborotalita group, G. miotumida group, G. menardii, Sphaeroidinellosis spp., Dentoglobigerina spp.

Cold/eutrophic species: G. bulloides, T. quinquela, G. glutinata, neogloboquadrinids, G. scitula group, C. parvalis

References


