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Stress-tolerant microfossils of a Messinian succession from the Northern Mediterranean basin (Pollenzo section, Piedmont, northwestern Italy)

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ABSTRACT - High resolution quantitative data on calcareous nannofossil and foraminifer assemblages of the upper part of the Pollenzo section (Alba, Piedmont, northwestern Italy) are discussed in order to investigate the palaeoenvironmental evolution within the time interval immediately preceding the Messinian Salinity Crisis (MSC) and coeval to its onset. The studied succession, measuring approximately 24 m in thickness, consists of the seven uppermost cycles (Pm1-Pm7) of the Sant'Agata Fossili Marls. The latter are characterized by euxinic shale/marl couplets that include a distinct carbonate-rich bed. Cyclical, orbitally controlled, fluctuations of warm/oligotrophic and temperate/mesotrophic conditions are documented in the lower cycles Pm1-Pm4 on the basis of opposite abundances of planktonic microfossils. An increasingly stressed palaeoenvironment is recorded from cycle Pm5 upward by the higher abundance of stress tolerant taxa among the calcareous nannofossils (Reticulofenestra *spp.,* Sphenolithus abies*,* Helicosphaera carteri*,* Umbilicosphaera rotula*, and* Rhabdosphaera procera)*, planktonic* (Turborotalita quinqueloba) *and benthic foraminifers* (Bolivina *spp.,* Bulimina echinata*, and* Cassidulina crassa)*. These data support the onset of the MSC within the time interval of the deposition of cycle Pm5. Small size planktonic foraminifers survived up to the lower part of cycle Pm7 while the more resistant calcareous nannofossils survive up to the upper part of cycle Pm7, positioned a few metres below the first gypsum bed (cycle Pg1). Micropalaeontological events (last peaks of* Turborotalita multiloba *and* Orbulina universa*, peak of* S. abies) *allow correlation of the lower Pm1-Pm4 cycles of the Pollenzo section with the upper cycles of the pre-evaporitic Mediterranean succession.*

RIASSUNTO - [Microfossili tolleranti condizioni di stress ambientale del Messiniano pre-evaporitico di Pollenzo (Piemonte, Italia nord-occidentale] - *In questo studio vengono analizzati nuovi dati quantitativi sulle associazioni messiniane a foraminiferi e nannofossili calcarei della parte superiore delle Marne di Santa Agata Fossili nella sezione di Pollenzo (Alba, Piemonte, Italia nord-occidentale), costituita da alternanze cicliche di peliti laminate e di marne omogenee. Nell'intervallo studiato sono presenti anche livelli carbonatici cementati, e le associazioni diventano progressivamente impoverite, fino a scomparire a circa 1.5 m al di sotto del primo livello di gessi primari. Lo studio quantitativo ad alta risoluzione dei foraminiferi è stato condotto sui residui >125 µm e tra 63-125 µm. Nelle alternanze di peliti laminate e marne è stata evidenziata una iniziale ciclicità nelle variazioni percentuali dei microfossili calcarei. Le associazioni diventano poi dominate da taxa tolleranti condizioni di stress ambientale. Tra i nannofossili calcarei, taxa indicativi di condizioni fortemente eutrofiche e/o a salinità variabile sono rappresentati da* Reticulofenestra *spp.,* Helicosphaera carteri*,* Umbilicosphaera rotula *e* Rhabdosphaera procera*, tra i foraminiferi da* Turborotalita quinqueloba*,* Bulimina echinata*,* Cassidulina crassa *e* Bolivina *spp. Drastici cambiamenti nelle associazioni a foraminiferi caratterizzano i cicli Pm4 e Pm5: scomparsa di esemplari e taxa >250 µm e >125 µm, impoverimento generale delle associazioni, aumento percentuale di* C. crassa*,* Eponides *cf.* tumidulus*, tipici di fondali ricchi di fitodetrito. Condizioni ambientali estremamente instabili e/o di stress sono inoltre suggerite dalle alte percentuali dei nannofossili calcarei* Sphenolithus abies *e di piccole* Reticulofenestra *spp. Foraminiferi planctonici* (T. quinqueloba) *di piccole dimensioni (<125 µm) sono presenti fino alla parte inferiore del ciclo Pm7, pochi metri al di sotto del primo banco di gessi (ciclo Pg1). I nannofossili calcarei risultano un poco più resistenti, sopravvivendo fino alla parte sommitale del ciclo Pm7. Gli ultimi picchi di abbondanza di* Turborotalita multiloba *e* Orbulina universa *nei cicli Pm1-Pm4 ed il picco d'abbondanza di* S. abies *alla base del ciclo Pm5 permettono la correlazione con i cicli sommitali della successione pre-evaporitica messiniana dell'area Mediterranea.*

INTRODUCTION

The Messinian Salinity Crisis (MSC), that affected the Mediterranean Basin between 5.96 and 5.33 Ma, was investigated by a number of studies, from the pioneering publication of Hsü et al. (1973) to CIESM (2008, with references therein). Up-to-date references can be found at the Messinian web-site: http://www.messinianonline.it. Recent researches (Lozar et al., 2010; Dela Pierre et al., 2011, 2012) reassessed the importance of the succession deposited during this time interval in the Tertiary Piedmont Basin (TPB) (Sturani, 1978). The TPB is located in northwestern Italy and during the Messinian was part of the central-northern edge of the Mediterranean Basin. The Messinian TPB succession was deposited in an area surrounded by the Alpine chain and at a higher latitude (now 44°41' N) than the reference sections from Spain (Vazquez et al., 2000; Krijgsman et al., 2001; Sierro et al., 2001, 2003), southern Italy (Suc et al., 1995; Sprovieri et al., 1996; Hilgen & Krijgsman, 1999; Bellanca et al., 2001; Blanc-Valleron et al., 2002; Rouchy & Caruso, 2006), Greece and Cyprus (Triantaphyllou et al., 1999; Krijgsmann et al., 2002; Kouwenhoven et al., 2006; Drinia et al., 2007; Morigi et al., 2007), as well as the successions cored in the Mediterranean Sea (Hsü et al., 1973; Cita et al., 1978), all comprised between 34°-38° N, and also

to the North of the Gello, Fanantello, Monte del Casino and Trave sections from central Italy (Negri et al., 1999; Manzi et al., 2007; Iaccarino et al., 2008; Roveri et al., 2008; Di Stefano et al., 2010), at latitude around 43° N.

Recent studies in the area focused on the succession cropping out along the Tanaro River, near Alba (Lozar et al., 2010; Dela Pierre et al., 2011, 2012). This comprises the pre-MSC sediments, and overlying deposits, which testify the three stages of the MSC (Roveri et al., 2008), and evidence the lateral facies transition between marginal and distal settings. In the Pollenzo section the marine deposits, pertaining to the Sant'Agata Fossili Marls, are well exposed, separated in a lower and an upper interval by a thick slumped portion. Previously cited studies evidenced a precession-driven cyclicity, more evident in the interval overlying the slump, on the basis of lithological, petrographic, geochemical and micropalaeontological analyses. The upper part of the Sant'Agata Fossili Marls is overlain by the first local gypsum-bearing cycle, correlated to the 4th cycle of the Primary Lower Gypsum unit deposited in the marginal sector of the Messinian basin (Dela Pierre et al., 2011). Preliminary semiquantitative micropalaeontological analyses recorded very impoverished assemblages in the upper Sant'Agata Fossili Marls, dated to the calcareous nannofossil Zone MNN11b/c (Raffi et al., 2003) on the basis of *Amaurolithus delicatus* occurrence and to the foraminifer Non Distinctive Zone (Iaccarino, 1985) or to the Zone MMi13c (Lourens et al., 2004) on the basis of the occurrence of *T. multiloba*, of dominantly dextral coiling *N. acostaensis* and of *Bulimina echinata* (Lozar et al., 2010). A more detailed study of the sediments above the slump is here presented, in order to better understand the basin evolution in the time interval immediately preceding the MSC and coeval to its onset.

A high resolution sampling and quantitative micropalaeontological analyses were performed on calcareous nannofossil and >125µm and 63-125µm foraminiferal assemblages. This procedure evidenced a cyclicity in the lowermost assemblages and a wider than expected foraminifer occurrence before the onset of the gypsum deposition as well as the importance of small planktonic and benthic taxa for the reconstruction of palaeoenvironmental changes.

GEOLOGIC AND STRATIGRAPHIC SETTING

During the Messinian, the TPB corresponded to a wide wedge top basin, developed above Alpine, Ligurian and Adria basement units (Rossi et al., 2009). The shallow marginal zones of the Messinian basin are presently exposed in the northern (Torino Hill and Monferrato) and southern (Langhe) sectors of the TPB, whereas the depocentral zones are buried below Pliocene and Quaternary sediments (Savigliano and Alessandria basins) (Fig. 1). The succession begins with deep water marine muddy sediments referred to as the Sant'Agata Fossili Marls (Tortonian-Lower Messinian) that record progressively more restricted conditions heralding the onset of the MSC (Sturani, 1978). This unit displays a precession-related cyclic stacking pattern, given by the repetition of euxinic shale/marl couplets and is followed, at basin margins, by primary sulphate evaporites of the Primary Lower Gypsum unit, representing here the Vena del Gesso Formation (Dela Pierre et al., 2011). In situ primary evaporites are not documented in the depocentral zones, but seismic data show that their time equivalent sediments are represented by shales (Irace et al., 2010). The transition between the shallow marginal area and the buried depocentre is exposed on the southern sector of the Piedmont Basin (Alba region) and was reconstructed in detail along a SW-NE transect. On the southern basin margins six Primary Lower Gypsum (PLG) cycles were recognised, composed of bottom grown-selenite layers; the sixth bed represents a distinct marker bed referred to as the Sturani Key-Bed (SKB) (Dela Pierre et al., 2011) and correlatable to the 6th PLG cycle (dated to about 5.84 Ma) (Lugli et al., 2010). Moving towards the NE (i.e., towards the depocentral zone), and in the Pollenzo section, only two gypsum beds are present below the SKB. They overlie a cyclical succession of euxinic shales, marls and carbonate-rich beds belonging to the Sant'Agata Fossili Marls. Because of their position with respect to the SKB, the uppermost three shales and marls cycles must be considered as the deeper water equivalent of the lower cycles of the PLG unit deposited in marginal setting (Dela Pierre et al., 2011).

In the Pollenzo section, a thick slumped interval divides the Sant'Agata Fossili Marls into two portions. In the lower one, seven cycles were recognised; in the upper portion, above the slump, seven cycles (Pm1-Pm7) were recorded, each one including a distinct carbonate-rich bed. According to physical-stratigraphic position (with respect

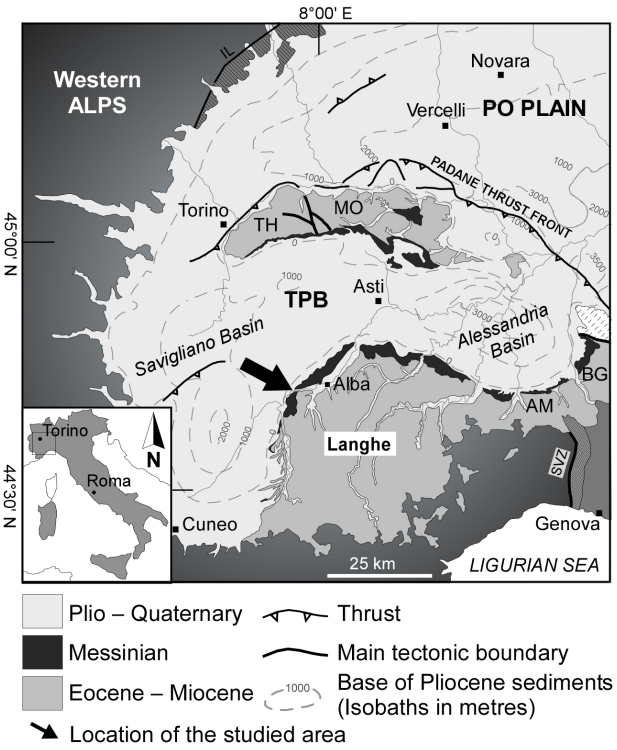

Fig. 1 - Structural sketch of NW Italy (modified from Bigi et al., 1990). The arrow shows the location of the Pollenzo section. AM: Alto Monferrato; BG: Borbera-Grue; IL: Insubric Line; MO: Monferrato; TPB: Tertiary Piedmont Basin; TH: Torino Hill; SVZ: Sestri-Voltaggio zone.

to the SKB), and biostratigraphic data (peak abundance of the calcareous nannofossil *Sphenolithus abies*, strong decrease in abundance and diversity of foraminifers), the onset of the MSC, dated at 5.96 Ma (Krijgsmann et al., 1999), was placed at the base of cycle Pm5 (Lozar et al., 2010; Dela Pierre et al., 2011). Each pre-MSC cycle is composed of a basal layer of laminated euxinic shales, transitionally followed by a calcareous marly bed that hosts a dm-thick carbonate-rich bed mainly composed of dolomite (Dela Pierre et al., 2012). The upper carbonate bed is overlain by the first gypsum-bearing cycle (Pg1), composed of muddy siltstones and by a 1 m thick massive selenite bed, and correlated to the 4th cycle of the PLG unit (Dela Pierre et al., 2011).

The PLG unit is followed by resedimented evaporites (Valle Versa Chaotic Complex; Dela Pierre et al., 2007; Natalicchio et al., 2012a, b) deposited during the second MSC stage (5.60-5.53 Ma) and fluvio-deltaic and lacustrine deposits (Cassano Spinola Conglomerates) recording the third MSC stage (5.53-5.33 Ma) (Dela Pierre et al., 2011).

MATERIAL AND METHODS

The studied succession, about 24 m thick, consists of the seven uppermost euxinic shale/marl couplets of the Sant'Agata Fossili Marls. It starts from the slumped interval, at bottom, and it is overlain by the Vena del Gesso barren deposits and gypsum (Lozar et al., 2010; Dela Pierre et al., 2011), corresponding to the PLG unit. 66 samples were collected at discontinuous intervals, ranging from 5 to 100 cm. These include 15 samples already studied in Lozar et al. (2010) and 51 samples deriving from a more detailed measurement and sampling of the section, performed in 2010, following a strong erosive phase of the Tanaro river, that allowed the exposition of about 12 metres of older sediments, previously not sampled. At least 5 (cycle Pm4) to 12 (cycle Pm1) samples per lithologic cycle were collected for micropalaeontological studies.

Calcareous nannofossil assemblages were studied in smear slides at 1250x under cross-polarized light microscope; slide preparation was kept simple using standard techniques in order to retain the original composition of the sediment (Bown & Young, 1998). Quantitative analyses were carried out by counting at least 500 specimens per sample, including small sized species (<3 μm) such as *Reticulofenestra minuta*; relative abundances are expressed in percentage of total assemblage; additional countings were performed for rare taxa, such as *Discoaster* spp. and *Amaurolithus* spp., over a known area of each slide (9 mm^2). Discoaster spp. data are thus expressed in number of specimens (=N)/mm^2.

For foraminiferal analyses 150-200 g of dry sediment were washed, sieved into grain size fractions: greater than 250 μm, 125-250 μm, 63-125 μm and 45-63 μm and weighed. Quantitative analyses were carried out on the >125 μm and 63-125 μm residues, split into aliquots in order to count at least 300 tests. Percentages of planktonic taxa on the total planktonic tests, of benthic taxa on the total benthic specimens and the P/(P+B) ratio were calculated. The Benthic Diversity (BD) was measured by the taxa richness (S) as the total number of taxa for each sample and by the Fisher's diversity index (α) which takes into account the number of taxa as well as the number of specimens for each sample, using PAST ver. 1.77 (Hammer et al., 2008). Qualitative analyses were also carried out on the 45-63 μm fraction.

The studied material is housed at the Museo di Geologia e Paleontologia dell'Università di Torino under repository numbers MGPT-PU134019 to MGPT-PU134084.

RESULTS

Calcareous nannofossils

In the studied interval calcareous nannofossils occur in moderate abundance and show moderate to poor preservation state. Three samples (at 107.35, 112.30, 124.25 m) are barren in calcareous nannofossils. The assemblages are generally dominated by "small" *Reticulofenestra* (<3 mm; *R. minuta*), but important taxa (in order of decreasing abundance) are *Coccolithus pelagicus*, *Calcidiscus leptoporus*, *Helicosphaera carteri*, *Umbilicosphaera jafari*, *U. rotula*, *Rhabdosphaera procera*, *Pontosphaera multipora*, *P. japonica*, *P. discopora*, *Discoaster variabilis*, *D. pentaradiatus*, and *Sphenolithus abies*. *Amaurolithus delicatus*, together with *A. primus*, also occur in very low abundances and their presence is discontinuous across the studied interval. *Nicklithus amplificus*, the marker species of Zone MNN11c (Raffi et al., 2003), was not recorded in the studied samples.

Distribution of calcareous nannofossils across the lower cycles (Pm1 to Pm4) shows increasing abundance of *C. pelagicus* in the homogeneous marls, whereas *Discoaster* spp. are present only in the laminated shales (Fig. 2).

From 119.95 m upward, calcareous nannofossil assemblages become dominated by few taxa; in particular the lower part of cycle Pm5 shows very high abundances of *S. abies* (up to 60%) and *H. carteri* (up to 20%) (Fig. 2). The latter taxon is also abundant upward (120.95 m), reaching 27%, together with *R. procera* (13%); both taxa reveal abundances below 10 and 5% respectively, below this level. At 121.55 m *U. rotula* records a peak abundance reaching 12%.

Foraminifers

Foraminifers are generally well preserved and are common in many samples up to 119.45 m, rare to very rare up to 126.25 m (lower half of cycle Pm7) and totally absent upward.

In >125 μm residues, planktonic specimens have been recognized up to 121.65 m, but large tests occur in the >250 μm fraction only up to 117.80 m (lower half of cycle Pm4). The P/(P+B) ratio shows very strong variations, from 0 to 60-80%, with very high percentages in the laminated shales and zero or very low values in the marly horizons (Fig. 3).

Frequent to abundant *Orbulina universa*, often with a not perfectly rounded test, occurs only in the laminated shales. In the same lithology other warm-water oligotrophic indicators such as the *Globigerina* (*Globoturborotalita*) apertura group (*G.*[*Gt.*] *apertura*, *G.*[*Gt.*] *decoraperta* and *G.*[*Gt.*] *woodi*) are rather common. *Globigerina*

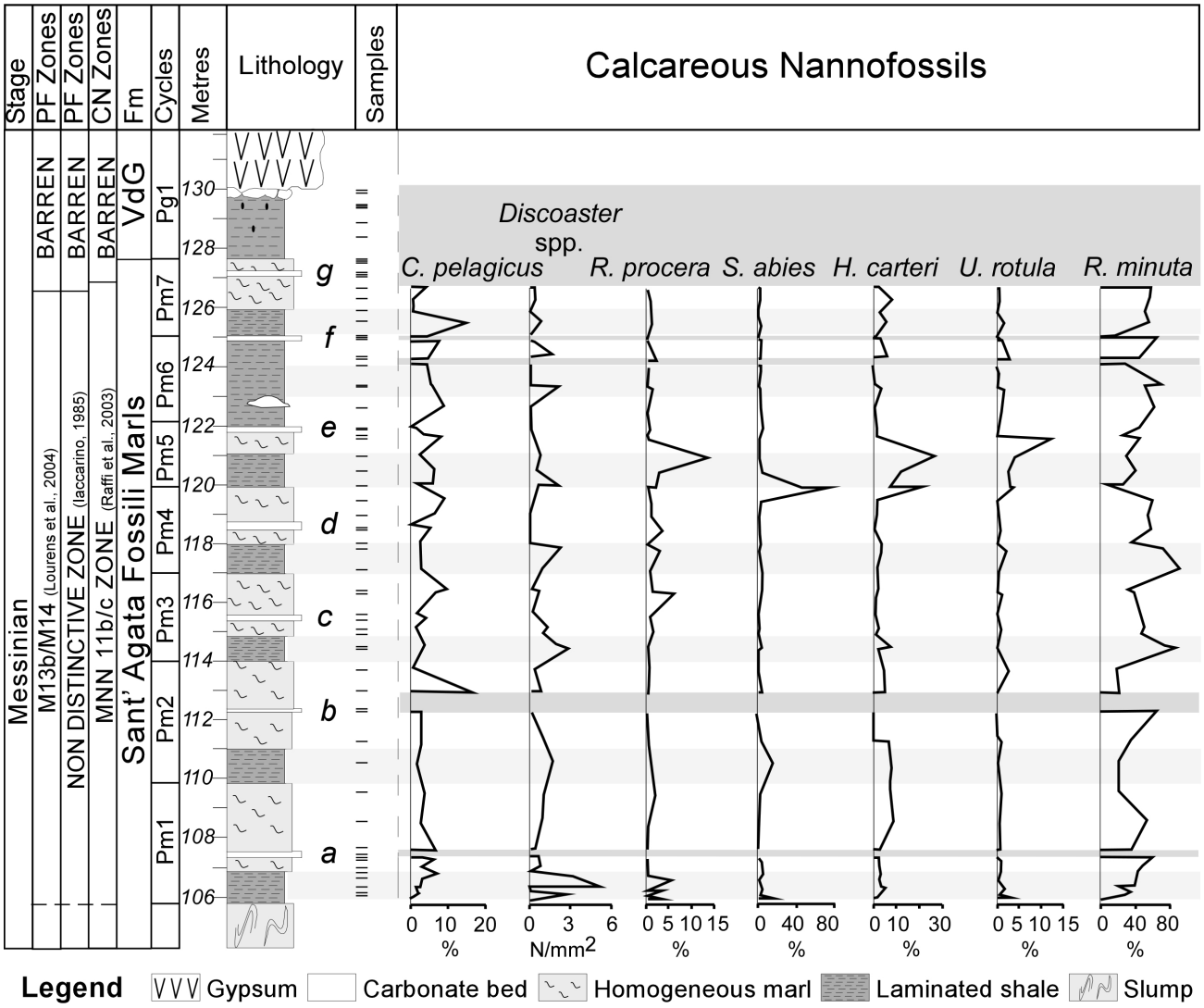

Fig. 2 - Biostratigraphy, lithological column, sample location, percentage variations of the main calcareous nannofossil taxa. Dark grey and light grey bands highlight respectively barren intervals and laminated shale intervals. Metre numbers correspond to measurement in Dela Pierre et al., 2011.

bulloides, *Globigerinella obesa*, *Globigerinita* spp. (*G. glutinata* and *G. uvula*), *Neogloboquadrina acostaensis* (dominantly dextral coiling) are also present. *Turborotalita quinqueloba* is frequent in the laminated shales of cycles Pm1 and Pm2, followed by very rare *Globigerinoides* spp. (almost exclusively *G. obliquus*).

Planktonic foraminifers are absent or very rare in the homogeneous and bioturbated marls, represented by the cool-water eutrophic forms *G. bulloides, G. glutinata, N. acostaensis* and *T. quinqueloba*. *Turborotalita multiloba*, an endemic Mediterranean Messinian taxon, occurs only in the cycle Pm1 and shows a frequency peak within its marly semicouplet (108.55 m). Very rare *Globorotalia scitula* specimens are present only in cycle Pm1. From the marl of cycle Pm4 upward, several samples are barren or yield scarce and strongly impoverished planktonic assemblages (*G. bulloides, N. acostaensis, T. quinqueloba*), progressively devoid of large and medium size tests.

Up to 126.25 m (lower part of cycle Pm7 marl), planktonic specimens occur in several samples and often with higher percentages in the 63-125 μm residue, than in the >125 μm fraction. The overlying samples are barren. Similarly to the >125 μm fraction, the P/(P+B) ratio displays very strong variations (Fig. 3). *T. quinqueloba* is often dominant, followed by *N. acostaensis*, *G. glutinata*, *G. obesa* and rare *G. bulloides*. *T. multiloba* is common only at 108.55 m. In the uppermost samples only *T. quinqueloba* and juvenile tests occur, also in the 63-45 μm residues, up to 126.25 m.

Benthic foraminifers from the >125 μm residue are very scarce or absent in the laminated shales. In contrast they are abundant but poorly diversified in the marls. Large specimens (>250 μm) occur up to 119.45 m, top cycle Pm4 marl; benthic tests >125 μm occur up to 124.35 m, upper part of cycle Pm6 shale. They consist almost totally of infaunal opportunistic forms such as the *Bolivina* group (*Brizalina catanensis, B. dilatata, B. spathulata, Bolivina dentellata, B. etrusca*, and *B. paralica*) and *Bulimina* spp. (almost exclusively *B. echinata,* very rare *B. aculeata,* and *B. elongata*). Frequencies of the *Bolivina* gr. and of *B. echinata* are often inversely correlated (Fig.

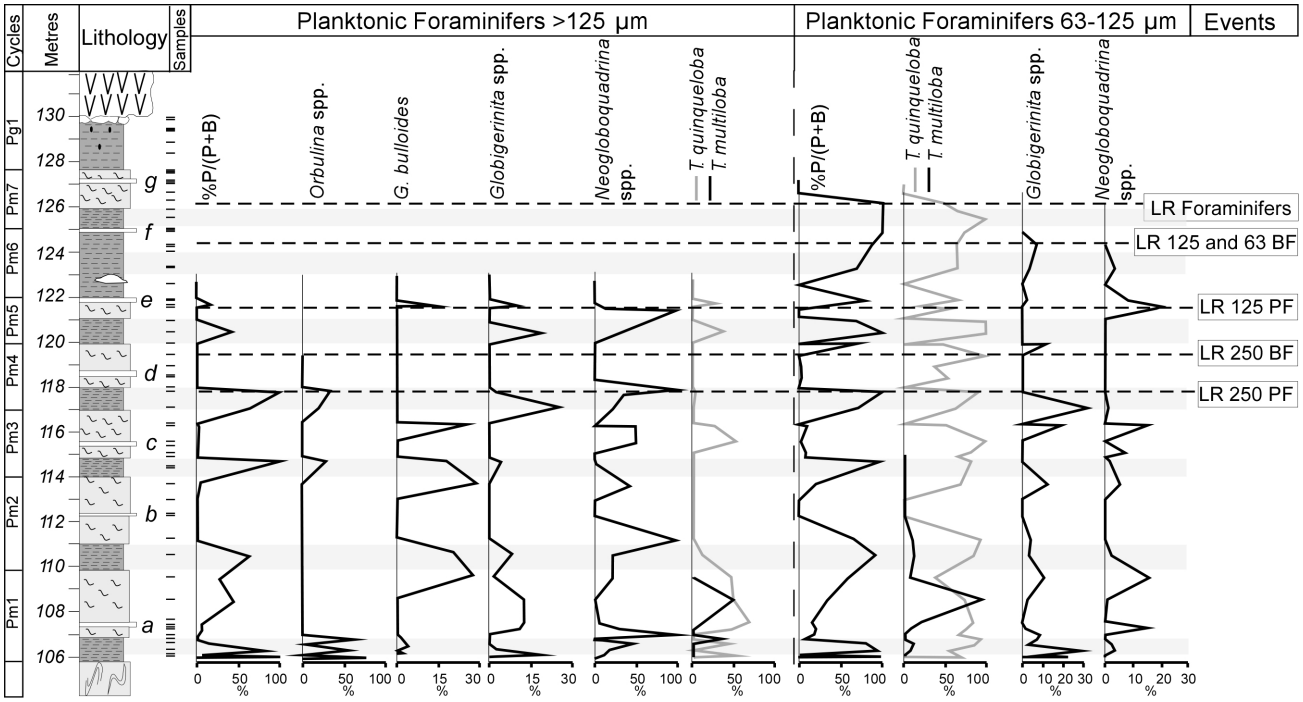

Fig. 3 - Lithological column, sample location, percentage variations of the main planktonic foraminiferal taxa. LR = Last Recovery. Legend as in Fig. 2. Light grey bands highlight laminated shale intervals.

4). The *Bolivina* gr. percentages are high in the lower cycles and decrease upward. *B. echinata* reaches its highest abundances in cycles Pm3-Pm4 and is relatively frequent in the uppermost marls of cycle Pm5. Rare *Cibicidoides pseudoungerianus*, *Globobulimina affinis* and *Uvigerina peregrina* occur in few samples of cycle Pm1. *Hanzawaia boueana* and *Valvulineria bradyana* are randomly common. Very rare shallow water forms (SW) (*Ammonia beccarii, A. tepida, Aubignyna perlucida* and Elphidiids) occur in the laminated shales. The Benthic Diversity (BD), expressed by the taxa richness (S) and by the Fisher's diversity index (α) (Hammer et al., 2008), is very low, showing the lowest values in the middle-upper samples.

Bolivina gr. is dominant in the 63-125 µm fraction, up to the lower part of cycle Pm3. *Cassidulina crassa*, absent in almost all the >125 µm assemblages, is one of the dominant species in many sample of cycles Pm3 to Pm5 (Fig. 4). *B. echinata*, mainly represented by juvenile specimens, is also common. *Eponides* cf. *tumidulus* is randomly frequent in some upper samples. The benthic taxa richness (S) and the Fisher's diversity index (α) show values equal or even lower than those recorded in the >125 µm assemblages.

DISCUSSION

Calcareous nannofossils

The overall trend among the relative abundances of calcareous nannofossil taxa outlines a sharp climate control up to cycle Pm4, disrupted by a dramatic environmental event recorded from 119.95 m upward. In the lower cycles *Discoaster* spp. is more abundant in the laminated shales, whereas *C. pelagicus* shows higher abundance in the homogeneous marls (Fig. 2). The extinct *Discoaster* spp. has been recorded in high abundances in Miocene sapropels (Negri et al., 1999; Flores et al., 2005) and in sediments deposited under warm oligotrophic surface waters (Chepstow-Lusty et al., 1989). *C. pelagicus* prefers cold-temperate surface waters and moderate to high nutrient availability (Negri et al., 1999; Ziveri et al., 2004). Negative correlation of their relative abundances has been shown to record orbitally driven climate cycles in Messinian sediments in the Sorbas Basin (Flores et al., 2005); their negative correlation documented also at Pollenzo reinforces the climatically controlled alternation of warm/oligotrophic and temperate/mesotrophic assemblages, driven by orbital (precessional) cycles during the pre-evaporitic Messinian.

From cycle Pm5 up to cycle Pm7, the orbitally driven climatic cyclicity is superimposed by a strong environmental signal, recorded by increased abundance of stress-tolerant taxa among calcareous nannofossil and planktonic foraminifer assemblages, as well as among benthic foraminifers. A frequency peak of the otherwise rare or scarce *S. abies* is registered at the base of cycle Pm5 and has been frequently recorded in uppermost pre-evaporitic sediments (Blanc-Valleron et al., 2002; Kouwenhoven et al., 2006; Morigi et al., 2007), suggesting changes in salinity and stratification of the water column. *H. carteri*, a taxon usually adapted to mesotrophic, high turbidity, and low salinity surface waters (Bukry, 1974; Ziveri et al., 2004; Triantaphyllou et al., 2009) is also abundant (20% of the assemblage) at the base of cycle Pm5. A highly variable palaeoenvironment, probably characterized by variable or low salinity, warm and mesotrophic waters, can be inferred during the deposition of the lower Pm5 cycle.

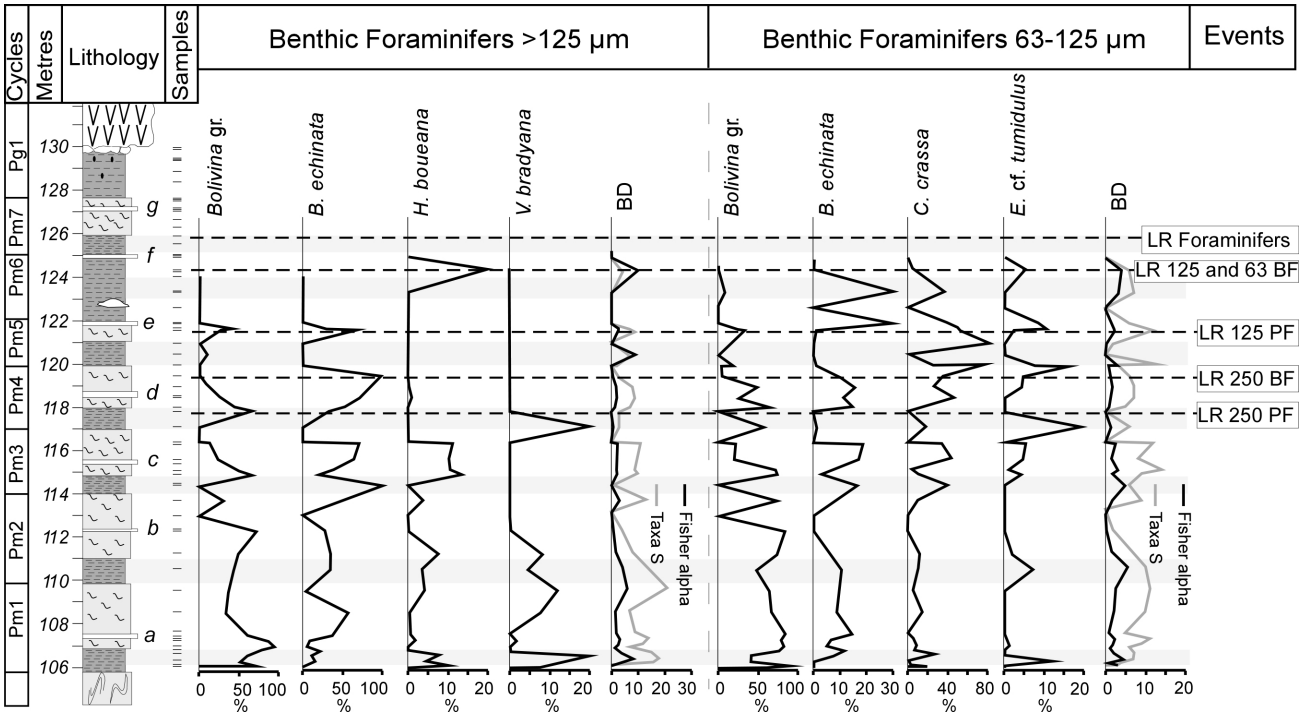

Fig. 4 - Lithological column, sample location, percentage variations of the main benthic foraminiferal taxa. BD = Benthic Diversity. LR = Last Recovery. Legend as in Fig. 2. Light grey bands highlight laminated shale intervals.

Only *U. rotula* and *R. procera*, both opportunistic (Haidar & Thierstein, 1997) and warm water tolerating taxa (Ziveri et al., 2004) show relatively high frequences in cycle Pm5; in particular, *U. rotula* is abundant in the marls overlaying the diatomite interval in the Messinian Sorbas basin, testifying its ability to thrive in surface waters where nutrients become depleted after diatom blooms (Flores et al., 2005).

In general, the base of cycle Pm5 is characterized by nearly oligotypic calcareous nannofossil assemblages (60% *S. abies*, 20% *H. carteri*), suggesting a highly stressed surficial water column where the more opportunistic taxa bloomed. Increasing environmental stress towards the top of the Sant'Agata Fossili Marls is also recorded from cycle Pm5 upwards, where the assemblages are dominated by *R. minuta*, possibly because this highly opportunistic taxon outcompete other taxa, less adapted to extreme environmental conditions occurring during the first stage of the MSC.

Foraminifers

Specimens are diluted in the terrigenous debris and gypsum aggregates and are poorly to very poorly diversified. Repeated changes in the foraminiferal assemblages, alternatively dominated by planktonic and benthic forms (Figs 3-4), and their progressive decrease in size and diversity before their disappearance, confirm the initially climate driven cyclicity and the progressively stressed palaeoenvironmental conditions suggested by calcareous nannofossils.

In cycles Pm1 and Pm2 planktonic assemblages from laminated shales are relatively diversified and mainly contain warm to warm-temperate oligotrophic taxa, typical of surface mixed water, such as the rare *Globigerinoides* spp., and of surficial to intermediate water, such as the dominant *O. universa*, or inferred to have lived above or near the thermocline, such as the extinct *G. (Gt.) apertura* gr. (Hemleben et al., 1989; Pujol & Vergnaud Grazzini, 1995; Serrano et al., 1999; Sierro et al., 2003). Also eutrophic phytofagous taxa (*G. bulloides*, *G. glutinata, N. acostaensis* and *T. quinqueloba*) living, or inferred to have thrived, in surface and intermediate nutrient-rich waters with strong vertical mixing and in upwelling areas (Bè & Tolderlund, 1971; Hemleben et al., 1989; Pujol & Vergnaud Grazzini, 1995; Schiebel et al., 2004) are represented. On the contrary, deep-dwelling planktonic taxa, such as the globorotalids, are nearly or totally absent. The co-occurence of shallow and intermediate water forms, of phytofagous and predator/omnivorous taxa suggests a water column well oxygenated in its surficial and intermediate portions as well as a diversified trophic structure of the planktonic assemblage. The absence of the oligotrophic mesopelagic species could be due to shallower or more eutrophic waters than needed by these taxa.

In the laminated shales of cycles Pm3 and Pm4, predator/omnivorous taxa are still dominant, represented by *O. universa* and *G. obesa*. The last occurrence of *O. universa* is registered in cycle Pm4 laminated shale. *O. universa* frequency peaks, commonly recorded in the upper pre-evaporitic succession (Suc et al., 1995; Sprovieri et al., 1996; Blanc-Valleron et al., 2002; Violanti et al., 2007), document its diffusion in stressed palaeoenvironments and could be related to the rather diversified trophic behaviour of this taxon. *O. universa* is a symbiont-bearing, predator and omnivore form, able to capture living zooplanton (copepods), phytoplankton (dinoflagellates, chrysomonad flagellates, diatoms) and

food remains, it has a herbivorous preference during its juvenile stage, a carnivorous diet in the spherical adult stage, and tolerates a salinity range of 23-46‰ (Hemleben et al., 1989). Abnormal tests, with a not completely enveloping last chamber, or bilobate, as occurring in the Pollenzo samples, are common in laboratory when food is abundant (Hemleben et al., 1989) and in ocean-margin waters with high nutrient levels (Robbins, 1988).

In cycles Pm3 and Pm4 the genus *Globigerinoides*, probably the most oligotrophic taxon among planktonics, is absent. Other eutrophic forms such as the *G. (Gt.) apertura* gr. disappear, whereas *G. glutinata* becomes more frequent in the >125 μm and 63-125 μm residues. *G. glutinata*, an exclusively diatom grazer (Hemleben et al., 1989), could be used as a proxy of diatom occurrence; therefore the absence of diatom frustules in the Pollenzo sediments has to be referred to their dissolution in the water column or at the sea floor.

Planktonic assemblages are even more impoverished in cycles Pm5 to Pm7, in which planktonic foraminifers are represented only by the eutrophic herbivorous taxa *T. quinqueloba, N. acostaensis* and *G. glutinata*, suggesting an altered trophic chain in the water column.

In the homogeneous marl from cycle Pm2 upward, planktonic assemblages are very scarce and poorly diversified. They yield almost exclusively eutrophic herbivorous taxa (*T. quinqueloba*, Neogloboquadrinids, *G. bulloides*, *G. glutinata*), abundant in nutrient-rich waters as well as in seasonal upwelling areas (Pujol & Vergnaud Grazzini, 1995; Schiebel et al., 2004). The extinct *T. multiloba* is present only in cycle Pm1 marl and is also considered to have been a cold, eutrophic species (Riforgiato et al., 2008). *T. quinqueloba*, often dominant in the finest fraction (Fig. 3), thrives in surface to intermediate cold-temperate waters and is abundant in high latitude, transitional and polar water masses, but also frequent in tropical or subtropical oceanic waters with an optimum at salinity near 34-35‰ (Bè & Tolderlund, 1971; Hilbrecht, 1996). High abundances of the phytophagous *T. quinqueloba* are reported in the Mediterranean Sea during spring blooms (Hernández-Almeida et al., 2011) and are linked to stratification induced by meltwater injected on the sea surface in the North Atlantic (Simstich et al., 2012). *T. quinqueloba* was frequent in Messinian successions (Sierro et al., 1999, 2003; Blanc-Valleron et al., 2002; Drinia et al., 2007; Manzi et al., 2007; Iaccarino et al., 2008; Di Stefano et al., 2010) and was inferred to tolerate a relatively wide range of salinity and fresh-water influence (Van der Poel, 1992) as well as hypersaline conditions (Sierro et al., 1999, 2003; Di Stefano et al., 2010). It appears to respond quickly to seasonal food supply and to have been able to thrive in very stressed conditions, as those of the Mediterranean Sea preceding the MSC. *T. quinqueloba* is the last foraminiferal species to survive up to the lower part of cycle Pm7, even if only recognizable in the finest residues.

The scantiness or absence of benthic foraminifers document strongly dysoxic to anoxic bottom conditions at time of laminated shales deposition (Fig. 4). Benthic assemblages are dominant in the homogeneous marls, mainly or totally composed by infaunal opportunistic and stress-tolerant taxa (*Bolivina* spp., *Brizalina* spp., *B. echinata* and *C. crassa*), adapted to high organic carbon and low oxygen bottom waters (Van der Zwaan, 1982; Kouwenhoven et al., 2006), thus suggesting disaerobic conditions at bottom, even if less severe than during the laminated shale deposition. The small *Eponides* cf. *tumidulus* occurs in the finest fraction also in some laminated shale and is more common in the middle part of the succession. It is very close to the species described by Parker (1958) in the bathyal Eastern Mediterranean, and recorded also from bottoms influenced by seasonal input of phytodetritus (Altenbach et al., 2003).

A palaeodepth typical of the deep outer shelf is documented by the dominance of Bolivinids and Buliminids, typical of muddy bottoms, by the scantiness of outer neritic to bathyal taxa such as *C. pseudoungerianus*, *G. affinis* and *U. peregrina* in the lowermost samples (cycle Pm1) and by the rarity of shallow water forms (*Ammonia* spp., Elphidiids) (Murray, 2006). In cycles Pm2 to Pm4 a slight shallowing on the outer shelf is suggested by the benthic diversity decrease and by the often common occurrence of *H. boueana* and *V. bradyana*. In particular, *V. bradyana* is frequent in shelf areas influenced by riverine input and rather high organic matter (Jorissen, 1987; Frezza & Carboni, 2009).

Age and Correlations

Tools to date and correlate the studied interval at a Mediterranean scale are given by physical-stratigraphic and micropalaeontological data. The evaporitic succession of the TPB yields the Sturani Key-Bed (SKB) (Dela Pierre et al., 2011), a well-recognizable marker bed, that here represents the 6th PLG cycle, dated in the Northern Apennine to about 5.84 Ma (Lugli et al., 2010). At Pollenzo, only two gypsum beds are present below the SKB. Consequently, the uppermost three lithologic cycles of the Sant'Agata Fossili Marls (Pm5, Pm6 and Pm7) were proposed as time-equivalents of the lower cycles of the PLG unit (Dela Pierre et al., 2011). The onset of the MSC, dated at 5.96 Ma (Krijgsman et al., 1999), was correlated to the base of cycle Pm5 (Lozar et al., 2010; Dela Pierre et al., 2011), in which a peak abundance of the calcareous nannofossil *Sphenolithus abies,* and a strong decrease in abundance, diversity and size of foraminifers also occur.

The Pollenzo cycles Pm1 to Pm4 can be correlated to the uppermost Abad cycles UA31 to UA34 of the Sorbas Basin (Spain) as well as to cycles 46-49 of Falconara, to the uppermost Tripoli layers at Capodarso (Sicily), to part of the Unit B of the Fanantello section (Northern Apennines) (Manzi et al., 2007) and to coeval levels of Pissouri and Tochni sections (Cyprus). The last abundance peak of *T. multiloba*, recognized at Pollenzo within the cycle Pm1 marls, could correspond to its last influx documented in the Sorbas Composite at cycle UA31 (Sierro et al., 2001, 2003) and in cycle 46 of the Falconara/ Gibliscemi composite section (Blanc-Valleron et al., 2002). At Capodarso, the last recovery of *T. multiloba* was reported in the clay between the diatomite layers m and n (Suc et al., 1995), whereas at Pissouri it occurred below the indurated level 2 (Kouwenhoven et al., 2006). Orszag-Sperber et al. (2009) recognized a *T. multiloba* influx around 7 metres under the base of the gypsum at Tochni (Cyprus).

Another useful event is the last abundance peak (and occurrence) of *O. universa*, occurring three diatomitic

layers, at Capodarso (Suc et al., 1995) and three laminated layers, at Pollenzo, above the last *T. multiloba* peak, as well as in the UA33 cycle of the Sorbas Composite (Sierro et al., 2003) and below the uppermost indurated level 1 at Pissouri (Kouwenhoven et al., 2006). The different palaeogeographical settings (northern/southern) and the different grain-size fraction studied, >125 μm for Pollenzo, Falconara/Gibliscemi (Blanc-Valleron et al., 2002), Pissouri (Kouwenhoven et al., 2006) and >150 μm for Sorbas (Sierro et al., 2003) and Capodarso (Suc et al., 1995), probably influence the recorded distribution of small or medium size taxa, such as *N. acostaensis*, *Globigerinita* spp., *T. quinqueloba*, Bolivinids and Buliminids.

CONCLUSIONS

Quantitative study of the uppermost Sant'Agata Fossili Marls at Pollenzo allows us to propose the following conclusions:

1. Cyclical, orbitally controlled, fluctuations of warm/oligotrophic and temperate/mesotrophic conditions are documented in the lower cycles Pm1-Pm4 by the opposite abundance peaks of planktonic microfossils: *Discoaster* spp. versus *C. pelagicus* among calcareous nannofossils and *O. universa* versus *N. acostaensis* among foraminifers.

2. From cycle Pm5 upward, an increasingly stressed palaeoenvironment both in the water column and at the bottom is recorded by the higher abundance of stress tolerant taxa among calcareous nannofossil (*S. abies, H. carteri, U. rotula, R. procera* and *R. minuta* high abundance) and planktonic (*T. quinqueloba*) as well as benthic foraminifers (*Bolivina* spp*., B. echinata*, and *C. crassa*). Other indices of unfavourable conditions are the progressive decrease in size and diversity of foraminifers. These data support the onset of the MSC at the base of cycle Pm5, as proposed by Dela Pierre et al. (2011, 2012), on physical-stratigraphic (SKB marker bed) and micropalaeontological data (*S. abies* abundance peak).

3. Cycles Pm1 to Pm4 can be correlated to the uppermost UA31 to UA34 cycles of the Sorbas Composite (Spain) (Sierro et al., 2003), to cycles 46-49 of the Falconara/Gibliscemi section (Blanc-Valleron et al., 2002), to the uppermost Tripoli layers of Capodarso (Sicily) (Suc et al., 1995), to part of the Unit B of the Fanantello section (Northern Apennines) (Manzi et al., 2007) and to the upper carbonate and marl levels of Pissouri (Kouwenhoven et al., 2006) and Tochni (Orszag-Sperber et al., 2009) sections (Cyprus), on the basis of the last abundance peaks of *T. multiloba* and *O. universa*.

4. Calcareous nannofossils and foraminifers suggest a deposition of the laminated shales during time of seasonal fresh water input, water column stratification, low salinity, oligotrophy or mesotrophy in the upper photic zone, and strongly dysoxic bottoms. On the contrary, deposition of the marls occurred at time of moderate to good mixing in the water column, probably wind-induced higher nutrient availability in surface waters, and slightly higher oxygen content at the sea floor.

5. Progressively more eutrophic, dysoxic to strongly dysoxic bottom conditions characterized all the succession up to cycle Pm6. Upwards, anoxic bottoms are indicated by the absence of benthic foraminifers.

6. Planktonic foraminifers appear to have been more sensitive to unsuitable water column conditions than calcareous nannofossils, which survive up to the upper part of cycle Pm7, few metres below the first gypsum layer.

7. Qualitative and quantitative analyses of the 63-125 μm and 45-63 μm fraction resulted of fundamental importance to detect the occurrence of planktonic foraminifers (*T. quinqueloba*) up to cycle Pm7. Analysis of the only >125 μm residue would result in underestimating the foraminifers distribution in such extreme palaeoenvironmental conditions as those heralding the MSC.

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