

Original article

# Integrated quantitative biostratigraphy of the latest Tortonian–early Messinian Pissouri section (Cyprus): An evaluation of calcareous plankton bioevents

## Biostratigraphie intégrée du passage Tortonien–Messinien dans le bassin de Pissouri (Chypre) : une évaluation des bio-événements dans le plancton calcaire

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Received 14 April 2005; accepted 5 February 2007

Available online 26 April 2007

### Abstract

A quantitative study was performed on planktonic foraminifera and calcareous nannofossils of the astronomically dated Late Miocene Pissouri section (Cyprus). Our results confirm the reliability of well-known planktonic foraminiferal events as *Catapsydrax parvulus* LO (Last Occurrence), sinistral coiling change of *Globorotalia scitula*, *Globorotalia miotumida* group FRO (First Regular Occurrence), *Globorotalia nicolae* FO (First occurrence) and LO, sinistral coiling change of *Neogloboquadrina acostaensis* and also of several important calcareous nannofossil events (*Amaurolithus primus* FO, *Amaurolithus delicatus* FO, *Reticulofenestra rotaria* FO and FCO). Integrated planktonic foraminifera and calcareous nannoplankton data contribute to an enhanced time resolution of the Tortonian - early Messinian interval in the Levantine basin, and contribute to detailed correlations throughout the Eastern Mediterranean. In addition, we compare methodologies commonly used in calcareous plankton biostratigraphy, and shortly outline sources of bias that can influence the results of stratigraphic studies.

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### Résumé

Une étude intégrée des foraminifères planctoniques et des nannofossiles calcaires a été effectuée sur la coupe de Pissouri (Chypre), au passage Tortonien supérieur–Messinien. Les résultats obtenus nous ont permis de mettre en évidence des événements micropaléontologiques déjà reconnus ailleurs en Méditerranée, en particulier la dernière présence de *Catapsydrax parvulus* [Last Occurrence (LO)], le changement d'enroulement senestre/dextre de *Globorotalia scitula*, la première présence régulière du groupe des *Globorotalia miotumida* [First Regular Occurrence (FRO)], l'apparition et la dernière présence de *Globorotalia nicolae* [First Occurrence (FO) et LO], le changement d'enroulement senestre/dextre de *Neogloboquadrina acostaensis*. Pour les nannofossiles calcaires, ont été caractérisées : l'apparition d'*Amaurolithus primus* (FO), celle d'*Amaurolithus delicatus* (FO), l'apparition et la première présence commune de *Reticulofenestra rotaria* (FO et FCO). Les nombreux bio-événements identifiés permettent une meilleure résolution chronologique de la période Tortonien–Messinien inférieur dans le bassin levantin. La coupe de Pissouri a permis d'élaborer une stratigraphie intégrée qui se corrèle bien avec celles d'autres coupes de la Méditerranée orientale. Nous

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avons aussi comparé les différentes méthodologies utilisées habituellement pour la biostratigraphie par le plancton calcaire et les différences qu'elles peuvent apporter aux études de stratigraphie.

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**Keywords:** Planktonic foraminifera; Calcareous nannofossils; Biostratigraphy; Eastern Mediterranean; Cyprus; Messinian

**Mots clés :** Foraminifères planctoniques ; Nannofossiles calcaires ; Biostratigraphie ; Méditerranée orientale ; Chypre ; Messinien

## 1. Introduction

The Messinian is one of the most extensively studied and debated stages in the geological history of the Mediterranean area due to the particular event that occurred at this time, the Messinian Salinity Crisis. The onset of the salinity crisis marked a strong environmental change in the entire basin, which has led to the accumulation of a huge series of evaporites (see elsewhere in this volume). Integrated stratigraphic studies, comprising bio-, magneto- and cyclostratigraphy and astronomical tuning have been applied before to many sections throughout the Mediterranean area (e.g. Hilgen et al., 1995; Hilgen and Krijgsman, 1999; Krijgsman et al., 1995, 1999, 2002; Negri et al., 1999; Negri and Villa, 2000; Sprovieri et al., 1999; Sierro et al., 2001; Raffi et al., 2003). The age control of the Messinian Stage is by now well defined, the more so since the International Commission on Stratigraphy (ICS) has accepted the Messinian Global Stratotype Section and Point (GSSP) in the Oued Akrech section (Hilgen et al., 2000a, 2000b).

Calcareous plankton biostratigraphy historically provides a first-order age control in many outcrops and cores, and is based on the appearance/disappearance and relative abundance patterns of selected species of planktonic foraminifera and calcareous nannofossils. At the same time, however, it is important to recollect that these organisms quickly respond to

oceanographic changes (temperature, salinity, primary production, water stratification, etc.) and their occurrence and disappearance can also be due to environmental variations (e.g. Hemleben et al., 1989; Sierro et al., 1993, 2003; Flores et al., 2003; Pérez-Folgado et al., 2003). At present, the Mediterranean Sea is characterized by geographical variations in oceanographic conditions: the eastern part of the basin is characterized by warm and oligotrophic surface waters whereas in the western part the surface waters are colder and richer in nutrients (Béthoux et al., 1999; Pinardi and Masetti, 2000). This difference in the hydrological condition is reflected in the distribution of the plankton community (Thunell, 1978; Pujol and Vergnaud-Grazzini, 1995). Based on the palaeogeographic reconstructions of the Mediterranean Sea (e.g. Rosenbaum et al., 2002), we may infer that the hydrological conditions were also different in the eastern and western sub-basins during the Late Miocene.

The Pissouri Motorway Section is located on the Island of Cyprus in the Levantine basin, Eastern Mediterranean (Fig. 1). The section covers the interval from  $\sim 7.6$  Ma (late Tortonian) up to the transition towards the Messinian evaporites, which was dated to occur at  $5.96 \pm 0.02$  Ma (Krijgsman et al., 2002). It is a suitable sedimentary succession to study the palaeoenvironmental changes in the Eastern Mediterranean that eventually lead to the onset of the Messinian Salinity Crisis (e.g. Kouwenhoven et al., 2006). The biostratigraphic study in

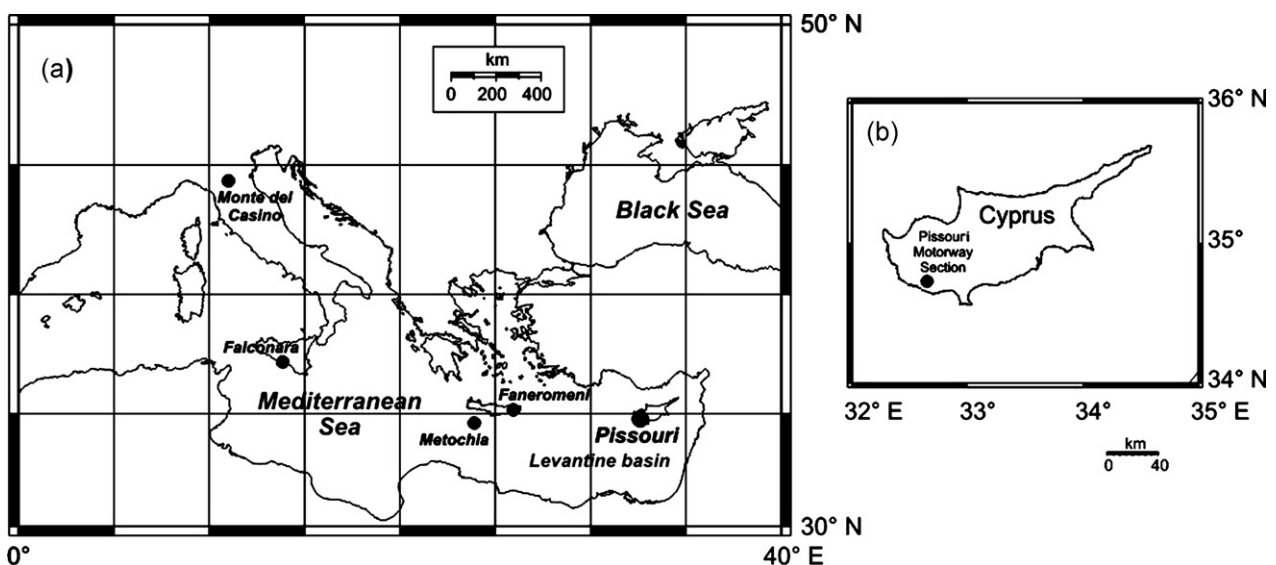


Fig. 1. Location map showing (a) the Mediterranean sections considered for the discussion and (b) the investigated section of Pissouri Motorway in Cyprus.

Fig. 1. (a) Carte générale de la Méditerranée avec localisation des coupes géologiques considérées ; (b) localisation de la coupe de Pissouri (Chypre).

Krijgsman et al. (2002) revealed ten well-defined planktonic foraminifera events that have been astronomically dated earlier in other Mediterranean sections and as such, together with the magnetostratigraphy, provided an excellent first-order age control for astronomical tuning of the section. Magnetostratigraphic results are in agreement with the biostratigraphic data and show that all magnetic chrons between C4n.1n and C3An.1n are present.

The aim of this paper is twofold: (1) to present an integrated biostratigraphy for the Pissouri section of the interval straddling the Tortonian–Messinian boundary up to the onset of gypsum deposition, based on quantitative data of planktonic foraminifera and calcareous nannofossils, and (2) to compare the quantitative counts of planktonic foraminifera to the bioevents published by Krijgsman et al. (2002) for the same section, which were obtained by a different methodology. In addition, we compare the bioevents recorded in the Pissouri section to those obtained in other land-based sections of the Mediterranean area, in order to test the correlation potential and the reliability of the bioevents in view of palaeohydrographical fluctuations that may have been important in determining the distribution of the planktonic taxa.

## 2. Materials and methods

### 2.1. Lithology

The Pissouri Motorway Section is located in the Pissouri sub-basin, SE Cyprus (Fig. 1). In the present study, we focus on the stratigraphic interval straddling the Tortonian–Messinian boundary up to the “*barre jaune*”, the transition to the evaporites (approximately 5.98 Ma). The succession is characterized by lithological cycles of centimetre to decimetre scale, that can be correlated to precessional cycles and predominantly consist of indurated calcareous beds and softer marls (Krijgsman et al., 2002). The expression of the sedimentary cyclicity changes throughout the section, from colour alternations in blue marls at the base of the section to lithological alternations of whitish, indurated homogeneous carbonates with laminated marls and marly limestones at the top. Bedding-parallel shear planes are described by Krijgsman et al. (2002) in the interval above the Tortonian–Messinian boundary (37–33 m). Crystalline and pseudomorphic gypsum is present in the upper 32 m of the section where the marls have a diatomitic appearance. A slumped interval between 10.40 and 6.60 m laterally contains reef limestone blocks. This interval, and the actual transition to the evaporites, a 1.5 m thick interval of laminated carbonates commonly referred to as the “*barre jaune*” in the adjacent Polemi Basin, were not sampled. For details on the lithology of the studied section, the reader is referred to Krijgsman et al. (2002).

### 2.2. Sample preparation

For planktonic foraminifera counts, the samples were disaggregated in water and wet-sieved over 63, 125 and 595  $\mu\text{m}$  sieves. After drying at room temperature, the 125–

595  $\mu\text{m}$  fraction of the washed residues was split in representative aliquots containing  $\sim 200$  specimens by use of an Otto microsampler. A quantitative analysis of the planktonic foraminifera fauna was performed on 66 samples and for each sample, when possible, about 200 specimens were counted. Several barren samples occur in the upper part of the section from 33.40 m to the top. Planktonic foraminifera were identified at specific and supraspecific level and 51 categories were distinguished and converted to relative frequency data. A taxonomic reference list for planktonic foraminifera is given in Appendix A.

Sample preparation for calcareous nannoplankton followed a methodology that assured a uniform distribution of the sediment on the cover glass. For this purpose, 1 mg of sediment was resuspended in 10 ml of distilled water, corrected to pH 8. After 30 sec, 1 ml of the suspension was collected with a micro-pipette and put on a cover glass to dry at 50 °C. Analyses were performed with a light microscope at 1250 $\times$  magnification by counting at least 300 specimens per sample, and include coccoliths of which the size is less than 3  $\mu\text{m}$ . Additional counting up to at least 100 specimens was performed for the genera *Helicosphaera* and *Discoaster*. Finally, as for the very rare *Amaurolithus* group, frequencies were estimated by counting the number of specimens encountered in 1000 fields of view at 1250 $\times$  magnification (22.22 mm<sup>2</sup>). Results were converted to numbers/mm<sup>2</sup> according to the methodology illustrated in Baumann et al. (1998). This methodology allows a better assessment of variations in the absolute abundances of the coccoliths. Baumann et al. (1998) showed that all major abundance patterns are reproducible using coccoliths/mm<sup>2</sup> instead of percentages, although there can be some differences in the absolute sizes of the individual abundance peaks. A taxonomic reference list for calcareous nannoplankton is given in Appendix B.

## 3. Results: general distribution patterns

The preservation of the planktonic foraminifera assemblage is variable in the Pissouri section. In the lower part of the section, below about 33.40 m (Tortonian–early Messinian), the plankton community is abundant, well diversified and mainly consists of *Globigerina bulloides*, *Globigerinita glutinata*, and *Globigerinoides* spp., *Globoturborotalita decoraperta*, *Globoturborotalita nepenthes*, showing frequencies higher than 10%, with a maximum abundance of 50%. Keeled globorotaliids are present in low relative frequencies (maximum 4%) together with other taxa such as *Globorotalia scitula* (about 5%), *Orbulina universa* (with percentages of about 5–8%), *Neogloboquadrina acostaensis* (about 5%), and several species of *Globigerina* such as, *G. parabulloides*, and *G. obesa* (with percentages varying from 2 to 5%).

In the upper part of the section (33.40–0 m) the assemblage is moderately to poorly preserved and some samples show very scarce foraminifera or are altogether barren. Diversity is low, and in some levels only one species occurs. Several taxa disappear, such as the globorotaliids and *G. nepenthes*. Other taxa, such as *Turborotalita quinqueloba* and *Turborotalita multiloba*, occur scattered but reach extremely high frequencies

(up to 100%) in some samples. Finally, other species are discontinuously distributed although they show high percentages in some levels (*G. bulloides* up to 100% in the top of the section, *G. glutinata* and *N. acostaensis* up to 60%, *O. universa* up to 40% (see also Kouwenhoven et al., 2006).

Calcareous nannofossils are poorly to moderately preserved throughout the Pissouri section. Many specimens show etching or overgrowth that affects their outline, but do not hamper identification of the small forms. Their diversity is generally low to moderate and the abundance pattern records an important decrease between 27.90 and 11.10 m.

The analysis shows an older part of the section where the assemblage is relatively well diversified and consists of *Coccolithus pelagicus*, *Calcidiscus leptoporus*, “normal sized” *Reticulofenestra* (including *R. haqii* Backman, 1978, *Reticulofenestra* sp. 3–5  $\mu\text{m}$ , *R. pseudoumbilicus* >7  $\mu\text{m}$  and *Reticulofenestra* sp. 5–7  $\mu\text{m}$ ), “small” *Reticulofenestra*, *Syracosphaera pulchra*, *Rhabdosphaera clavigera*, *Thoracosphaera* spp., *Sphenolithus abies*, *Helicosphaera carteri*, and *Umbilicosphaera* spp. Subordinated and in some cases spot-wise occurrences are recorded for *Helicosphaera stalis*, *Helicosphaera orientalis*, *Helicosphaera sellii*, *Reticulofenestra rotaria*, *Geminilitella rotula*, *Amaurolithus delicatus*, *Amaurolithus primus*, *Nicklithus amplificus* and the genus *Discoaster*. These taxa are continuously recorded although they show fluctuating values of abundance until 34.50 m. Above this level we recognize a succession of events: “normal sized” *Reticulofenestrae* strongly decrease at 34.50 m, *C. pelagicus* abruptly disappears at 33.15 m, *R. clavigera* also shows a strong decrease in abundance at 21.15 m. Slightly below this level, at 27.90 m *C. leptoporus* shows a spike in abundance. This development of the nannofossil assemblage culminates at 20 m with the almost complete collapse of the assemblage. From 20 to 5.40 m the calcareous nannofossil assemblage is poorly preserved and very scarce. However, at 5.40 m we observe a re-entry of several species such as the “normal sized” *Reticulofenestrae*, *R. clavigera* and *H. carteri* and, some samples (i.e. sample PIS 3, 2.45 m) show a monospecific assemblage consisting almost completely of *Sphenolithus abies*.

#### 4. Biostratigraphy and comparisons with other Mediterranean sections

A number of calcareous plankton bioevents are by now well established for the late Tortonian and early Messinian of the Mediterranean area. Planktonic foraminifera bioevents, that were found to be synchronous throughout the Mediterranean (e.g. Hilgen et al., 1995; Hilgen and Krijgsman, 1999; Sierro et al., 2001) were used as a first order age control for astronomical tuning of the Pissouri section (Krijgsman et al., 2002). These datum levels were based on qualitative assessment of the distribution of the foraminifera. Below we present data on quantitative counts of the planktonic foraminifera based on splits of ~200 specimens and compare these to the results obtained in the study by Krijgsman et al. (2002).

In addition, we evaluate the reliability of important bioevents based on calcareous nannoplankton distribution. Ongoing research reveals several well-established datum levels, but uncertainty and discussion about several others (Flores et al., 1992; Negri et al., 1999; Negri and Villa, 2000; Raffi et al., 2003).

##### 4.1. Planktonic foraminifera

The quantitative distribution pattern of the most representative planktonic foraminifera taxa in the Pissouri section is represented in Fig. 2 and the ages of the first, first common, first regular, last common, and last occurrences (FO, FCO, FRO, LCO, LO) based on the quantitative counts are shown in Table 1. A comparison of the bioevents in the Pissouri section with those reported in other land-based sections of the Mediterranean (Monte del Casino, Falconara, Metochia and Faneromeni section) is reported in Table 2. Astrochronology provides a useful tool to date marine sections level by level in the entire Mediterranean area (e.g. Hilgen et al., 1995; Hilgen and Krijgsman, 1999; Sierro et al., 2001). Krijgsman et al. (2002), started from ten planktonic foraminifera bioevents as first-order age control, in order to correlate the Pissouri Motorway Section with the insolation curve, obtaining ages for every sedimentary cycle of the section. In the following, distribution patterns of the main biostratigraphic marker species are discussed in more detail

Table 1  
Stratigraphic position, astronomical age of the planktonic foraminiferal events in the Pissouri Motorway Section  
Tableau 1  
Distribution stratigraphique et âge astronomique des foraminifères planctoniques de la coupe Pissouri

Planktonic Foraminiferal event	Pissouri section			
	Sample	Level (m)	Age (Ma)	Chron
Influx (>40%) of sinistral Neogloboquadriniids	37	15.60	6.199	C3An.1n
Sinistral/dextral coiling change of <i>N. acostaensis</i>	57	23.50	6.342	C3An.1r
LO <i>G. miotumida</i> group	91	34.10	6.713	C3Ar
LO <i>G. nicolae</i>	92	34.70	6.760	C3Ar
FO <i>G. nicolae</i>	99	35.40	6.814	C3Ar
LO <i>G. menardii</i> 5 (dx)	117	37.80	7.016	C3Ar
FCO <i>G. miotumida</i> group	140	41.45	7.244	C3Br.1r
LO <i>G. menardii</i> 4 (sin)	153	43.40	7.343	C3Br.2r
LCO dominantly sinistral <i>G. scitula</i>	153	43.40	7.343	C3Br.2r
FO <i>G. menardii</i> 5 (dx)	163	45.20	7.419	C3Br.2r
LO <i>C. parvulus</i>	168	46.25	7.456	C3Br.2r



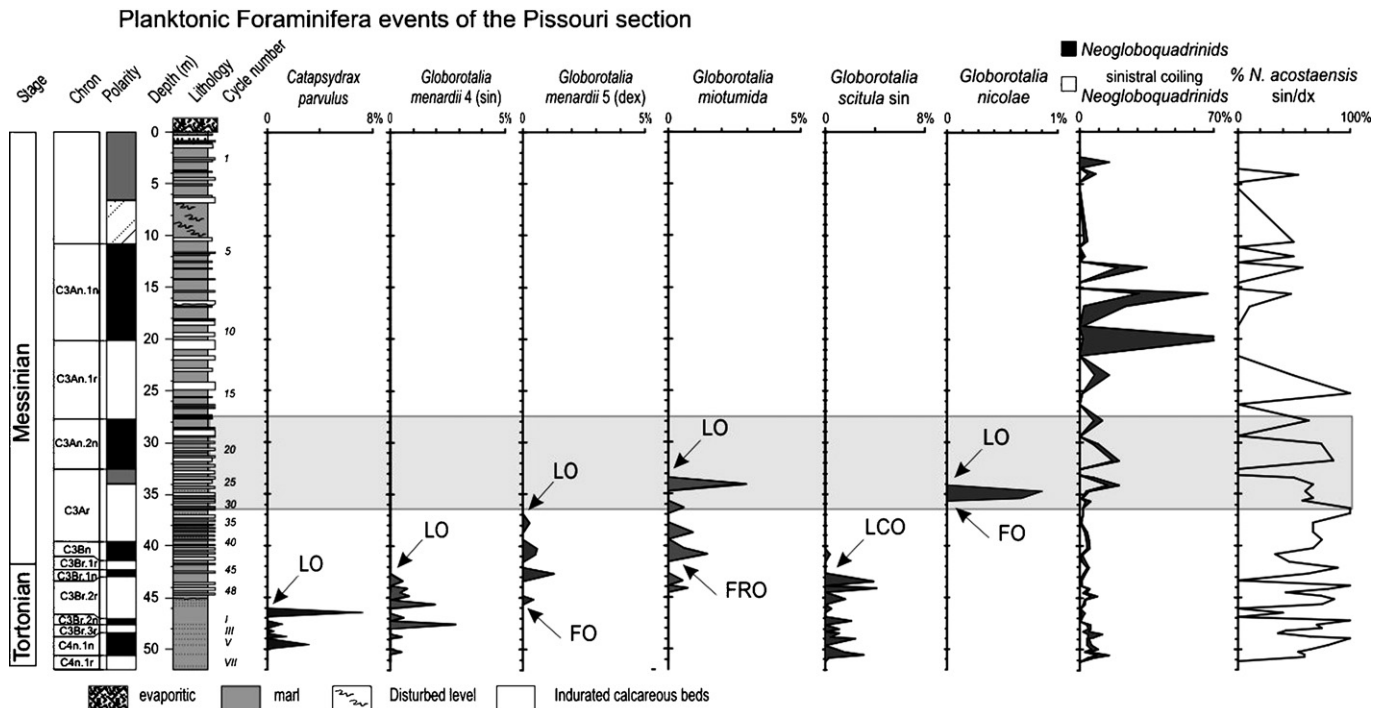


Fig. 2. Quantitative distribution pattern of planktonic foraminiferal marker species (as percentage of the total planktonic foraminiferal fauna) and *N. acostaensis* sin/dx coiling change. The following acronyms indicate bioevents: FO (First Occurrence); LO (Last Occurrence); FCO (First Common Occurrence); LCO (Last Common Occurrence). Please note differences in scaling. Magnetostratigraphy, cyclostratigraphy and simplified lithology, is taken from Krijgsman et al. (2002). The grey shaded area indicates the interval where cyclicity is not well resolved. For more details see text and Krijgsman et al. (2002) and Kouwenhoven et al. (2006).

Fig. 2. Fréquences relatives (pourcentage du total des foraminifères planctoniques) des principales espèces de foraminifères planctoniques dans la coupe de Pissouri et variations des formes sénestres/dextres de *Neogloboquadrina acostaensis*; FO (apparition), LO (dernière présence), FCO (première présence commune), LCO (dernière présence commune). Magnétostratigraphie, cyclostratigraphie et colonne lithostratigraphique simplifiée d'après Krijgsman et al. (2002). L'intervalle gris indique la zone où la cyclicité n'est pas très précise. Pour plus de précisions sur la lithologie voir Krijgsman et al. (2002) et Kouwenhoven et al. (2006).

in stratigraphic order. We will discuss differences with the previous study of Krijgsman et al. (2002) in the light of sample coverage and methodology (qualitative versus quantitative analysis).

#### 4.1.1. *Catapsydrax parvulus* LO

For this species we adopted the concept utilised by several authors (Zachariasse, 1992; Krijgsman et al., 1995; Foresi et al., 2001, 2002) who consider *Globorotaloides falconarae* as a junior synonym of *Catapsydrax parvulus*. *C. parvulus* occurs from the base of the studied interval and is characterized by a rather low abundance, never exceeding 6% of the assemblage. At 46.50 m this species shows the LO, astronomically dated at 7.456 Ma (Table 1). In the Metochia section, the *C. parvulus* LO is dated at 7.446–7.466 Ma (Hilgen et al., 1995), while at Monte del Casino section the same event is dated at 7.440–7.446 Ma (Krijgsman et al., 1997). In all three sections the *C. parvulus* LO is present within Chron C3Br.2r, confirming the reproducibility of the bioevent in the Mediterranean.

#### 4.1.2. *Globorotalia menardii* group FO and LO

The taxonomic distinction of *Globorotalia menardii* forms 4 and 5 of Tjalsma (1971), equivalent to *G. menardii* group I and II of Sierro et al. (1993) is based on the predominantly dextral coiling of *G. menardii* 5 and prevalent sinistral coiling of *G. menardii* 4.

The *G. menardii* group occurs in low abundances in the section, not exceeding 2.5–3%. *G. menardii* 4 is present from the base of the studied interval, showing abundances of about 2–3% that decreases until its disappearance at 43.40 m. Krijgsman et al. (2002) observed the LCO of this species slightly above dark layer PC II, at about 48 m and assigned an age of 7.504–7.509 Ma (Krijgsman et al., 1997) and in other two sections, Faneromeni and Metochia, this event is dated at 7.511–7.519 and at 7.507–7.512 Ma, respectively (Hilgen et al., 1995). Due to the low abundance of this species, the LCO is difficult to detect whereas the LO of *G. menardii* 4 in the Pissouri section is observed at 7.343 Ma.

*G. menardii* 5 shows low (less than 2%) and scattered occurrences from 45.20 to 37.80 m. The ages of the FO and LO of *G. menardii* 5 are 7.419 and 7.016 Ma, respectively. Krijgsman et al. (2002) found the FO of *G. menardii* 5 higher in the stratigraphic section (43.90 m); this difference could be due to the different methodology used to analyse the planktonic foraminifera and to the low abundances of keeled Globorotaliids in the assemblage. In fact the analysis of one split, although containing at least 200 specimens is perhaps not sufficient to detect the presence of rare species, as is the case for *G. menardii* in the Pissouri section. The FO of this species, located in Chron C3Br.2r is reported at the astronomically derived ages of

Table 2  
Comparison of calcareous plankton biochronology in the Eastern Mediterranean area for the Late Miocene  
Tableau 2

Comparaison des distributions stratigraphiques du plancton calcaire dans le Miocène supérieur de différentes coupes de la Méditerranée orientale

Pissouri Motorway section	Faneromeni					Metochia			Falconara			Monte del Casino		
	Age (Ma)	Chron	Age (Ma)	Chron	REF	Age (Ma)	Chron	REF	Age (Ma)	Chron	REF	Age (Ma)	Chron	REF
Second influx of sinistral Neogloboquadrinids	C3An.1n								6.087		V			
First influx of sinistral Neogloboquadrinids	6.199	C3An.1n							6.126		V			
LO <i>R. rotaria</i>	6.275	C3An.1r				5.999		X				6.760–6.771	C3Ar	VI
FO <i>N. amplificus</i>	6.275	C3An.1r				6.141		X						
Sinistral/dextral coiling change of <i>N. acostaensis</i>	6.342	C3An.1r							6.337/6.34		V/IX			
FCO <i>H. sellii</i>	6.526	C3An.2n	7.049–7.053	C3Ar	VIII	6.478		X				6.964–6.968	C3Ar	VI
LO <i>G. miotumida</i> group	6.713	C3Ar							6.506/6.51		V/IX			
LO <i>G. nicolae</i>	6.760	C3Ar							6.722		IX			
FO <i>G. nicolae</i>	6.814	C3Ar	6.822–6.831	C3Ar	I	6.826–6.831		I	6.82		IX	6.822–6.832		IV
LO <i>G. menardii</i> 5 (dx)	7.016	C3Ar	7.110–7.128		II									
FO <i>A. delicatus</i>	7.197	C3Bn	7.249–7.250	C3Br.1r	VIII	7.134	C3Bn	X				7.218–7.226	?	VI
FRO <i>G. miotumida</i> group	7.244	C3Br.1r	7.243–7.246	C3Br.1r	VII	7.244–7.247	C3Br.1r	VII				7.236–7.241		IV
LCO <i>H. orientalis</i>	7.283	C3Br.1n	7.075–7.078	C3Ar	VIII							7.226–7.233		VI
FCO <i>R. rotaria</i>	7.302	C3Br.1n	7.262–7.267	C3Br.1n	VIII							7.218–7.226	?	VI
LO <i>G. menardii</i> 4 (sin)	7.343	C3Br.2r										7.289		IV
Sinistral/dextral coiling change <i>G. scitula</i>	7.343	C3Br.2r				7.283–7.29		VII				7.305–7.311		VII
FO <i>G. menardii</i> 5 (dx)	7.419	C3Br.2r	7.353–7.359	C3Br.2r	I	7.353–7.356	C3Br.2r	I				7.367–7.371		IV
FO <i>R. rotaria</i>	7.435	C3Br.2r	7.419–7.423	C3Br.2r	VIII	7.4	C4Br.2r	X				7.398–7.405	C3Br.2r	VI
FO <i>A. primus</i>	7.449	C3Br.2r	7.429–7.432	C3Br.2r	VIII	7.423	C4Br.2r	X				7.440–7.446	C3Br.2r	VI
LO <i>C. parvulus</i>	7.456	C3Br.2n				7.446–7.466	C3Br.2r	I				7.440–7.446	C3Br.2r	IV
LCO <i>G. menardii</i> 4 (sin)			7.511–7.519		I	7.507–7.512		I				7.504–7.509		IV

(I) Hilgen et al. (1995), (II) Calieri (1996), (III) Sprovieri et al. (1996), (IV) Krijgsman et al. (1997), (V) Hilgen and Krijgsman (1999), (VI) Negri et al. (1999), (VII) Hilgen et al. (2000a), (VIII) Negri and Villa (2000), (IX) Blanc-Valleron et al. (2002), (X) Raffi et al. (2003).

7.353–7.359 Ma at Faneromeni (Hilgen et al., 1995), 7.353–7.356 Ma in the Metochia section (Hilgen et al., 1995), whereas in the Monte del Casino section the FO is dated slightly earlier at 7.367–7.371 Ma (Krijgsman et al., 1997). A LO of *G. menardii* 5 is only reported in the Faneromeni section by Calieri (1996) with an age of 7.110–7.128 Ma. In the Sorbas Basin, Western Mediterranean, the same bioevent is dated at 7.26 Ma (Sierro et al., 2001) and appears to be diachronous, possibly influenced by local hydrographic conditions.

#### 4.1.3. *Globorotalia miotumida* group FRO and LO

The *G. miotumida* group (earlier also referred to as *G. conomiozea* gr.) comprises those globorotaliids showing a planoconvex axial outline, crescent-shape chambers, an arched aperture and dominantly sinistral coiling (e.g. Sierro et al., 1993; Hilgen et al., 2000a). The *Globorotalia miotumida* group never exceeds 3% of the assemblage, and occurs discontinuously with rare specimens in the lower part of the section. From 41.45 m onward, it increases slightly in abundance but shows an oscillating distribution pattern and it disappears at 34.10 m. We located the FRO of the *G. miotumida* group at 41.45 m (7.244 Ma) whereas the LO was found at 34.10 m (6.713 Ma). The FRO of *G. miotumida* correlates throughout the whole Mediterranean Basin showing a high degree of reproducibility, and is commonly used as marker for the Tortonian–Messinian boundary. Instead, the reported LO and LRO of this species show some diachroneity: the LO at Falconara section was found at 6.506 Ma (Hilgen and Krijgsman, 1999) and at 6.51 Ma by Blanc-Valleron et al. (2002), the LRO in the Sorbas Basin at 6.504 Ma (Sierro et al., 2001) but in the Ain el Beida section in the age range of 6.308–6.311 Ma (Krijgsman et al., 2004). According to Sierro et al. (1993) the *G. miotumida* group was confined to the Northern part of the Atlantic Ocean during the Tortonian, and southward migration of this species allowed it to enter in the Mediterranean Sea at the Tortonian–Messinian boundary. This could explain why in the Western Mediterranean (Sorbas Basin) this species accounts for 20–30% of the planktonic foraminifera assemblage (Sierro et al., 2003), which is one order of magnitude larger than in the Pissouri section, and suggests that the easternmost Mediterranean palaeoceanographic conditions were not optimal for the development of this taxon. The low abundance holds a risk that its presence is missed when standard analyses are performed on low numbers of specimens. This could explain the early disappearance of the *G. miotumida* group from the Pissouri section.

#### 4.1.4. *Globorotalia scitula* (sinistral) LCO

*Globorotalia scitula* occurs in frequencies never exceeding 5% of the total assemblage from the base of the studied interval up to 38.70 m, and from 43.40 m to its disappearance we observe a further drop in abundance. The coiling direction of *G. scitula* is dominantly sinistral from the base of the investigated interval up to 43.40 m where it shows its LCO, that according to astrochronological tuning, dates at 7.343 Ma. This age is slightly older than those obtained in the section of Metochia (7.283–7.29 Ma, according to Hilgen et al., 1995) and Monte del Casino (7.305–7.311 Ma according to Krijgsman et al.,

1997). The age of 7.095 Ma determined by Krijgsman et al. (2002) that observed the LCO of sinistral coiling *G. scitula* slightly above in the section (38.9 m) and of Sierro et al. (2001) that also found an age of 7.095 for the LCO of *G. scitula* in the Sorbas Basin could concern a different coiling shift. Also in this case, as we already observed for other taxa, we can attribute this discrepancy to the different methodology. The quantitative analysis allows to obtain the distribution of the abundance of the taxa and to define a first LCO (see Fig. 2). In this case, counting procedure could help to distinguish decreasing in the abundance when taxa are not common in the assemblage.

#### 4.1.5. *Globorotalia nicolae* FO and LO

The occurrence of *G. nicolae* in the Pissouri section is restricted to a short stratigraphic interval, between 35.40 and 34.70 m. The FO and LO in the quantitative analysis are therefore astronomically dated at 6.814 and 6.760 Ma, a small discrepancy with Krijgsman et al. (2002), who found the FO at 6.829 and the LO at 6.722. The FO of *G. nicolae* has been reported in other sections to occur in the same time interval: Metochia: 6.829 (Hilgen et al., 1995); Falconara: 6.82 Ma (Blanc-Valleron et al., 2002); Monte del Casino: 6.827 Ma (Krijgsman et al., 1997); Faneromeni: 6.826 Ma (Hilgen et al., 1995). The LO of *G. nicolae* LO in the Falconara section was dated at 6.722 Ma by Hilgen and Krijgsman (1999), in agreement with Blanc-Valleron et al. (2002).

#### 4.1.6. Coiling change of the *Neogloboquadriniids*

Under this label, we included *N. acostaensis*, *N. humerosa*, and *Neogloboquadrina* four-chambered type and for each species we distinguished between sinistral and dextral coiling. *N. humerosa* and *Neogloboquadrina* four-chambered type show low abundances, whereas *N. acostaensis* is continuously present throughout the investigated stratigraphic interval, in some cases accounting for 65% of the assemblage. In the first part of the studied interval, sinistrally coiled *N. acostaensis* prevails up to 23.50 m (dated at 6.342 Ma), after this level dextrally coiled *N. acostaensis* increases in abundance and dominates the plankton community. At 15.60 m (6.199 Ma), an influx (>40%) of sinistral *Neogloboquadrinids* occurs. Krijgsman et al. (2002) observed the first bioevent at 6.337 Ma and the first influx (>80%) of sinistral *Neogloboquadrinids* at 6.126 Ma. The sinistral/dextral coiling change direction of *Neogloboquadriniids* is reported in several sites of the Mediterranean area: Falconara: 6.337 Ma (Hilgen and Krijgsman, 1999) and at 6.34 Ma (Blanc-Valleron et al., 2002); Sorbas Basin: 6.360 Ma (Sierro et al., 2001); Ain el Beida: 6.380–6.375 Ma (Krijgsman et al., 2004). The age of the first influx (>80%) of sinistral coiling specimens is reported for Falconara section at 6.126 Ma (Hilgen and Krijgsman, 1999) and Sorbas Basin: 6.125 Ma (Sierro et al., 2001) and the age of the second influx (>40%) of sinistral *Neogloboquadrinids* at 6.087 Ma is reported only for the Falconara section (6.087 Ma, Hilgen and Krijgsman, 1999) (see Table 2). The discrepancy between ages suggests that local environmental factors could influence at least the first and the second influx of sinistral

## Calcareous Nannofossil events of the Pissouri section

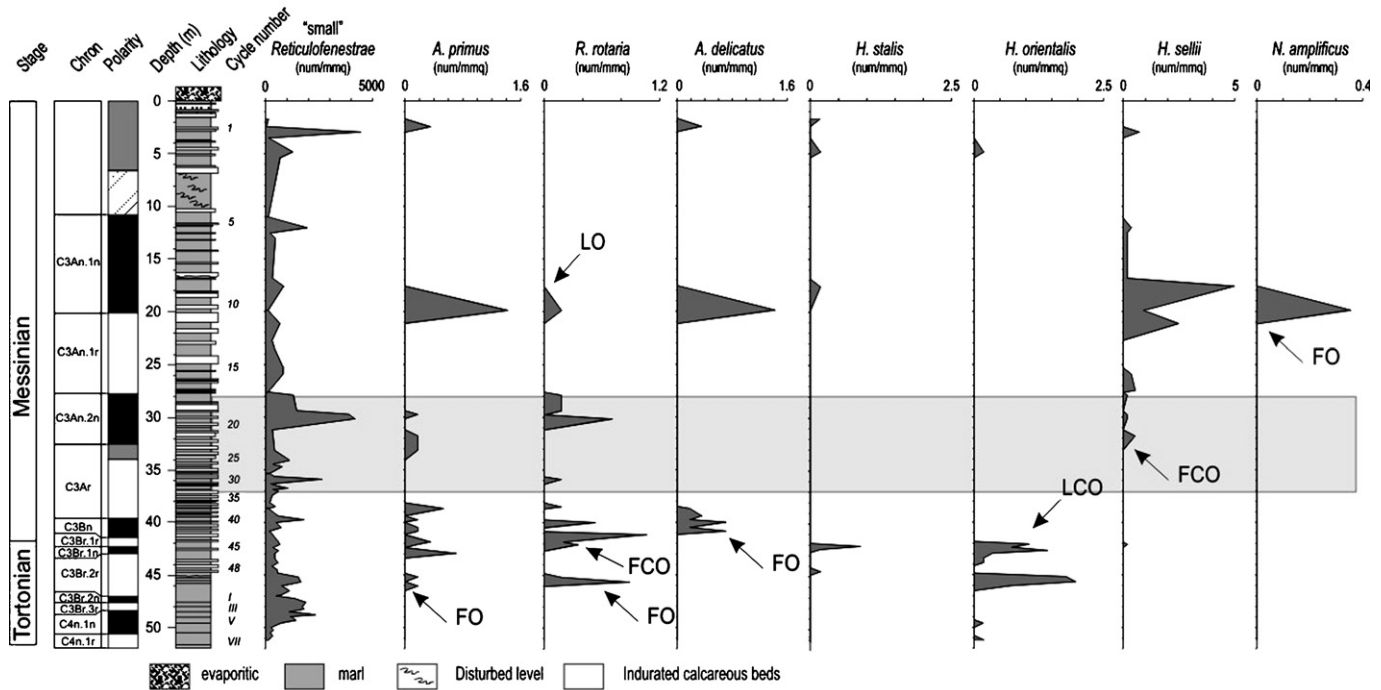


Fig. 3. Quantitative distribution pattern of calcareous nannoplankton marker species (as number of specimens per  $\text{mm}^2$ ). The following acronyms indicate bioevents: FO (First Occurrence); LO (Last Occurrence); FCO (First Common Occurrence); LCO (Last Common Occurrence). Please note differences in scaling. Magnetostratigraphy, cyclostratigraphy and simplified lithology, is taken from Krijgsman et al. (2002). The grey shaded area indicates the interval where cyclicity is not well resolved. For more details see text and Krijgsman et al. (2002) and Kouwenhoven et al. (2006).

Fig. 3. Fréquence des nannofossiles calcaires (nombre de spécimens par  $\text{mm}^2$ ) dans la coupe de Pissouri ; FO (apparition), LO (dernière présence), FCO (première présence commune), LCO (dernière présence commune). Magnétostratigraphie, cyclostratigraphie et colonne lithostratigraphique simplifiée d'après Krijgsman et al. (2002). L'intervalle grisé indique la zone où la cyclicité n'est pas très précise. Pour plus de précisions sur la lithologie voir Krijgsman et al. (2002) et Kouwenhoven et al. (2006).

Neogloboquadrinids, causing a slight diachroneity. Modern Neogloboquadrinids live today in stratified waters, when the nutricline and the pycnocline are located above the base of the euphotic zone (Fairbanks and Wiebe, 1980; Rohling and Gieskes, 1989). They are indicative of cold-temperate waters, and the sinistral coiling *N. pachyderma*, that is the descendant of *N. acostaensis* (Sierra et al., 2003), in particular is present when winter water temperature is below  $8^\circ\text{C}$ , whereas dextral coiling *N. pachyderma* lives at higher temperature (Reynolds and Thunell, 1986). For this reason an increase in sinistral coiled Neogloboquadrinids could be related to environmental factors for example a cooling phase that not necessarily is synchronous in the entire basin or could not have the same intensity in the western and eastern part.

#### 4.2. Calcareous nannofossils

In the following section we will discuss those biostratigraphic calcareous nannofossil events (Fig. 3 and Table 3) that appear to be useful to improve the biostratigraphic resolution of the time interval straddling the Tortonian–Messinian boundary up to the evaporites. In particular we will compare these events to the existing quantitative studies performed in recent years in the Central and Eastern Mediterranean by Negri et al. (1999), Negri and Villa (2000), Raffi et al. (2003) in which ages of bioevents are astronomically calibrated (Table 2).

##### 4.2.1. Acme of “small” Reticulofenestrids

Abundance variation of reticulofenestrids of very small size (with the long axis  $<3\ \mu\text{m}$ ) has been used as a marker in the Tortonian–Messinian biostratigraphy by several authors (Flores et al., 1992; Negri et al., 1999; Negri and Villa, 2000). Although this abundance pattern is probably driven by local changes in the palaeoceanography it has to be explored since on a local scale (i.e. Mediterranean) and has a potential ecostratigraphic value. Negri et al. (1999), in the Monte del Casino section made

Table 3

Stratigraphic position and astronomical ages of calcareous nannoplankton events in the Pissouri Motorway section

Tableau 3

Distribution stratigraphique et âge astronomique des nannofossiles calcaires de la coupe Pissouri

Calcareous nannoplankton event	Pissouri section			
	Sample	Level (m)	Age (Ma)	Chron
LO <i>R. rotaria</i>	49	19.90	6.275	C3An.1r
FO <i>N. amplificus</i>	49	19.90	6.275	C3An.1r
FCO <i>H. sellii</i>	81	31.80	6.526	C3An.2n
FO <i>A. delicatus</i>	137	40.85	7.197	C3Bn
LCO <i>H. orientalis</i>	145	42.10	7.283	C3Br.1n
FCO <i>R. rotaria</i>	147	42.40	7.302	C3Br.1n
FO <i>R. rotaria</i>	165	45.65	7.435	C3Br.2r
FO <i>A. primus</i>	167	46.05	7.449	C3Br.2r



a first attempt to use the beginning and end of this acme as a biostratigraphic event. The methodology adopted by Negri et al. (1999) was criticized by Raffi et al. (2003), who emphasized the fact that the proposed methodology lacked any statistical values since it considered the abundance of the species in a single field of view. Considering that a single field of view in the acme of small *Reticulofenestra* shows more than 200 specimens, we think that this method clearly indicates the acme occurrence. With this method, the event has been clearly recognized in the Monte del Casino section (Negri et al., 1999), and also the Faneromeni shows very high abundances of “small sized” *Reticulofenestra* from the very base of the section (Negri and Villa, 2000) even though one order of magnitude lower than in Monte del Casino (2000 versus 20,000 specimens/mm<sup>2</sup>), suggesting that this section spans the interval bracketed by the beginning and the end of the acme occurrence of “small sized” *Reticulofenestra*. In the Metochia section (Raffi et al., 2003) did not quantitatively evaluate the abundance of “small sized” *Reticulofenestra* yielding a semi quantitative data that evidenced abundant “small sized” *Reticulofenestra* occurring in the higher portion of the section below cycle M69 at an age of approximately 7.6 Ma. In the Pissouri section “small sized” *Reticulofenestra* are not strikingly abundant (see Fig. 3 in Kouwenhoven et al., 2006) reaching occasionally 4–5000 specimens/mm<sup>2</sup>, but show high fluctuations that does not permit to clearly assess the occurrence of the “small sized” *Reticulofenestra* acme. All these data then indicate that lower abundances of this group occur in the easternmost sections, and therefore the “small sized” *Reticulofenestra* acme interval has to be considered carefully although it likely has a potential for (eco-) stratigraphic correlations.

#### 4.2.2. *Amaurolithus primus* FO

The appearance of the genus *Amaurolithus* in the Late Miocene is an evolutionary event recognized at the global scale and used in the Okada and Bukry (1980) standard biozonal scheme to subdivide the zone CN9 straddling the Tortonian–Messinian boundary. In the Mediterranean area, this genus is very rare but consistently recorded in the Western Mediterranean (Flores et al., 1992) and Moroccan (Hilgen et al., 2000a; Krijgsman et al., 2004) sections. In the Pissouri section, the FO of *Amaurolithus primus* is located at 46.05 m with an astronomically derived age of 7.449 Ma. In the Faneromeni section, the *A. primus* FO is observed in Chron C3Br.2r, in sapropel F8 at 17.25 m with a detailed astronomically derived age of 7.432–7.429 Ma (Negri et al., 1999). In the Monte del Casino section, the *A. primus* FO is also located in Chron C3Br.2r, with an astronomically derived age estimate of 7.443 Ma (Krijgsman et al., 1997). In the Metochia section, Raffi et al. (2003) assigned an age of 7.423 Ma to this event. These data confirm the reliability of the event for the central and Eastern Mediterranean area.

#### 4.2.3. *Amaurolithus aff. amplificus* FO

In previous papers by Krijgsman et al. (1997) and Negri et al. (1999) the occurrence of this form has been reported in the same stratigraphic interval as *Amaurolithus cf. amplificus*. The taxonomy of the *Amaurolithus cf. amplificus* is ambiguous and

it probably corresponds to a morphotype of *A. primus*, although the event, discussed by Negri et al. (1999), was also recorded at Faneromeni (Negri and Villa, 2000 - *Amaurolithus aff. A. amplificus*) at a slightly different position. In the Pissouri section, we were not able to find specimens unambiguously to be referred to as *A. aff. A. amplificus* and, after a careful taxonomic analysis, we agree with Raffi et al. (2003) and consider the specimens recorded in the previously mentioned sections probably belonging to *A. primus*. Consequently we will not consider this event any further.

#### 4.2.4. *Reticulofenestra rotaria* FO, FCO and LO

In the present study, the FO of *R. rotaria* is observed at 45.65 m slightly above the FO of *A. primus*. After this FO, *R. rotaria* is not continuously detected until the FCO, which is located higher in the section at 42.40 m, slightly after the *A. delicatus* FO, in Chron C3Br.1n. The astronomically derived ages for these two bioevents are 7.435 Ma for the FO and 7.302 Ma for the FCO, respectively. Just as in other studied sections, Monte del Casino (Negri et al., 1999) and Faneromeni (Negri and Villa, 2000), the *R. rotaria* FO (respectively with an age of 7.401 and 7.421 Ma) is followed by a prolonged interval in which the species was not detected. In these sections, the astronomically derived age of the *R. rotaria* FCO is 7.222 for the Monte del Casino and 7.264 Ma for Faneromeni sections, respectively. In the Metochia section (Raffi et al., 2003), the authors report the FO of this species at 7.4 Ma but no indication is given for the age of the FCO. In the Oued Akrech section (Morocco, Hilgen et al., 2000a), the FO is astronomically dated in the age range of 7.458–7.466 Ma and the FCO in the age range of 7.276–7.279 Ma. Comparisons with the other sections indicate that the FO and FCO of *R. rotaria* represent a reproducible secondary event useful for the biostratigraphy of the latest Tortonian interval. We detected the LO of *R. rotaria* at 19.9 m (6.275 Ma). Other authors report the event at different ages. Negri et al. (1999) report an age of 6.766 Ma at Monte del Casino and Raffi et al. (2003) record *R. rotaria* LO at 5.999 Ma in the Metochia section. In the Ain el Beida section (Western Morocco, Krijgsman et al., 2004), the event is astronomically dated in the age range of 6.435–6.431 or 6.434–6.430 Ma (depending on the astronomical solution chosen). This evidence suggests that, contrary to the FO and FCO, the LO of *R. rotaria* LO is a highly diachronous event.

#### 4.2.5. *Amaurolithus delicatus* FO

The present study locates the *A. delicatus* FO at 40.9 m with an interpolated astronomical age of 7.197 Ma. In Faneromeni section, the event was dated at 7.249–7.250 Ma (Negri and Villa, 2000) and at Monte del Casino, the *A. delicatus* FO was dated at 7.218–7.226 Ma (Negri et al., 1999). At Gavdos (the Metochia section) Raffi et al. (2003) date the *A. delicatus* FO at 7.134 Ma. Hilgen et al. (2000a) found the FO of *A. delicatus* in the astronomically derived age range of 7.260–7.262 Ma. These data point to a good reliability of this bioevent, even though we observe a slight diachroneity (less than 0.1 Ma between the youngest and the oldest age obtained). Only Raffi et al. (2003) data seems to be in contrast with our data and since in that paper is

not clear if the methodology used to detect this bioevent is the same adopted for the study presented here, therefore we suggest that this difference can be due to different analytical methods. In addition, the Pissouri section study points once again that the *A. delicatus* FO indeed is the closest event to the *G. miotumida* FO and represents a good approximation for the T/M boundary as previously postulated by other authors (Mazzei, 1977; Salvatorini and Cita, 1979; Flores et al., 1992; Cosentino et al., 1997).

#### 4.2.6. *Helicosphaera stalis* LCO

In our record, the occurrence of *H. stalis* is scarce and discontinuous: it has been recorded only in six samples. It is thus not possible to report a LCO. The diachroneity of the event was already suggested by Negri et al. (1999), Negri and Villa (2000) and Raffi et al. (2003). The present paper confirms that this event is not reliable for biostratigraphic purposes.

#### 4.2.7. *Helicosphaera orientalis* LCO

In our record, the LCO of *H. orientalis* could be tentatively located at 42 m, however the scattered occurrence of this species suggests that this datum is biased and unreliable. Previous findings also show diachrony for this event that appears to be unreliable for stratigraphic correlations (Negri and Villa, 2000).

#### 4.2.8. *Helicosphaera sellii* FCO

*Helicosphaera sellii* occurs at 42.10 m but its distribution only becomes continuous at a higher level (31.80 m) where we tentatively place the *H. sellii* FCO. The astronomical age of the FCO of *H. sellii* is thus 6.526 Ma and differs from the FCO's found in the Monte del Casino and Faneromeni sections that are dated at 7.051 and 6.966 Ma, respectively (Negri et al., 1999; Negri and Villa, 2000). These data confirm that the species, although it shows a diachronous FO, occurs in Mediterranean sediments since the Late Miocene. Raffi et al. (2003) do not consider the Late Miocene specimens observed in the Metochia section as belonging to *H. sellii*. They base their observation on the difference in total length and opening length and exclude the intraspecific variability that characterizes many coccolithophorid species. However, we do not agree with this species definition and thus we infer that the Pliocene FO of this species, currently adopted to define the Lower Pliocene MNN 12/MNN 13 in the zonation of Rio et al. (1990), likely corresponds to a re-entry of a morphotype of this species after the end of the Mediterranean Messinian Salinity Crisis.

#### 4.2.9. *Nicklithus amplificus* FO

This is a species rarely occurring in the Mediterranean area, Sprovieri et al. (1996) tentatively correlated the FO of this species to Chron C3An.2n. Raffi et al. (2003) located this bioevent at the cycle D2 of the Metochia section with an interpolate age of 6.690 Ma. Comparing this result to La Sardella, Raffi et al. (2003) report that in this section the species distribution shows a similar trend and also a comparable stratigraphic position of the FO and LO position. Based on these findings, the authors define the *N. amplificus* FO as a reliable and synchronous datum since they only find a

diachrony of about 0.1 Ma with extra-Mediterranean sections (ODP site 927, Ceara Rise, Atlantic Ocean, Backman and Raffi, 1997). In the Monte del Casino and Faneromeni sections, Negri et al. (1999) and Negri and Villa (2000) observed some forms similar to *Nicklithus* but characterized by smaller size, that probably belong to morphotypes of *A. primus*. No specimens were clearly defined as *N. amplificus*. Therefore, Negri et al. (1999), and Negri and Villa (2000) did not recognize the *N. amplificus* FO. In the Pissouri section, this species occurred in only one sample at 6.275 Ma (19.90 m), indicating that this event is neither easily recognizable nor synchronous as suggested by Raffi et al. (2003).

## 5. Concluding remarks

Most of the planktonic foraminifera events discussed here have been found earlier to occur synchronously throughout the basin (e.g. Krijgsman et al., 1999). Despite the sometimes rather large differences in relative abundance between different sub-basins, as is for instance illustrated by the percentages of the *G. miotumida* group that differ an order of magnitude between the Western Mediterranean Sorbas Basin and the Eastern Mediterranean Pissouri Basin, most bioevents can be reliably traced.

The quantitative analyses of the calcareous nannofossils in the Pissouri section confirm the usefulness for biostratigraphic purposes of several bioevents, and confirm that several others are not reliable. The *Amaurolithus primus* FO and *Amaurolithus delicatus* FO are reliable bioevents, even though a slight diachroneity is observed for the latter event. The *Reticulofenestra rotaria* FO and FCO are well reproducible secondary events, refining the biostratigraphy of the latest Tortonian in the Mediterranean area. In addition, the data confirm earlier findings that the *Helicosphaera stalis* LCO, *H. orientalis* LCO and *Nicklithus amplificus* FO are diachronous events. Some uncertainty remains about other taxa, such as the FCO of *H. sellii*, and the potential ecostratigraphic value of small reticulofenestrids.

Integrated biostratigraphy, combining data of planktonic foraminifera with those of calcareous nannofossils, enables construction of a solid biostratigraphic framework, as first order age control and as basis for highly detailed correlations throughout the basin. Integrated biostratigraphy permits to improve the resolution across the studied interval, where in particular an important role is played by the genus *Amaurolithus*: as previously reported (Colalongo et al., 1979; Rakic-El Bied and Benson, 1996; Hilgen et al., 2000b), also in this study we recognise the *A. delicatus* FO as the closest event to the *G. miotumida* datum.

However, we need to be aware of several potential sources of bias. This study also indicates that in some cases it can be difficult to trace events such as last common occurrences (LCO's) when abundances are very low, as is the case for several planktonic foraminifera taxa in the Pissouri section. In addition, poor preservation can be a potential source of bias, especially if it leads to a lower sample density than is desirable. Another potential source of error is the ecological response of

taxa to changing environments. Although the most important bioevents are often enough encountered to be of great value, the dependence of organisms on ecological parameters has been sufficiently illustrated. For instance, it has been shown that calcareous plankton abundance and presence can fluctuate on a precessional scale (e.g. Flores et al., 2003; Sierro et al., 2003). Moreover, Pérez-Folgado et al. (2003) showed that the lithological expression of precessional cyclicity differed between the Eastern and Western Mediterranean during the Messinian, and led to different successions of planktonic taxa within precessional cycles. Some considerations about the ecological aspects affecting the planktonic taxa in the Pissouri section were summarized in Kouwenhoven et al. (2006).

Finally, we need to spend a thought on methodology. This includes both counting procedures and taxonomy. In comparing our quantitative planktonic foraminifera data with the datums arrived at by Krijgsman et al. (2002), which were based on qualitative assessment of the same samples, we arrive at some minor discrepancies. Most likely this is caused by the numbers of specimens observed: the quantitative data were derived from splits of approximately 200 specimens, whereas the presence-absence data in Krijgsman et al. (2002) were derived from strews, which do not put a limit on the number of specimens observed. The amount of 200 specimens appears to be too low to recognize events such as LO's in a reliable way when the species are extremely rare. In contrast, the quantitative analyses provide objective data that are useful to support and to identify bioevents such as the FCO or LCO. These bioevents, a slight increase/decrease of species, detected by way of the observation of the residue, in particular in poorly preserved material and/or when the frequency of the species is low, could not be located in a reliable way.

With respect to taxonomy: as is illustrated by the FCO of *Helicosphaera sellii*, different taxonomic concepts, valid as they may be, may hamper the recognition of bioevents when the data are collected by scientists with a different view on certain aspects of taxonomy.

### Acknowledgements

This study was supported by Italian Ministry of University and Scientific and Technologic Research (MURST) (COFIN2003 to A. Negri). We want to thank A.M. Borsetti for her kindness and helpful suggestions. G. van't Veld and G. Ittmann of Utrecht University are thanked for processing the foraminifera samples. We appreciate the comments by two anonymous reviewers, which helped to improve an earlier version of the manuscript. We are particularly grateful to Jean-Pierre Suc for his support and encouragement.

### Appendix A: taxonomic list of the planktonic foraminifera counted in the Pissouri section.

The taxonomic concepts are those of Hemleben et al. (1989) and Iaccarino (1985) and those discussed in the text.

*Catapsydrax parvulus* Bolli, Loeblich and Tappan  
*Globigerina bulloides* d'Orbigny

*Globigerina obesa* (Bolli)  
*Globigerina parabulloides* Blow  
*Globigerina falconensis* Blow  
*Globigerinita glutinata* (Egger)  
*Globigerinoides bollii* Blow  
*Globigerinoides bulloideus* Crescenti  
*Globigerinoides obliquus* Bolli  
*Globigerinoides trilobus* (Reuss)  
*Globigerinoides quadrilobatus* (d'Orbigny)  
*Globorotalia menardii* form 5 Tjalsma  
*Globorotalia menardii* form 4 Tjalsma  
*Globorotalia nicolae* Catalano and Sprovieri  
*Globorotalia miotumida* Jenkins  
*Globorotalia scitula* group  
*Globorotalia suterae* Catalano and Sprovieri  
*Globorotalia ventriosa* Ogniben  
*Globoturborotalita decoraperta* (Takayanagi and Saito)  
*Globoturborotalita nepenthes* (Todd)  
*Globoturborotalita woodii* (Jenkins)  
*Neogloboquadrina acostaensis* (Blow)  
*Neogloboquadrina numerosa* (Takayanagi and Saito)  
*Neogloboquadrina* four-chambered type noted by Turco et al. (2001)  
*Orbulina bilobata* (d'Orbigny)  
*Orbulina suturalis* Brönnimann  
*Orbulina universa* d'Orbigny  
*Turborotalita multiloba* (Romeo)  
*Turborotalita quinqueloba* Natland

### Appendix B: taxonomic list of the calcareous nannoplankton counted in the Pissouri section.

Calcareous nannoplankton: taxa list and notes taxonomy in general follows that outlined in Perch-Nielsen (1985) and Young (1998).

*Amaurolithus delicatus* Gardtner and Bukry (1975)  
*Amaurolithus primus* Bukry and Percival (1971) Gardtner and Bukry (1975)  
*Calcidiscus leptoporus* (Murray and Blackman, 1898) Loeblich and Tappan (1978)  
*Coccolithus pelagicus* (Wallich, 1871) Schiller (1930)  
*Discoaster asymmetricus* Gartner (1969)  
*Discoaster brouweri* Tan (1927) emend. Bramlette and Riedel (1954)  
*Discoaster challengerii* Bramlette and Riedel (1954)  
*Discoaster icarus* Stradner (1973)  
*Discoaster loeblichii* Bukry (1971)  
*Discoaster intercalaris* Bukry (1971)  
*Discoaster pentaradiatus* Tan (1927) emend. Bramlette and Riedel (1954)  
*Discoaster tamalis* Kamptner (1967)  
*Discoaster variabilis* Martini and Bramlette (1963)  
*Helicosphaera carteri* (Wallich, 1877) Kamptner (1954)  
*Helicosphaera intermedia* Martini (1965)  
*Helicosphaera orientalis* Black (1971)  
*Helicosphaera sellii* (Bukry and Bramlette, 1969) Jafar and Martini, 1975



*Helicosphaera stalis* Theodoridis (1984)  
*Helicosphaera walbersdorfensis* Muller (1974)  
*Reticulofenestra* Hay et al., 1966. These are generally size-defined following the taxonomy outlined in Young (1998).  
*Reticulofenestra haqii* Backman, 1978/R. sp. 3–5  $\mu\text{m}$   
*Reticulofenestra minuta* Roth, 1970/R. sp. b3  $\mu\text{m}$  (small *Reticulofenestra*)  
*Reticulofenestra pseudoumbilicus* Gartner (1967, 1969). N7  $\mu\text{m}$   
*Reticulofenestra* sp. 5–7  $\mu\text{m}$ , noted by Backman and Shackleton (1983)  
*Reticulofenestra rotaria* Theodoridis (1984)  
*Rhabdosphaera clavigera* Murray and Blackman (1898)  
*Sphenolithus abies* Deflandre in Deflandre and Fert, 1954  
*Syracosphaera pulchra* Lohmann (1902)  
*Thoracosphaera* Kamptner (1927)

## References

- Backman, J., Raffi, I., 1997. Calibration of Miocene nanofossil events to orbitally tuned cyclostratigraphies from Ceara Rise. In: Curry, W.B., Shackleton, N.J., Richter, C. et al. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Results*, 154. pp. 83–99.
- Baumann, K.H., Andruleit, H.A., Xin, S., 1998. Comparison of different preparation techniques for quantitative nanofossil studies. *Journal of Nanoplankton Research* 20, 75–80.
- Béthoux, J.-P., Gentili, B., Morin, P., Nicolas, E., Pierre, C., Ruiz-Pino, D., 1999. The Mediterranean Sea: a miniature ocean for climatic and environmental studies and a key for the climatic functioning of the North Atlantic. *Progress in Oceanography* 44, 131–146.
- Blanc-Valleron, M.-M., Pierre, C., Caulet, J.-P., Caruso, A., Rouchy, J.-M., Cespuglio, G., Sprovieri, R., Pestrea, S., Di Stefano, E., 2002. Sedimentary, stable isotope and micropaleontological records of paleoceanographic change in the Messinian Tripoli Formation (Sicily, Italy). *Palaeogeography, Palaeoclimatology Palaeoecology* 185, 255–286.
- Calieri, R., 1996. Planktonic foraminiferal biostratigraphy and cyclostratigraphy of the Tortonian–Messinian boundary: preliminary results from the Faneromeni section (Crete). *Paleoelagos* 6, 329–338.
- Colalongo, M.L., Di Grande, A., D’Onofrio, S., Giannelli, L., Iaccarino, S., Mazzei, R., Poppi Brigatti, M.F., Romeo, M., Rossi, A., Salvatorini, G., 1979. A proposal for the Tortonian/Messinian boundary. *Annales Géologiques des Pays Helléniques, hors série* 1, 285–294.
- Cosentino, D., Carboni, M.G., Cipollari, P., Di Bella, L., Florindo, F., Laurenzi, M.A., Sagnotti, L., 1997. Integrated stratigraphy of the Tortonian/Messinian boundary: The Pietrasecca composite section (central Apennines Italy). *Eclogae Geologicae Helvetica* 90, 229–244.
- Fairbanks, R.G., Wiebe, P.H., 1980. Foraminifera and chlorophyll maximum: vertical distribution, seasonal succession, and paleoceanographic significance. *Science* 209, 1524–1526.
- Flores, J.A., Sierro, F.J., Glaçon, G., 1992. Calcareous plankton analysis in the pre-evaporitic sediments of the ODP Site 654 (Tyrrhenian Sea, Western Mediterranean). *Micropaleontology* 38, 279–288.
- Flores, J.A., Marino, M., Sierro, F.J., Hodell, D.A., Charles, C.D., 2003. Calcareous plankton dissolution pattern and coccolithophore assemblages during the last 600 kyr at ODP Site 1089 (Cape Basin, South Atlantic): paleoceanographic implications. *Palaeogeography, Palaeoclimatology, Palaeoecology* 196, 409–426.
- Foresi, L.M., Bonomo, S., Caruso, A., Di Stefano, A., Di Stefano, E., Iaccarino, S., Lirer, F., Mazzei, R., Salvatorini, G., Sprovieri, R., 2002. High resolution calcareous plankton biostratigraphy of the Serravaliano succession of the Tremiti Islands (Adriatic Sea, Italy). *Rivista Italiana di Paleontologia e Stratigrafia* 108, 257–273.
- Foresi, L.M., Iaccarino, S., Mazzei, R., Salvatorini, G., Bambini, A.M., 2001. Il plancton calcareo (Foraminiferi e nanofossili) del Miocene delle Isole Tremiti. *Paleontographia Italica* 88, 1–62.
- Hemleben, C., Spindler, M., Anderson, O.R., 1989. *Modern Planktonic Foraminifera*. Springer-Verlag, New York, 1–363.
- Hilgen, F.J., Bissoli, L., Iaccarino, S., Krijgsman, W., Meijer, R., Negri, A., Villa, G., 2000a. Integrated stratigraphy and astrochronology of the Messinian GSSP at Oued Akrech (Atlantic Morocco). *Earth and Planetary Science Letters* 182, 237–251.
- Hilgen, F.J., Iaccarino, S., Krijgsman, W., Langereis, C.G., Villa, G., Zachariasse, W.J., 2000b. The global boundary stratotype section and point (GSSP) of the Messinian Stage (uppermost Miocene). *Episodes* 23, 172–178.
- Hilgen, F.J., Krijgsman, W., 1999. Cyclostratigraphy and astrochronology of the Tripoli diatomite formation (pre-evaporite Messinian, Sicily Italy). *Terra Nova* 11, 16–22.
- Hilgen, F.J., Krijgsman, W., Langereis, C.G., Lourens, L.J., Santarelli, A., Zachariasse, W.J., 1995. Extending the astronomical (polarity) time scale into the Miocene. *Earth and Planetary Science Letters* 136, 495–510.
- Iaccarino, S., 1985. Mediterranean Miocene and Pliocene planktic foraminifera. In: Bolli, H.M., Saunders, J.B., Perch-Nielsen, K. (Eds.), *Plankton Stratigraphy*. Cambridge University Press, New York, pp. 283–314.
- Kouwenhoven, T., Morigi, C., Giunta, S., Negri, A., Krijgsman, W., Rouchy, J.-M., 2006. Unravelling Messinian marine environments in the Eastern Mediterranean (Pissouri Basin, Cyprus): Constraints from integrated microfossil data. *Marine Micropaleontology* 60, 17–44.
- Krijgsman, W., Blanc-Valleron, M.-M., Flecker, R., Hilgen, F.J., Kouwenhoven, T.J., Merle, D., Orszag-Sperber, F., Rouchy, J.-M., 2002. The onset of the Messinian salinity crisis in the Eastern Mediterranean (Pissouri Basin, Cyprus). *Earth and Planetary Science Letters* 194, 299–310.
- Krijgsman, W., Gaboridi, S., Hilgen, F.J., Iaccarino, E., de Kaenel, S., Van der Laan, E., 2004. Revised astrochronology for the Ain el Beida section (Atlantic Morocco): No glacio-eustatic control for the onset of the Messinian Salinity Crisis. *Stratigraphy* 1, 87–101.
- Krijgsman, W., Hilgen, F.J., Langereis, C.G., Santarelli, A., Zachariasse, W.J., 1995. Late Miocene magnetostratigraphy, biostratigraphy and cyclostratigraphy in the Mediterranean. *Earth and Planetary Science Letters* 136, 475–494.
- Krijgsman, W., Hilgen, F.J., Negri, A., Wijbrans, J.R., Zachariasse, W.J., 1997. The Monte del Casino section (Northern Apennines, Italy): a potential Tortonian/Messinian boundary stratotype? *Palaeogeography, Palaeoclimatology, Palaeoecology* 133, 27–47.
- Krijgsman, W., Hilgen, F.J., Raffi, I., Sierro, F.J., Wilson, D.S., 1999. Chronology, causes and progression of the Messinian salinity crisis. *Nature* 400, 652–655.
- Mazzei, R., 1977. Biostratigraphy of the Rio Mazzapiedi-Castellania Section (type section of the Tortonian) based on calcareous nanoplankton. *Atti Società Toscana di Scienze Naturali, Memoria* 84, 15–25.
- Negri, A., Giunta, S., Hilgen, F., Krijgsman, W., Vai, G.B., 1999. Calcareous nanofossil biostratigraphy of the M. del Casino section (northern Apennines, Italy) and paleoceanographic conditions at times of Late Miocene sapropel formation. *Marine Micropaleontology* 36, 13–30.
- Negri, A., Villa, G., 2000. Calcareous nanofossil biostratigraphy, biochronology, paleoecology at the Tortonian/Messinian boundary of the Faneromeni section. *Palaeogeography, Palaeoclimatology, Palaeoecology* 156, 195–209.
- Okada, H., Bukry, D., 1980. Supplementary modification and introduction of code numbers to the low latitude coccolith biostratigraphic zonations. *Marine Micropaleontology* 5, 321–325.
- Perch-Nielsen, K., 1985. Cenozoic calcareous nanofossils. In: Bolli, H.M., Saunders, J.B., Perch-Nielsen, K. (Eds.), *Plankton Stratigraphy*. Cambridge University Press, Cambridge, pp. 427–554.
- Pérez-Folgado, M., Sierro, F.J., Barceña, M.A., Flores, J.A., Vazquez, A., Utrilla, R., Hilgen, F.J., Krijgsman, W., Filippelli, G.M., 2003. Western versus Eastern Mediterranean paleoceanographic response to astronomical forcing: a high-resolution microplankton study of precession-controlled sedimentary cycles during the Messinian. *Palaeogeography, Palaeoclimatology, Palaeoecology* 190, 317–334.



- Pinardi, N., Masetti, E., 2000. Variability of the large scale general circulation of the Mediterranean Sea from observations and modelling: a review. *Palaeogeography, Palaeoclimatology, Palaeoecology* 158, 153–173.
- Pujol, C., Vergnaud-Grazzini, C., 1995. Distribution of live planktic foraminifers as related to regional hydrography and productive systems of the Mediterranean Sea. *Marine Micropaleontology* 25, 187–217.
- Raffi, I., Mozzato, C., Fornaciari, E., Hilgen, F.J., Rio, D., 2003. Late Miocene calcareous nannofossil biostratigraphy and astrochronology for the Mediterranean region. *Micropaleontology* 49, 1–26.
- Rakic-El Bied, K., Benson, R.H., 1996. La stratigraphie à Haute Résolution : théorie et application au Néogène supérieur du Maroc. *Notes et Mémoires du Service Géologique du Maroc* 383, 5–50.
- Reynolds, L.A., Thunell, R.C., 1986. Seasonal production and morphologic variation of *Neogloboquadrina pachyderma* (Ehrenberg) in the Northeast Pacific. *Micropaleontology* 32, 1–18.
- Rio, D., Raffi, I., Villa, G., 1990. Pliocene-Pleistocene calcareous nannofossil distribution patterns in the Western Mediterranean. In: Kastens, K.A., Masclé, J. et al. (Eds.), *Proceeding of the Ocean Drilling Program, Scientific Results* 107, pp. 513–533.
- Rohling, E.J., Gieskes, W.W.C., 1989. Late Quaternary changes in Mediterranean Intermediate Water density and formation rate. *Paleoceanography* 4, 531–545.
- Rosenbaum, G., Lister, G.S., Duboz, C., 2002. Reconstruction of the tectonic evolution of the Western Mediterranean since the Oligocene. *Journal of the Virtual Explorer* 8, 107–126.
- Salvatorini, G., Cita, M.B., 1979. Miocene foraminiferal stratigraphy, DSDP Site 397 (Cape Bojador, North Atlantic). *Initial Reports of the Deep Sea Drilling Project* 47. U.S. Government Printing Office, Washington, 317–373.
- Sierro, F.J., Flores, J.C., Civis, J., González Delgado, J.A., Francés, G., 1993. Late Miocene globorotaliid event-stratigraphy and biogeography in the NE-Atlantic and Mediterranean. *Marine Micropaleontology* 21, 143–168.
- Sierro, F.J., Flores, J.C., Francés, G., Vazquez, A., Utrilla, R., Zamarreño, I., Erlenkeuser, H., Barcena, M.A., 2003. Orbitally-controlled oscillations in planktic communities and cyclic changes in Western Mediterranean hydrography during the Messinian. *Palaeogeography, Palaeoclimatology, Palaeoecology* 190, 289–316.
- Sierro, F.J., Hilgen, F.J., Krijgsman, W., Flores, J.C., 2001. The Abad composite (SE Spain): A Messinian reference section for the Mediterranean and the APTS. *Palaeogeography, Palaeoclimatology Palaeoecology* 168, 141–169.
- Sprovieri, R., Bellanca, A., Neri, R., Mazzola, S., Bonanno, A., Bernardo, P., Sorgente, R., 1999. Astronomical calibration of Late Miocene stratigraphic events and analysis of precessional driver paleoceanographic changes in the Mediterranean Basin. *Memorie della Società Geologica Italiana* 54, 7–24.
- Sprovieri, R., Di Stefano, E., Caruso, A., Bonomo, S., 1996. High resolution stratigraphy in the Messinian Tripoli Formation in Sicily. *Paleopelagos* 6, 415–435.
- Thunell, R.C., 1978. Distribution of recent planktonic foraminifera in surface sediments of the Mediterranean Sea. *Marine Micropaleontology* 3, 147–173.
- Tjalsma, R.C., 1971. Stratigraphy and foraminifera of the Neogene of the Eastern Guadalquivir basin, S. Spain. *Utrecht Micropaleontological Bulletin* 4, 1–161.
- Turco, E., Hilgen, F.J., Lourens, L.J., Shackleton, N.J., Zachariasse, W.J., 2001. Punctuated evolution of global climate cooling during the late Middle to early Late Miocene: High-resolution planktonic foraminiferal and oxygen isotope records from the Mediterranean. *Paleoceanography* 16, 405–423.
- Young, J.R., 1998. Chapter 9: Neogene. In: Bown, P.R. (Ed.), *Calcareous Nannofossil Biostratigraphy*. Kluwer Academic Publishing, Dordrecht, pp. 225–265.
- Zachariasse, W.J., 1992. Neogene planktonic foraminifers from sites 761 and 762 off Northwest Australia. In: Von Rad, U., et al. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Results* 122, pp. 665–675.