Rivista Italiana di Paleontologia e Stratigrafia	volume 108	numero 2	tavole 2	pagine 337-353	Luglio 2002

AN INTEGRATED CALCAREOUS PLANKTON BIOSTRATIGRAPHIC SCHEME AND BIOCHRONOLOGY FOR THE MEDITERRANEAN MIDDLE MIOCENE

RODOLFO SPROVIERI [1], SERGIO BONOMO [1], ANTONIO CARUSO [1], AGATA DI STEFANO [2], ENRICO DI STEFANO [1], LUCA MARIA FORESI [3], SILVIA M. IACCARINO [4], FABRIZIO LIRER [4], ROBERTO MAZZEI [3] & GIANFRANCO SALVATORINI [3]

Received July 15 2001; accepted January 26, 2002

Key words: Biostratigraphy, Biochronology, Middle Miocene, Mediterranean.

Riassunto. In seguito allo studio quantitativo di estremo dettaglio dell'associazione a nannofossili calcarei e a foraminiferi planctonici in tre sezioni mediterranee che coprono l'intervallo stratigrafico compreso tra la sommità del Langhiano e la parte bassa del Tortoniano, la posizione stratigrafica relativa di 30 bioeventi appartenenti ai nannofossili calcarei e ai foraminiferi planctonici è stata identificata nell'intervallo temporale compreso tra 13.75 Ma e 10.53 Ma. Tali eventi sono stati correlati alla curva astronomica per mezzo di analisi ciclostratigrafiche condotte nelle singole sezioni. Pertanto è risultata una suddivisione biostratigrafica e biocronologica molto dettagliata dell'intervallo interessato. Lo schema zonale di Fornaciari et al. (1996) è stato adottato per i nannofossili calcarei, ma la biozona MNN7 è stata informalmente suddivisa in tre sottozone. Per quanto riguarda i foraminiferi planctonici, è stato fatto riferimento allo schema zonale riportato in Foresi et al. (1998), ma esso è stato leggermente modificato in modo da aumentare la risoluzione biostratigrafia. Viene infine riportata l'età di tutti i limiti zonali proposti.

Abstract. Based on the quantitative study of the calcareous nannofossils and planktonic foraminifera in three Mediterranean sections which cover the late Langhian - lower Tortonian stratigraphic interval, the relative position of 30 main bioevents belonging to the calcareous nannofossils and planktonic foraminifera have been identified in the time interval between 13.75 Ma and 10.50 Ma. They have been correlated, by a cyclostratigraphic approach, to the astronomic target curve. They thus allow for a very detailed biostratigraphic and biochronologic subdivision of the interval.

The zonal scheme proposed by Fornaciari et al. (1996) is adopted for the calcareous nannofossils, but three subzones were identified in the MMN7 Zone. For the planktonic foraminifera, reference is made to the zonal scheme recently proposed by Foresi et al. (1998), but it is slightly modified in order to increase its biostratigraphic resolution. The age of all the zonal boundaries are reported.

Introduction

Several biostratigraphic schemes have been recently proposed for the Mediterranean Middle Miocene based on calcareous nannofossils (Fornaciari et al. 1996) and planktonic foraminifera (Iaccarino & Salvatorini 1982; Iaccarino 1985; Foresi et al. 1998). This paper is not intended to present a totally new biostratigraphic zonation for this stratigraphic interval. Actually, the calcareous nannofossil biostratigraphic scheme of Fornaciari et al. (1996) is adopted. As far as planktonic foraminifera are concerned, the zonal scheme proposed here strongly echoes, with only some changes and improvements, the biostratigraphic scheme of Foresi et al. (1998). The main improvement is that it is based on a high resolution that allowed us to analyze the quantitative distribution of the markers used for the definition of the biostratigraphic boundaries. Quantitative results allowed a more accurate identification of the abundance fluctuations useful for the recognition of absence (paracme) intervals, abundance (acme) intervals, last common and regular occurrences (LCO, LRO), first common and regular occurrences (FCO, FRO). These prominent changes in species frequency distribution provide biohorizons which may increase biostratigraphic resolution by increasing the number of the biohorizons in addition to those based only on first and last occurrences (FO, LO). They are also often more easily detectable and can be more consistently correlated (especially for relatively short distance correlations) than the FO and LO levels, which may be coincident with very rare and/or discontinuous distribution of the marker.

The four aims of this paper are:

1)To establish for the two groups of fossils a detailed integrated ranking of the index species, based

[1] Dipartimento di Geologia e Geodesia, Università di Palermo, Corso Tukory 131, 90134 Palermo, Italy, e-mail: rspr@unipa.it.
[2] Dipartimento di Scienze Geologiche - Università di Catania, Corso Italia 55, 95129 Catania, Italy.
[3] Dipartimento di Scienze della Terra, Università di Siena, Via Laterina 8, 53100 Siena, Italy.
[4] Dipartimento di Scienze della Terra, Università di Parma, Parco Area delle Scienze 157/A, 43100 Parma, Italy.

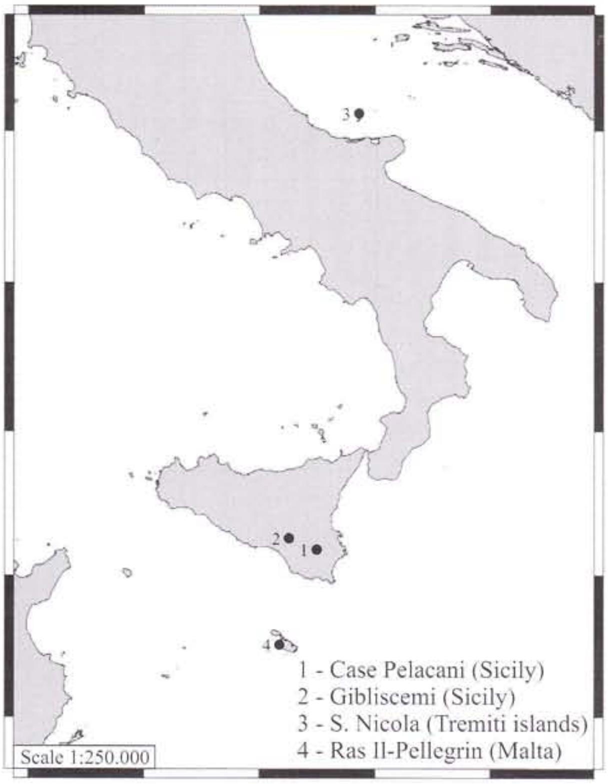


Fig. 1 - Location map of the studied sections.

on the quantitative distribution obtained in the studied sections.

2) To propose for the Middle Miocene an integrated calcareous plankton (calcareous nannofossils and planktonic foraminifera) biostratigraphy based on the results obtained by the fully quantitative analysis of the calcareous plankton assemblages in the same, strictly spaced samples along the three studied sections.

3) To present for all the stratigraphic interval the correlation of the zonal boundaries to a well defined and independent timescale. Up to now this task was essentially obtained in the Mediterranean by assuming that the ages of the Mediterranean biohorizons were approximately the same than the ages reported in the oceanic realm, where they are often correlated to the sequence of paleomagnetic reversals. In the Mediterranean region paleomagnetic data can be rarely obtained and are still missing for the interval considered in this paper. We could however obtain a reliable and well detailed time scale for the studied sections by the cyclostratigraphic approach (Sprovieri M. et al. 2002; Lirer et al. 2002; Caruso et al. 2002), based on the sequence of lithological couplets and/or the sequence of faunal fluctuations. Therefore all the biohorizons are linked to an astronomical precession cycle, and the relative (astro)chronology is used.

4) All the Zones and Subzones are labelled by the name of one or two species which represent their main paleontological feature. For easier communication they have been given also a numerical notation (for instance, MMi 5, Mediterranean Miocene 5). On the assumption that five Zones are possibly present in the Miocene segment older than the here discussed stratigraphic interval (from the *Globorotalia kugleri* FO to the *Orbulina suturalis* FO), the here proposed oldest Zone for the planktonic foraminifera is numbered as MMi 5.

Materials

The proposed biostratigraphic zonal scheme is based on the data obtained from three Mediterranean sections (Fig. 1) studied for the project "Paleoceanography and chronology of the Middle to Late Miocene in the Mediterranean realm through the calcareous plankton stratigraphy, cyclostratigraphy and stable isotope stratigraphy. Comparison with oceanic areas" (Cofin 1998). The composite sequence of the three sections, easily obtained by biostratigraphic correlation (Fig. 2), covers the interval from the uppermost Langhian to the lower Tortonian. The three sections are briefly described below. More data are reported in the papers in which they are discussed in detail (see below).

The Ras Il-Pellegrin section (Malta)

The section outcrops in the Ras-Il Pellegrin locality, along the western coast of the Malta Island. Composed of two subsections, it is totally included in the Blue Clay Formation, with the basal sample collected just above the transition between the underlying Globigerina Limestone and the Blue Clay Formations. The topmost sample was collected just below the lowermost bed of fossiliferous glauconitic sands which identifies the stratigraphic hiatus in the upper part of the Blue Clay Formation (Giannelli & Salvatorini 1975). The section is about 68.8 meters thick. A total of 451 samples were studied, collected at a mean interval of about 15 cm. The lithology is essentially represented by massive blue-gray marls, but seventeen whitish, more carbonatic bands, 0.5 to 2 meters thick, are present, more or less irregularly distributed along the section (Fig. 2).

The S. Nicola section (Tremiti Islands)

The section, composed of two subsections, outcrops in the S. Nicola island. It is entirely comprised in the Cretaccio Formation. The lower subsection, about 19 meters thick, is located on the NW coast of the island, below the cemetery. The upper subsection, also about 19 meters thick, is located on the SE coast, below the castle. The lithological record is composed by a quasi regular alternation of indurated, whitish colored, carbonate rich beds, which are 0.25 to 1 meter thick, and gray colored, less indurated marls. The gray marly beds,

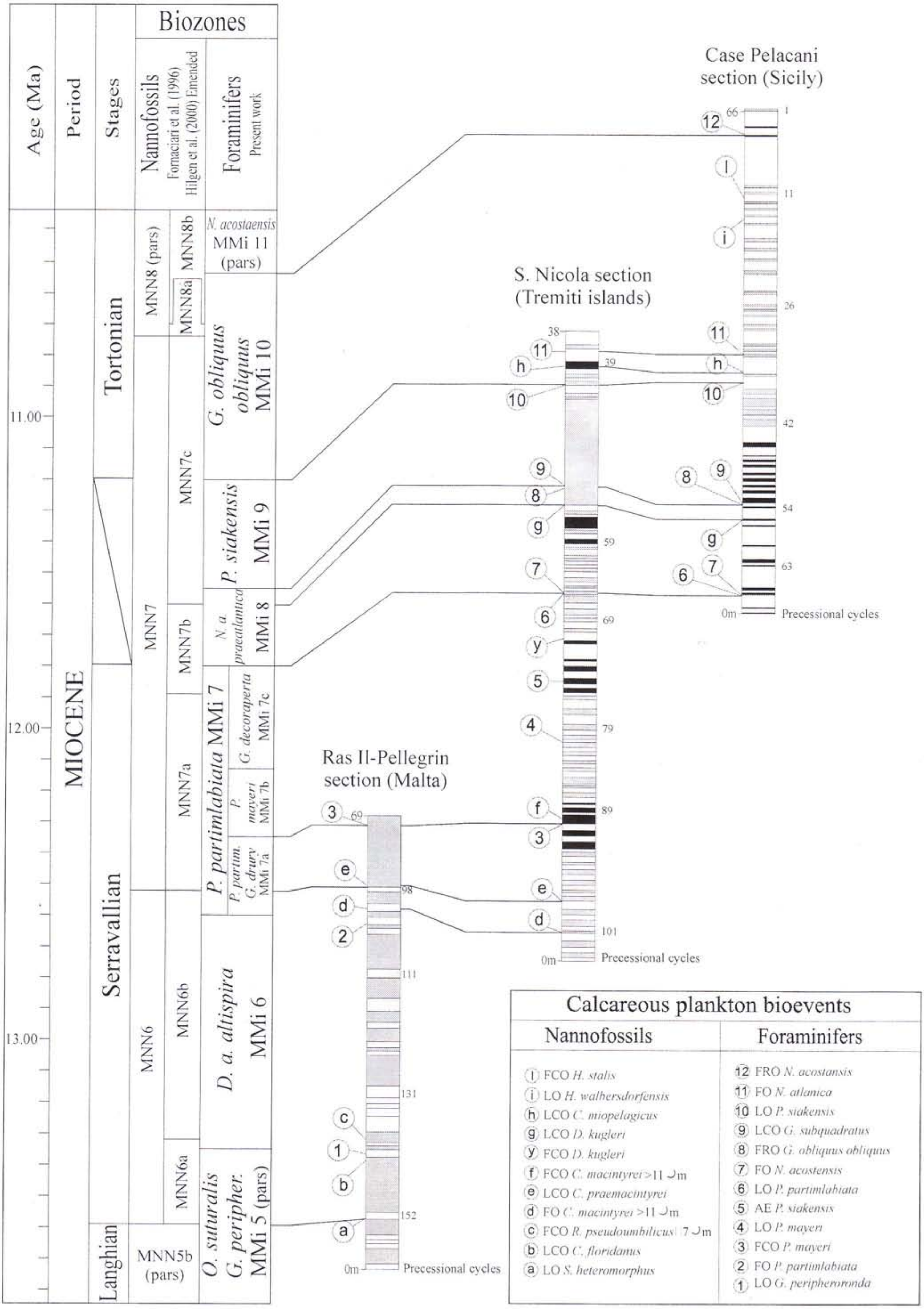


Fig. 2 - Biostratigraphic correlation of the studied sections. See Figs. 3, 4 and 5 for lithology.

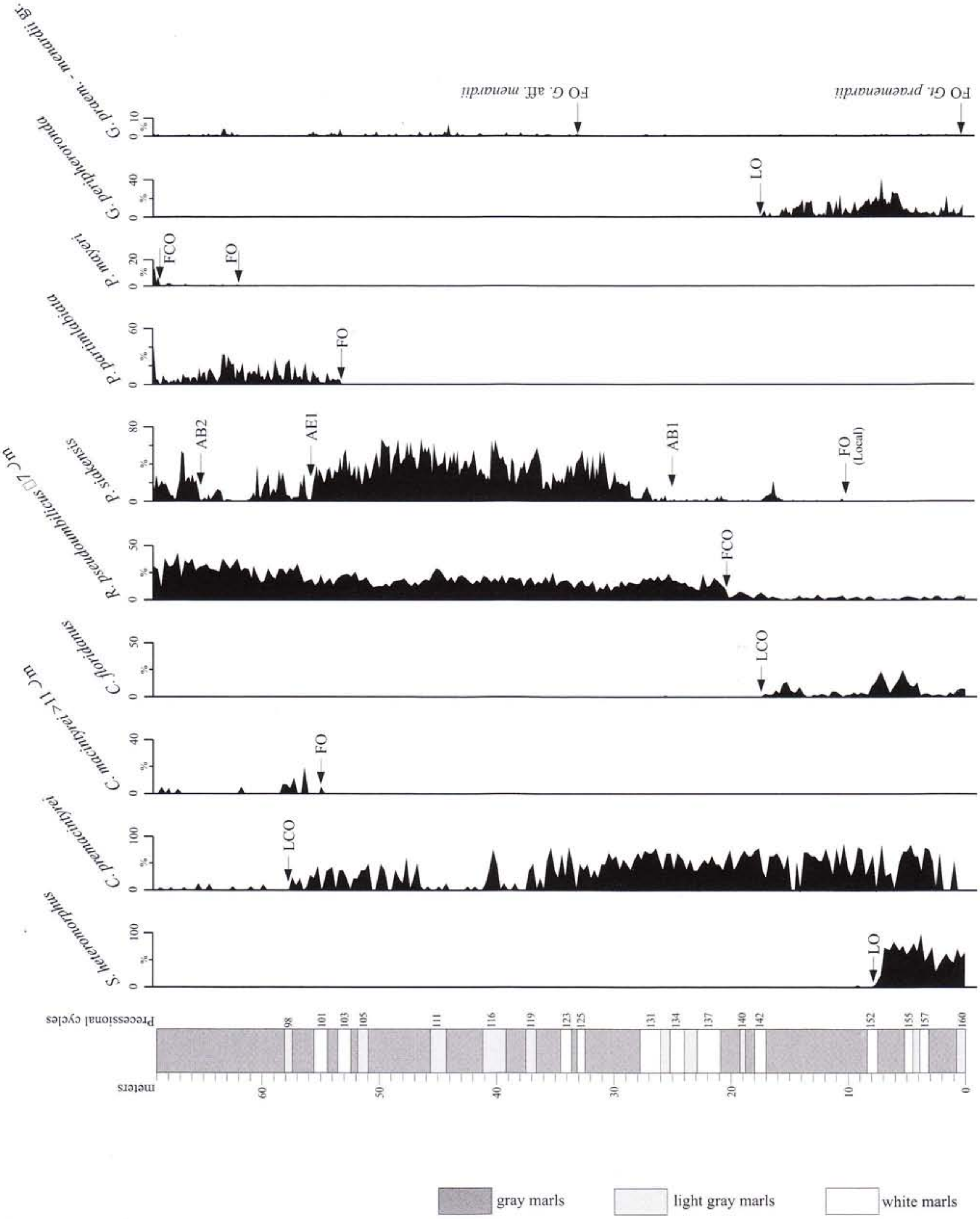


Fig. 3 - Quantitative distribution of the marker species in the Ras il-Pellegrin section. Modified from Foresi et al., 2002. PE = Paracme End.

which are sometime replaced by reddish colored marls, are up to 80 cm thick. The lithological cycles, each composed by one marly and one carbonate bed, are not evenly distributed, but reveal a distinct cluster distribution. It is more evident in the lower subsection. In the upper subsection, the lithological cycles are not well distinct between 8 and 15.30 meters above its base (between 28 and 33.30 meters above the base of the composite section) (Fig. 2). A total of 429 samples were studied, collected at a mean interval of 10-15 cm.

The Case Pelacani section (Sicily)

The section outcrops in the Eastern Sicily, near the Palazzolo Acreide village. It belongs to the Ragusa Platform of the southeastern Sicily foreland and covers the middle-upper part of the Tellaro Formation. It is composed of four segments, which outcrop near each other. They were easily correlated on the base of the small-scale lithological cycles and of biostratigraphic events. The entire section is 66.35 meters thick. It consists of open marine, epibathyal sediments, that show a cyclic alternation of two main lithologies. In the lower part, up to 24 meters above the base, the lithological alternation is represented by gray homogeneous marls and brown colored, faintly laminated beds. In the upper part, up to 57 meters above the base, the lithology consists of an alternation of whitish colored, indurated, carbonate rich beds and gray colored, carbonate poor marls. Above 57 meters no apparent lithological cycles were identified (Fig. 2), but this may be due to the difficulty to analyze the outcrop in detail, which is here particularly steep. A total of 316 samples were studied, collected at a mean interval of 20 cm.

Methods

Reliability, reproducibility, ranking and synchroneity of the biohorizons used for the definition of zonal and subzonal boundaries are the most important properties that make species-events useful as biostratigraphic markers. We fully agree with the methodological concepts reported by Fornaciari et al. (1996), to whom the reader is referred.

The definition (in the planktonic foraminifera biostratigraphic scheme) and the recognition (in the calcareous nannofossil biostratigraphic scheme) of the zonal and subzonal boundaries are based on the FO (First Occurrence), LO (Last Occurrence), FCO (First Common Occurrence), LCO (Last Common Occurrence) and FRO (First Regular Occurrence) events identified, in the three above described sections, by high resolution quantitative data. In Figures 3 to 5 only the quantitative distribution of the marker species used to identify the zonal boundaries of the two fossil groups are reported. The quantitative distribution of all the species identified in the sections are reported in the referred biostratigraphic papers by Foresi et al. (this volume), for the Ras-Il Pellegrin section, by Foresi et al. (this volume) for the S. Nicola section and by Di Stefano et al. (this volume) for the Case Pelacani section. The biostratigraphic boundaries of the planktonic foraminifera biozones never coincide with the biostratigraphic boundaries of the calcareous nannofossil biozones. The contemporaneous recognition in the same samples and the integration of the two sequences of events therefore allow a more detailed biostratigraphic resolution. The ages of the events were obtained by a cyclostratigraphic approach. Cyclostratigraphic methods and results are discussed in detail in the paper by Sprovieri et al. (2002) for the Ras-Il Pellegrin section, Lirer et al. (2002) for the S. Nicola section and Caruso et al. (2002) for the Case Pelacani section.

The Biohorizons

Calcareous nannofossils

The species concept used to recognize the markers which define the calcareous nannofossil biozones are illustrated in Plates 1 and 2. Their biostratigraphic meaning and reliability in the Miocene Mediterranean marine record were discussed by Fornaciari & Rio (1996) and are followed here. We only point out that our quantitative data confirmed that a subzonal division of the MNN7 Zone, based on the recognition of a subzone coincident with the stratigraphic interval of the common occurrence of *Discoaster kugleri* (cfr. Hilgen et al. 2000), can be adopted with caution. As a consequence, we only informally subdivided the MNN7 Zone into three intervals, labelled as a, b and c. The base and top of subzoned coincide with the FCO and LCO of *D. kugleri* respectively.

A brief discussion on the reliability of the calcareous nannofossil biohorizons proposed in the literature follows below, essentially on the base of their quantitative distribution recorded in the studied sections. Comments by Fornaciari et al. (1996) and Hilgen et al. (2000) are also taken into account. The ages of the biostratigraphic events are reported in Tab. 1.

LO of *Sphenolithus heteromorphus*

The reliability of this event was defined as excellent by Fornaciari et al. (1996). Our high resolution distribution pattern confirms this statement. The extinction of this species is very sharp, with high abundance values still within the underlying levels. Consequently, its recognition is very easy. It represents an excellent marker for zonal boundary definition in standard (Martini 1971; Okada & Bukry 1980) and Mediterranean zonations (Theodoridis 1984; Fornaciari et al. 1996). Its age in the Ras-Il Pellegrin section (Malta) is 13.59 Ma, in good agreement with previous estimates reported from extra-Mediterranean records. The isochronous occurrence of its extinction event makes this biohorizon an excellent tool for world-wide biostratigraphic and chronostratigrafic correlations.

LCO of *Cyclicargolithus floridanus*

This event is considered as a second order biohorizon, which occurs just below the boundary between the MNN6a and MNN6b biozones. Our high resolution data set point out that this taxon has a common and continuous occurrence for a short interval above the *Sphenolithus heteromorphus* LO. Above this short segment only rare and scattered specimens that do not enter the counting are present. A LCO biohorizon can therefore be identified. It is considered a moderately reliable but useful bioevent to improve the resolution in the Mediterranean Middle Miocene record. Its age in the Ras-Il Pellegrin section (Malta) is 13.39 Ma. Fornaciari et al. (1996) listed the *Cyclicargolithus floridanus* LO event among the alternative and additional biohorizons, but they considered it difficult to be detected.

FCO of *Reticulofenestra pseudoumbilicus*

Following the taxonomic concept of Fornaciari et al. (1996), an horizon of common and continuous occurrence (FCO) of this taxon was easily detected in the Ras-Il Pellegrin section (Malta). It fall well above the LO of *Sphenolithus heteromorphus* and just above the LCO of *C. floridanus*. It can be considered reliable in the Mediterranean record and useful, as proposed by Fornaciari et al. (1996), to recognize the sub-zonal boundary between MNN6a and MNN6b. Its age in the Ras-Il Pellegrin section (Malta) is 13.32 Ma.

FO of *Calcidiscus macintyrei*

Fornaciari et al. (1996) considered this event as moderately good among the additional biohorizons. Following the same taxonomic concept our data also prove that this taxon is very rare and scattered in the basal part of its range. Consequently, the recognition of its entry level may be identified at different time levels (before, or in coincidence, or just after the LCO of *C. premacintyrei*) depending on sampling resolution. Only by studying very closely spaced samples we could identify this event which slightly predates the LCO of *C. premacintyrei* in isochronous levels both in the Ras-Il Pellegrin (Malta) and S. Nicola (Tremiti Islands) sections. Its actual appearance level, below the LCO of *C. premacintyrei*, can be useful to improve the stratigraphic resolution in the topmost part of the MNN6b Subzone. In our sections the time interval between the two bioevents corresponds to three precession cycles. The age value of 12.57 Ma was obtained for this event.

LCO of *Calcidiscus premacintyrei*

This event marks the MNN6b/MNN7 boundary (Fornaciari et al. 1996). Our data confirm that it can be considered a good and reliable event for correlations in the Mediterranean region. We identified its LCO in isochronous levels both in the Ras-Il Pellegrin (Malta) and S. Nicola (Tremiti Islands) sections with an age of 12.51 Ma.

FCO of *Calcidiscus macintyrei*

In our high resolution study performed in the Tremiti record, a distinctive horizon of common occurrence (FCO) of *C. macintyrei* (>11mm) can be detected shortly above the LCO of *C. premacintyrei*. Maiorano (1995) reported a similar position for these events in other Mediterranean Miocene land sections.

We consider the FCO event of *C. macintyrei* a useful and reliable additional horizon to implement the biostratigraphic resolution in the lowermost MNN7 biozone (or MNN7a subzone). Its astronomical age estimate is 12.34 Ma.

FCO and LCO of *Discoaster kugleri*

The significance of the occurrence and abundance of *Discoaster kugleri* in the Mediterranean has recently been re-evaluated by Hilgen et al. (2000). According to these authors a distinctive horizon of FCO and another of LCO are also recognizable in the Mediterranean record and useful for subzonal boundary definitions within the MNN7 Zone of Fornaciari et al. (1996). We could not recognize the base of the subzone MNN7b in the Case Pelacani section, because the base of this section is just above this level. This event was recognized in the Tremiti composite sequence, at a stratigraphic level fully correlatable with the level in which, in the Gibliscemi section, this event was reported by Hilgen et al. (2000). The LCO event of *D. kugleri* was identified in the Case Pelacani and S. Nicola sections. It is well recognizable above a stratigraphic interval during which this taxon, even if scattered and rare, can be generally found in the samples. In both our sections this interval coincides with an increase in abundance in the *Discoaster* population. Above the level that we interpret as its LCO the taxon is extremely rare and is present only in very few, discrete samples. The age of the LCO level in both sections is 11.60 Ma, very close to the age reported in the Monte Gibliscemi section (Hilgen et al. 2000) and in the equatorial Atlantic (Backman & Raffi 1997). Our results confirm that these biohorizons are reliable, but they can be detected only by a high resolution sampling, in which a rich population of *Discoaster* is well preserved. For these reasons, they can be used only with caution for subzonal subdivisions in the Miocene Mediterranean record.

LCO of *Coccolithus miopelagicus*

Due to a long tail of more or less rare specimens of this taxon above its Late Miocene Mediterranean abundant distribution, the recognition of its LO is dif-

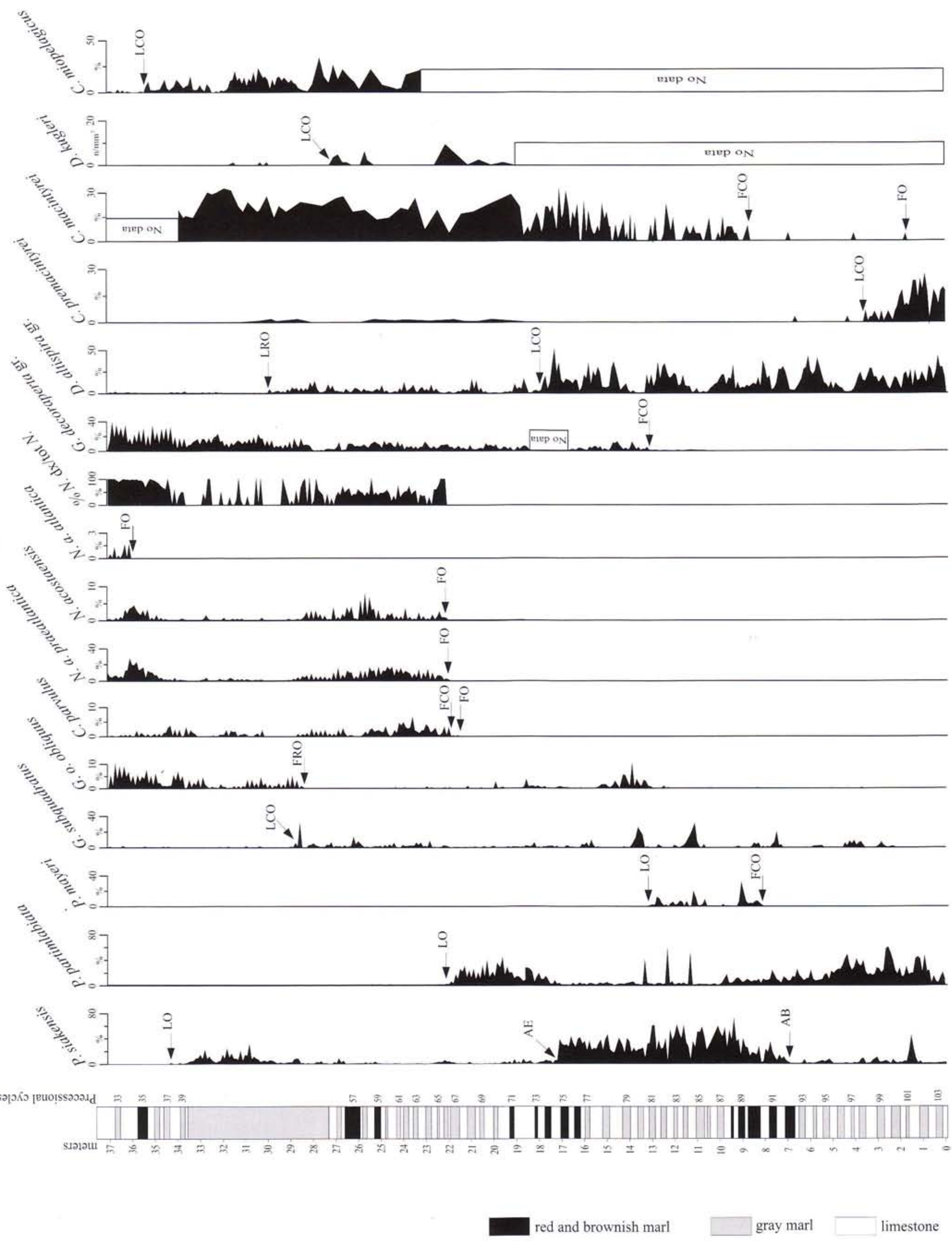


Fig. 4 - Quantitative distribution of the marker species in the S. Nicola section. Modified from Foresi et al., 2002. AB = Acme Base; AE = Acme End.

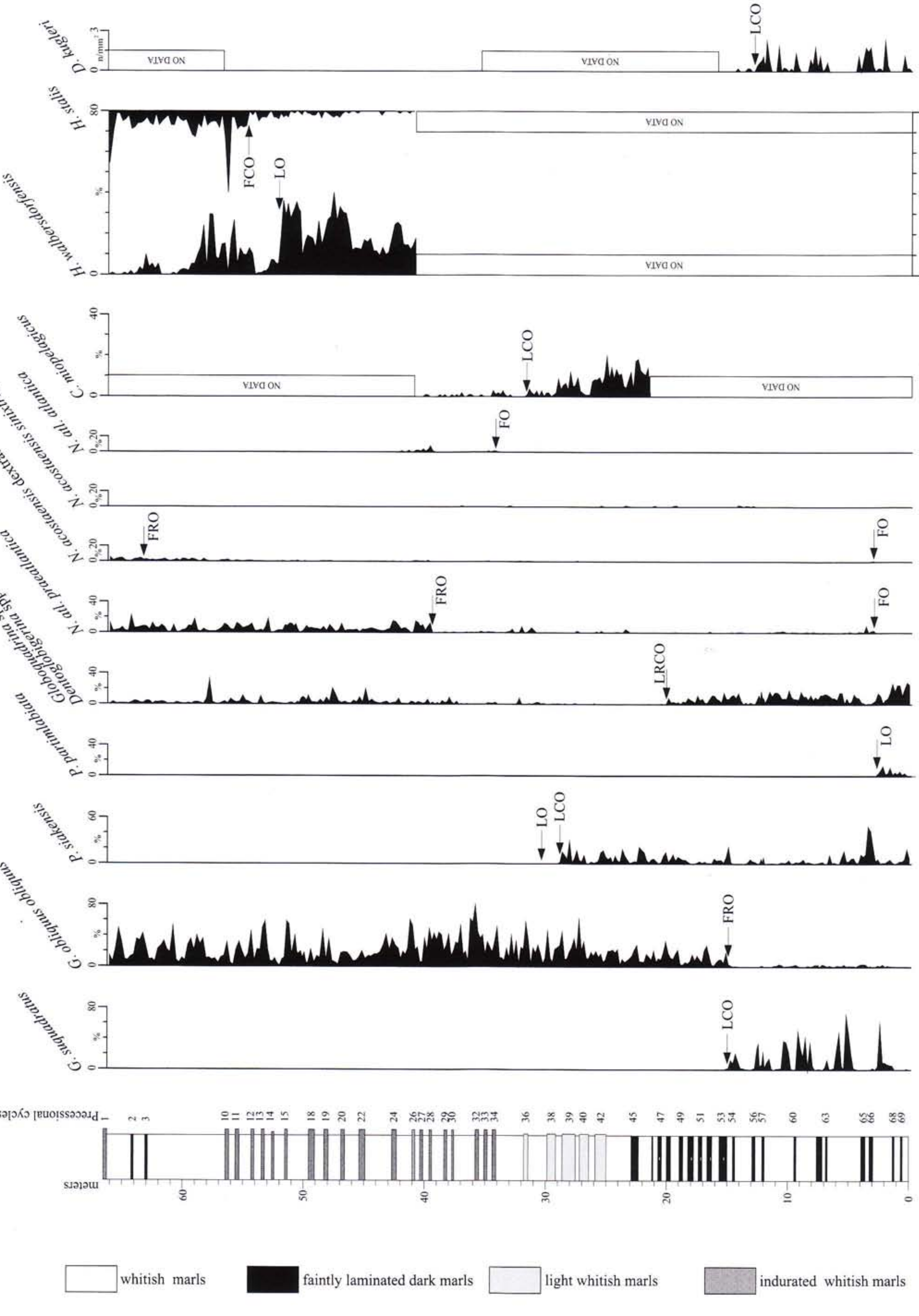


Fig. 5 - Quantitative distribution of the marker species in the Case Pelacani section. Modified from Di Stefano et al., 2002.

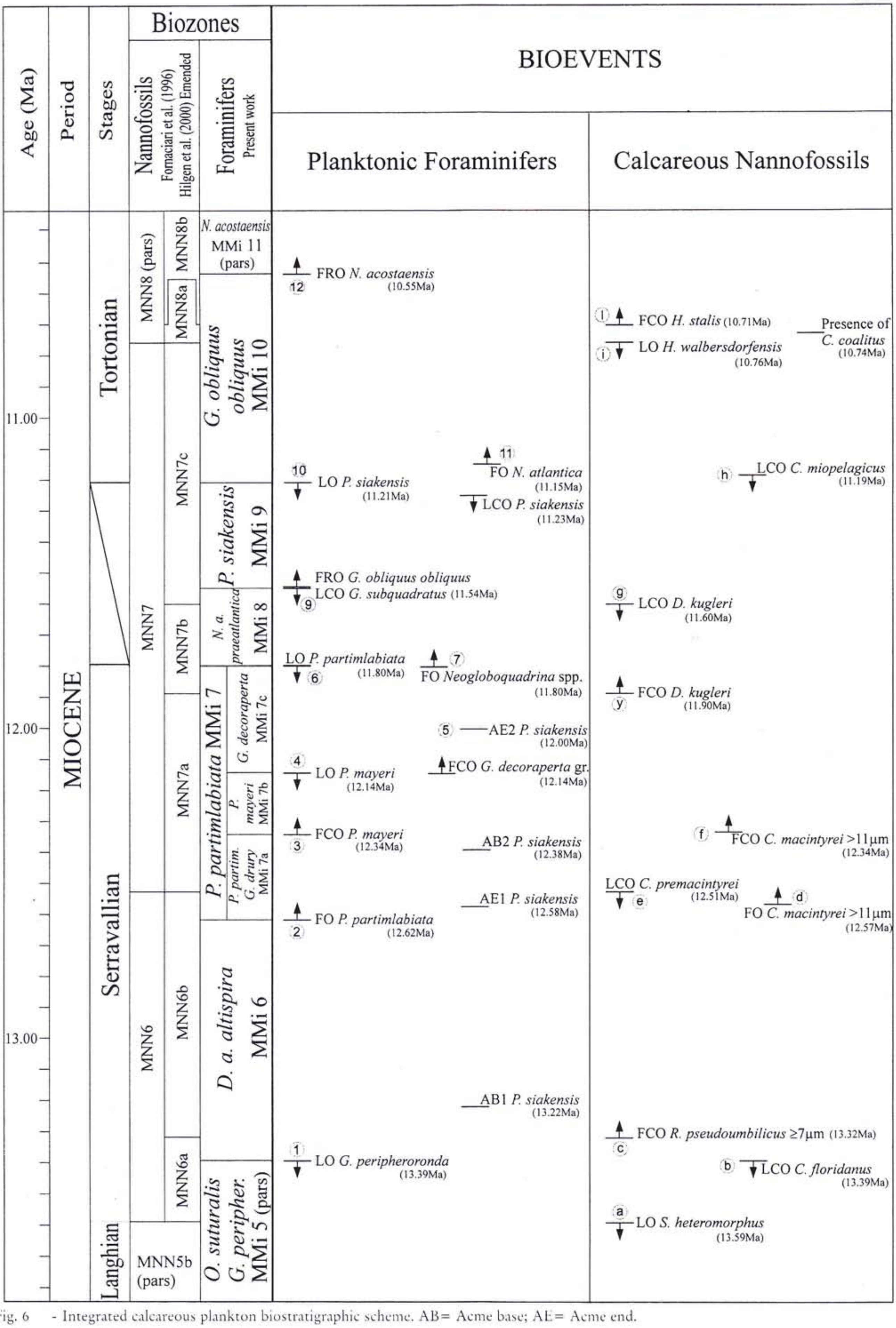


Fig. 6 - Integrated calcareous plankton biostratigraphic scheme. AB= Acme base; AE= Acme end.

ficult to detect (Fornaciari et al. 1996). These authors reported as a reliable event only the top of its continuous and common occurrence and do not use it as a zonal marker. Hilgen et al. (2000), in the Monte Gibliscemi record, identified a LRO biohorizon above the occurrence of rare and scattered specimens in the highest part of the MNN7 Zone. In our detailed distribution pattern it is very hard to select a consistent LCO horizon because a repetitive discrete presence, with decreasing abundance values of the taxon, occurs above a short interval in which it is virtually absent. Both in the S. Nicola and Case Pelacani sections this very short absence interval, that we consider a short paracme interval, can be distinguished with isochronous basal and top levels. We select as *Coccolithus miopelagicus* LCO horizon the abundance decrease that marks the beginning of the first persistent absence interval that occurs above the so called "paracme" interval. We consider the so recognized LCO of *C. miopelagicus* in the Mediterranean as a useful and reliable event to identify the uppermost part of the MNN7 Zone or the uppermost part of the MNN7c Subzone (Hilgen et al. 2000). Its age is estimated at 11.19 Ma.

Occurrence of *Discoaster brouweri*

At the Case Pelacani section the first very rare and scattered six rayed asteroliths of this taxon occur in the uppermost part of the MNN7c Subzone below the LO of *H. walbersdorfensis*. We consider it as an event of limited biostratigraphic applicability because, at the beginning of its range, this taxon is very rare and discontinuously present and may not always be detected in the standard counting.

LO of *Helicosphaera walbersdorfensis*

Fornaciari et al. (1996) consider the LO of this taxon as a reliable event and use it as the boundary marker between the MNN7/MNN8 Zones in their Mediterranean zonal system. This event slightly precedes the FCO of *H. stalis*. These two events are adopted for the definition of the base and top of the MNN8a Subzone. In our section a considerable amount of silty fraction and of reworked forms occurs in the uppermost twenty meters of the section. Di Stefano et al. (this volume) interpreted the common, but badly preserved specimens of *Helicosphaera walbersdorfensis* that occur into this interval as reworked. They selected the decrease in abundance of *Helicosphaera walbersdorfensis* that occurs at the end of its common and continuous occurrence to mark its LO horizon. It falls shortly below the FCO horizon of *H. stalis* and these events allow the recognition of the MNN8a Subzone. The age referred to the thus defined LO of *H. walbersdorfensis is* 10.76 Ma and is correlatable to the age from the Monte Gibliscemi record for an horizon reported as LCO of this taxon by Hilgen et al. (2000).

Occurrence of *Catinaster coalitus*

The occurrence of this taxon in the Mediterranean Miocene record was not reported by Theodoridis (1984) and Fornaciari et al. (1996). Hilgen et al. (2000) recognized the lowest occurrence of very rare specimens by means of a very close-spaced sampling within the interval referred to the MNN8a Subzone. In the Case Pelacani section we detected the lowest occurrence of extremely rare specimens in a sample just below the *H. stalis* FCO. This is isochronous with the level in which it was identified at the Monte Gibliscemi section. Nevertheless, we consider this occurrence to represent a not reliable event, because the taxon is very rare or missing in most Mediterranean sections. But, where present, it is very useful to increase the biostratigraphic resolution of the section. Its age in the Case Pelacani section is 10.74 Ma.

FCO of *Helicosphaera stalis*

Fornaciari et al. (1996) reported for this event a good reliability and used it as subzonal boundary marker in their zonal system (MNN8a/MNN8b). In our high resolution distribution pattern an horizon above which this taxon becomes common and continuously present is easily recognized. Its age in the Case Pelacani section is 10.71 Ma. This value agrees well with the age reported in the Monte Gibliscemi section by Hilgen et al. (2000), thus confirming that this event is reliable for intra Mediterranean correlations.

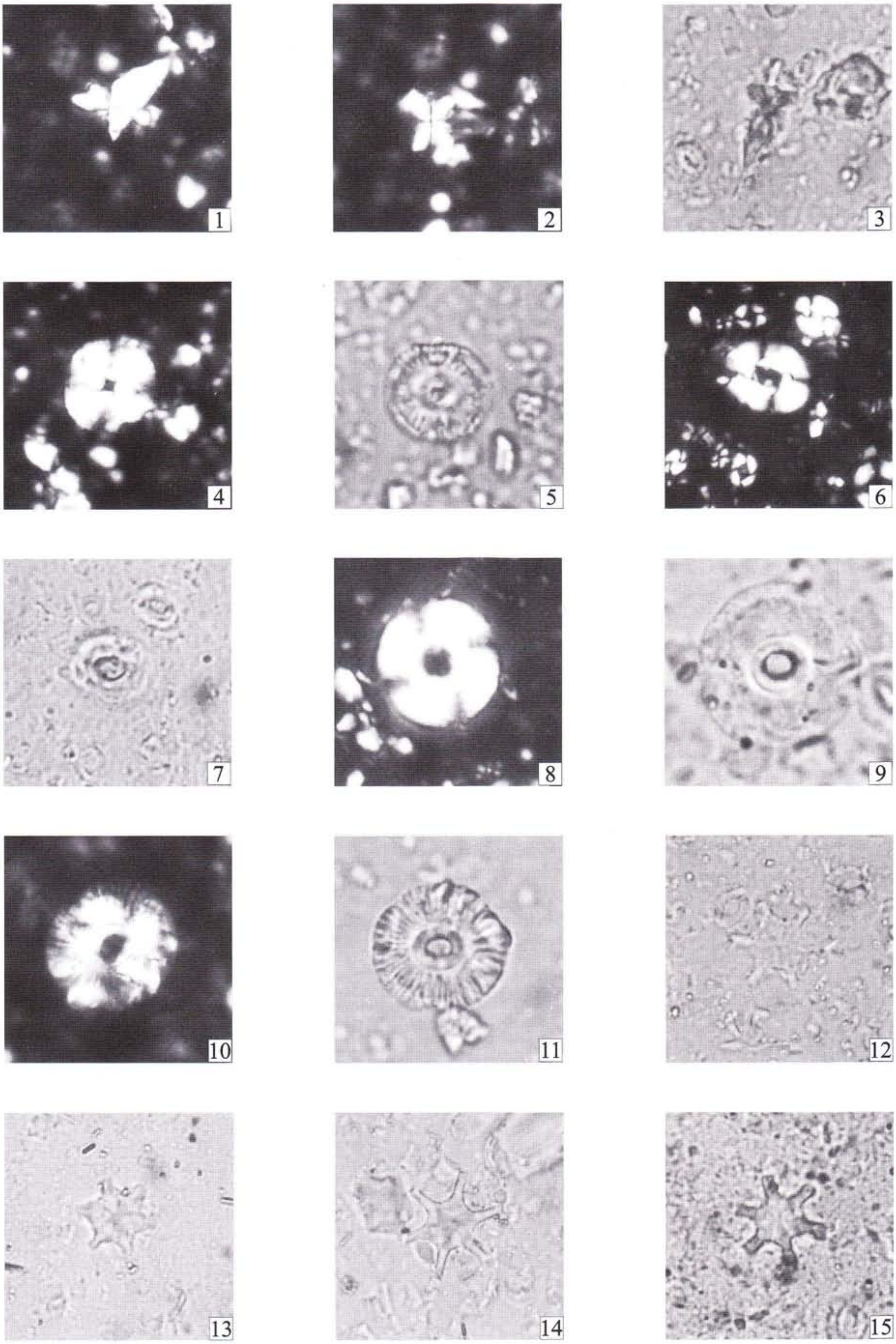
Planktonic foraminifera.

As far as planktonic foraminifera markers are concerned, we refer to Foresi et al. (1998) for their illustra-

PLATE 1

Specimens in 1-12: X2500.

Figg. 1 - 3. *Sphenolithus heteromorphus* (Deflandre), 45° and 0°, crossed and parallel nicols, sample ML-012, section Ras Il-Pellegrin. Figg. 4 - 5. - *Cyclicargolithus floridanus* (Bukry), crossed and parallel nicols, sample ML-04, section Ras-Il Pellegrin. Figg. 6 - 7. *Reticulofenestra pseudoumbilicus* ≥7μm (Gartner), crossed and parallel nicols, sample ML-58.60, section Ras Il-Pellegrin. Figg. 8 - 9. *Calcidiscus macintyrei* >11μm (Loeblich & Tappan), crossed and parallel nicols, sample ML-509, section Ras Il-Pellegrin. Figg. 10 - 11. *Calcidiscus premacintyrei* (Theodoridis), crossed and parallel nicols, sample ML-012, section Ras Il-Pellegrin. Fig. 12 - *Discoaster kugleri* (Martini & Bramlette), parallel nicols, sample PEL-288, section Case Pelacani. Fig. 13 - 14. *Discoaster kugleri* (Martini & Bramlette), parallel nicols, sample. Fig. 15. *Discoaster kugleri* (Martini & Bramlette), parallel nicols, sample PEL-261, section Case Pelacani.


1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

tion. A brief discussion on their reliability follows below, essentially on the basis of their quantitative distribution recorded in the studied sections. Comments by Foresi et al. (1998) are however also taken into account. The age of the biostratigraphic events of the calcareous planktonic assemblages are shown in Tab. 1.

LO of *Globorotalia peripheroronda*

The species is easily recognizable. The quantitative pattern clearly shows that the extinction of this species is sharp, with the just preceding levels still bearing common specimens. It is considered an excellent marker for a zonal boundary definition, isochronous in different Mediterranean areas and possibly only slightly diachronous in extra-Mediterranean sequences. In the Malta section its age is 13.39 Ma.

FO of *Paragloborotalia partimlabiata*

This medium sized species is only rarely recorded from outside the Mediterranean (Salvatorini & Cita 1979; Iaccarino & Salvatorini 1979; Zachariasse 1992). It can easily be recognized by its undulating intercameral suture between the last two chambers on the spiral side and by the not complete lip on the external margin of the aperture. It is already frequent in the first sample of the basal range of its distribution. It is considered an excellent marker for the definition of a zonal boundary. Its age in the Malta section is 12.62 Ma.

FCO and LO of *Paragloborotalia mayeri*

We refer to Foresi et al. (2002, b and in press) for the criteria we used to distinguish this fairly large species from *Paragloborotalia siakensis*. Its first occurrence is difficult to pinpoint, because the species is very rare and scattered at the base of its range. But its FCO was clearly identified by a sudden increase in abundance in isochronous levels both in the Ras-Il Pellegrin and S. Nicola sections. Above its appearance level the species is generally present, more or less frequent, in all the samples up to its extinction level, which is marked by a sharp, sudden disappearance. Both events are considered good marker horizons. We used them to define a subzone in the middle part of the *P. partimlabiata* Zone. Their ages are 12.34 Ma and 12.14 Ma respectively.

LO of *Paragloborotalia partimlabiata*

This event is rather easy to identify, even if the abundance decrease of *P. partimlabiata* in the top part of its range is gradual. The uppermost presence of the rare specimens of this species (at 11.80 Ma) is virtually coincident with the more easily recognizable and sudden appearance of the Neogloboquadrinids in the Mediterranean stratigraphic record. We consider the LO of *P. partimlabiata* as a good biostratigraphic event, but we preferred to use the Mediterranean FO of the Neogloboquadrinids population (coincident with the *Neogloboquadrina atlantica praeatlantica* FO) for the definition of a zonal boundary, even if the two biohorizons virtually coincide. Reference is made to the paper by Di Stefano et al. (this volume) and Foresi et al. (in press) for the morphological differences we used to discriminate *P. partimlabiata* and *P. challengeri*.

FO of Neogloboquadrinids population

The virtually isochronous appearance of *N. acostaensis* and *N. atlantica praeatlantica* (Di Stefano et al. this volume; Foresi et al. this volume, a) is a clear event (the so called Neogloboquadrinids FO event) in the Mediterranean Miocene sequences, even if *N. acostaensis* is very rare in the basal part of its range. We used this excellent biostratigraphic event (as the *N. atlantica praeatlantica* FO) as a zonal marker. The age of this event is 11.80 Ma.

LCO of *Globigerinoides subquadratus*

This event is easily detectable by the sharp decrease in abundance of the marker species, which is still common to abundant in the underlying levels. Only very rare and scattered specimens are present above, often not included in the counting of 300 planktonic foraminifera specimens. The LCO of *G. subquadratus* coincides more or less with the FCO of *Globigerinoides obliquus obliquus*, which is generally rare and scattered in the older stratigraphic levels. The LCO of *G. subquadratus*, which has an age of 11.53 Ma, is considered an excellent maker for zonal boundary definition.

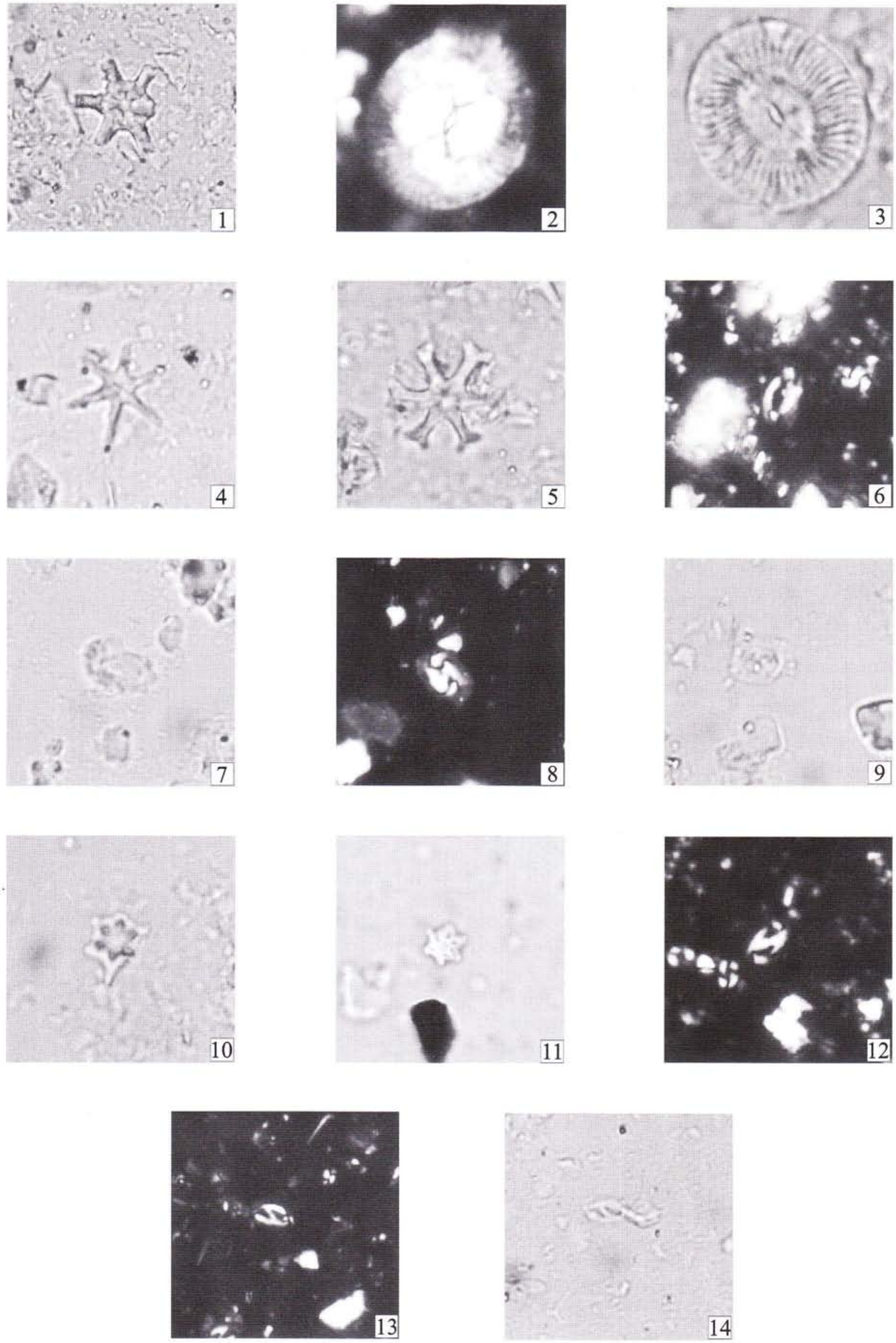
LO of *Paragloborotalia siakensis*

This level occurs just above a sharp decrease in abundance of the species, which is recognized only one

PLATE 2

Specimens in 1-12: X2500.

Fig. 1 - *Discoaster* cf. *kugleri*, parallel nicols, sample PEL-269, section Case Pelacani. Fig. 2 - 3. *Coccolithus miopelagicus* (Wise), crossed and parallel nicols, sample ML-058, section Ras-Il Pellegrin. Fig. 4. *Discoaster brouweri* (Bramlette & Riedel), parallel nicols, sample CP99-66, section Case Pelacani. Fig. 5. *Discoaster variabilis* (Martini & Bramlette), parallel nicols, sample CP99-21, section Case Pelacani. Fig. 6 - 7. *Helicosphaera walbersdorfensis* (Theodoridis), crossed and parallel nicols, sample ML-089, section Ras-Il Pellegrin. Fig. 8 - 9. *Helicosphaera orientalis* (Theodoridis), crossed and parallel nicols, sample CP99-113, section Case Pelacani. Fig. 10 - 11. *Catinaster coalitus* (Martini & Bramlette), parallel light, sample CP99-61, section Case Pelacani. Fig. 12 - 14. *Helicosphaera stalis* (Theodoridis), crossed and parallel nicols, sample PEL99-75, section Case Pelacani.


1
2
3
4
5
6
7
8
9
10
11
12
13
14

precessional cycle below, at 11.23 Ma. In this short interval the species is very rare and scattered and generally it is not detected in the standard counting of 300 specimens. We used the LO (not the LCO) of this species as zonal marker because this level is possibly better correlatable with intra-Mediterranean sequences. The position of *P. siakensis* LO may be easily indicated by the identification of its just preceding LCO level. The age of this event is 11.21 Ma.

FRO of *Neogloboquadrina acostaensis*

This species first occurs in the level in which the Neogloboquadrinids population appears in the Mediterranean Miocene sequences. Nevertheless, it is rare and scattered in the lower part of its range. Only from a level above the short interval during which the large specimens of *Neogloboquadrina atlantica* are present, *N. acostaensis* increases in abundance and is more regularly present in the samples. The coiling direction of the specimens is scattered (right and left coiling). The *N. acostaensis* FRO which defines the homonymous zone, with an age of 10.55 Ma, is considered good, even if it can be used only with difficulty to recognize the base of the Zone in isolated samples.

The Middle Miocene integrated calcareous plankton zonal scheme

Zones and Subzones are included in our planktonic foraminifera zonal scheme, as are also used in the adopted calcareous nannofossil biostratigraphic scheme. Zones generally cover stratigraphic intervals longer than subzones and their boundaries are defined by major biostratigraphic events. Zones are easily recognizable even in isolated samples or short sections. Subzones cover shorter stratigraphic intervals and their boundaries are defined by events the level of which may be not so clear in terms of sharp paleontological changes, with the consequence that they may not always be easily and everywhere identified, or they may be identified at slightly different stratigraphic levels due to the rarity or scantiness of the marker form.

Even if partial-range Zones could be more appropriate, all the proposed stratigraphic intervals are identified as interval zones, because the International Stratigraphic Code (ISC) (Hedberg 1976; Salvador 1994) reports the partial-range zones as a synonym of the Interval Zone. Even the *P. partimlabiata* Zone, which actually corresponds to the total range of the nominal taxon, is considered an Interval Zone, because its top is not strictly defined by the extinction level of the nominal taxon.

Dentoglobigerina altispira altispira Interval Zone (MMi 6)

Authors: Iaccarino & Salvatorini (1982) (Reported as the lowest subzone of the proposed *P. siakensis* Zone).

Definition. From the LO of *Gt. peripheroronda* to the FO of *P. partimlabiata*.

Reference section. Ras-Il Pellegrin (Malta)

Astrochronology. From 13.39 Ma to 12.62 Ma.

Remarks. According to Foresi et al. (1998; this volume, b and in press) the FO of *Globorotalia* aff. *menardii* occurs in this subzone.

Integrated biostratigraphy. The LO of *S. heteromorphus* slightly predates the base of this zone, at 13.59 Ma and the LCO of *C. premacintyrei* slightly postdates the FO of *P. partimlabiata*, at 12.51 Ma. Therefore the MNN6 nannofossil biozone of Fornaciari & Rio (1996), defined at the base and at the top by these two nannofossil events, is practically coincident with this zone. More over the LO of *G. peripheroronda* occurs only tree precessional cycles below the FCO of *R. pseudoumbilicus* >7 μm, the marker event which defines the MNN6a/MNN6b subzonal boundary at 13.32 Ma and in coincidence of the LCO of *Cycl. floridanus*.

Paragloborotalia partimlabiata Interval Zone (MMi 7)

Authors: Foresi et al. (1998).

Definition: from the FO of *P. partimlabiata* to the FO of *Neogloboquadrina atlantica praeatlantica*.

Reference section. Integrated sequences outcropping in the Ras-Il Pellegrin (Malta) and S. Nicola (Tremiti Island) sections.

Astrochronology. From 12.62 Ma to 11.80 Ma.

Remarks. Even if defined at the top by the first occurrence of *N. atlantica praeatlantica*, this zone practically coincides with the total range of the zonal marker.

Three subzones have been distinguished on the bases of the LO and FO of *P. mayeri*.

Paragloborotalia partimlabiata-Globoturborotalita druryi Interval Subzone (MMi 7a)

Authors: this paper.

Definition: from the FO of *P. partimlabiata* to the FCO of *P. mayeri*.

Reference section: Ras-Il Pellegrin (Malta).

Astrochronology. From 12.62 Ma to 12.34 Ma.

Remarks. The first, very rare and scattered specimens of *P. mayeri* occur in the topmost part of this Subzone. At the very top *P. siakensis* increases in abundance, at the base of an acme interval. According to Foresi et al. (in press) *Globigerina bulloides* first occurs in this subzone.

Integrated biostratigraphy. This subzone straddles the MNN6b/MNN7 boundary of Fornaciari & Rio (1996), defined by the LCO of *C. premacintyrei*. The FO of *C. macintyrei* > 11 μm occurs just above the base of this subzone, at 12.57 Ma.

Paragloborotalia mayeri Interval Subzone (MMi 7b)

Authors: this paper.
Definition. From the FCO of *P. mayeri* to the LO of *P. mayeri*.
Reference section. S. Nicola (Tremiti Islands).
Astrochronology. From 12.34 Ma to 12.14 Ma.

Remarks. *P. siakensis* is rare and scattered in the middle part of this Subzone and sharply increases in abundance in its uppermost part. According to Foresi et al. (in press) *Gt. menardii* s.l. appears within this Subzone.

Integrated biostratigraphy. This subzone covers the lower part of the MNN7 Zone of Fornaciari & Rio (1996).

Globoturborotalita decoraperta Interval Subzone (MMi 7c)

Authors: this paper.
Definition. From the LO of *P. mayeri* to the FO of *N. atlantica praeatlantica*.
Reference section. S. Nicola (Tremiti Island).
Astrochronology. From 12.14 Ma to 11.80 Ma.

Remarks. *P. partimlabiata* disappears at the very top of this subzone, virtually coincident with its upper boundary. In coincidence with the LO of *P. mayeri*, the FCO of *G. decoraperta* occurs. In the middle part of this subzone a sharp decrease in abundance of *P. siakensis* identifies the end of its acme interval, at 12.00 Ma.

Integrated biostratigraphy. This Subzone covers the middle-lower part of the MNN7 Zone of Fornaciari et al. (1996). The FCO of the calcareous nannofossil *D. kugleri*, which identifies the base of its acme interval, occurs in the middle-upper part of this subzone..

Neogloboquadrina atlantica praeatlantica
Interval Zone (MMi 8)

Authors: this paper.
Definition. From the FO of *N. atlantica praeatlantica* to the LCO of *Gld. subquadratus*.
Reference section. S. Nicola (Tremiti Islands).
Astrochronology. From 11.80 Ma to 11.54 Ma.

Remarks. This zone coincides with the *Neogloboquadrina continuosa* subzone of Foresi et al. (1998). *N. acostaensis* first appears at the very base of this biozone, but it is extremely rare and scattered in the entire interval. *Catapsydrax parvulus* also virtually occurs from the base of this Zone, after a long time interval of absence. However, it is common only in the upper part of Zone.

Integrated biostratigraphy. This Zone can be correlated with the middle part of the MNN7 nannofossil Zone of Fornaciari et al (1996). The LCO of *D. kugleri*, coincident with the top of its acme interval, occurs in its topmost part, at 11.60 Ma.

Paragloborotalia siakensis Interval Zone (MMi 9)

Authors: this paper.
Definition. From the LCO of *Gld. subquadratus* to the LO of *P. siakensis*.
Reference section. Case Pelacani (Sicily).
Astrochronology. From 11.53 Ma to 11.21 Ma.

Remarks. This Zone coincides with the *Gt. menardii* Subzone of Foresi et al. (1998). *Gld. obliquus obliquus* sharply increases in abundance from the base of this zone. *G. nepenthes* first appears in the lover part of this Zone. *D. altispira* s.l. sharply decrease in abundance from the middle part of Zone. *N. acostaensis* is always very rare and scattered. The nominal taxon is extremely rare in a very short interval at the topmost part of its range, above its LCO level.

Integrated biostratigraphy. This Zone can be correlated with the upper part of the MNN 7 nannofossil Zone of Fornaciari & Rio (1996). In its upper part, virtually coincident with the LCO of *P. siakensis*, the level we interpret as the LCO of *C. miopelagicus* occurs at 11.19 Ma in the Case Pelacani section.

Globigerinoides obliquus obliquus Interval Zone (MMi 10)

Authors: this paper.
Definition. From the LO of *P. siakensis* to the FRO of *N. acostaensis*.
Reference section. Case Pelacani (Sicily).
Astrochronology. From 11.21 Ma to 10.55 Ma.

Remarks. A short interval with discontinuously present, more or less abundant, large specimens of *N. atlantica atlantica* occurs in the lower part of this Zone, between 11.15 Ma and 11.02 Ma. According to Foresi et al (1998) *G.* aff. *menardii* and *G. subquadratus* disappear in the lower part of this Zone. *Globorotalia lenguaensis* first occurs in this Zone (Foresi et al., inpress).

Integrated biostratigraphy. This Zone covers the upper part of the MNN7 Zone, all the MNN8a, defined at the base and at the top respectively by the LCO of *H. walbersdorfensis* at 10.76 Ma and by the FCO of *H. stalis* at 10.71 Ma, and the lower part of the MNN8b nannofossil Subzones of Fornaciari & Rio (1996). In its lower part the first very rare and scattered specimens of *D. brouweri* are present.

Conclusion

The detailed, fully quantitative analysis of the planktonic assemblages (calcareous nannofossils and planktonic foraminifera) in the same, closely spaced samples from three Mediterranean sections which cover the Middle Miocene interval between 13.75 Ma 10.50 Ma continuously, allowed us to propose a new integrated biostratigraphic zonal scheme for the interval (Fig. 6). The cyclostratigraphy of the three sections provided the ages of all the bioevents used to identify the boundaries of the adopted biozones and of the other minor bios-

Bioevents	Pelacani Section		S. Nicola Section		Ras Il-Pellegrin Section	
	Age (MA)	Preces. Cycles	Age (MA)	Preces. Cycles	Age (MA)	Preces. Cycles
FRO *N. acostaensis*	10.55	3				
FCO *H. stalis*	10.71	11/12				
Presence of *C. coalitus*	10.74	13/14				
LO *H. walbersdorfensis*	10.76	14/15				
FO *N. atlantica* (large)	11.15	34	11.15	34		
LCO *C. miopelagicus*	11.19	35/36	11.18	35/36		
LO *P .siakensis*	11.21	37	11.21	37		
LCO *P. siakensis*	11.23	38				
FRO *G. obliquus obliquus*	11.54	53/54	11.54	53/54		
LCO *G. subquadratus*	11.54	53/54	11.54	53/54		
LCO *D. kugleri*	11.60	56	11.60	56		
FO *N. atlantica preatlantica*	11.80	66	11.80	66		
FO *N. acostaensis* dextral	11.80	66	11.80	66		
LO *P. partimlabiata*	11.80	66	11.80	66		
FCO *D. kugleri*			11.90	71		
AE2 *P. siakensis*			12.00	75		
FCO *G. decoraperta* gr.			12.14	81		
LO *P. mayeri*			12.14	81		
FCO *C. macintyrei* >11μm			12.34	90		
FCO *P. mayeri*			12.34	90	12.34	90
AB2 *P. siakensis*			12.38	92	12.38	91/92
LCO *C. premacintyrei*			12.51	98	12.51	98/99
FO *C. macintyrei* >11μm			12.57	101	12.57	101
AE1 *P. siakensis*					12.58	101
FO *P. partimlabiata*					12.62	104
AB1 *P. siakensis*					13.22	131
FCO *R. pseudoumbilicus* ≥7μm					13.32	138
LO *P. peripheroronda*					13.39	142/143
LCO *Cycl. floridanus*					13.39	142/143
LO *S. heteromorphus*					13.59	151

Tab. 1 - Precessional cycles and ages of the biovents discussed in the text. Precessional informal cycle 1 coincides with the uppermost cycle of the Case Pelacani section.

tratigraphic events. Eight biostratigraphic intervals (Zones and Subzones) are proposed for the planktonic foraminifera biostratigraphy. Some acme and paracme intervals can be used to improve the biostratigraphic resolution. For the calcareous nannofossils, the zonal scheme of Fornaciari et al. (1996) was adopted, but the subdivision into three Subzones of the MNN7 Zone was included, following Hilgen et al. (2000). The age of all the bioevents is reported in Tab. 1.

Acknowledgments. We thank F.J. Sierro, K. v. Salis and W. A. Berggren for reviewing the manuscript and for their valuable comments and criticism which improved the initial version of the manuscript. This research has been supported by Murst Cofin 98.

REFERENCES

Backman J & Raffi I. (1997) - Calibration of Miocene nannofossil events to orbitally tuned cyclostratigraphies from Ceara Rise. In Shackleton N.J., Curry W.B., Richter C. & Bralower T.J. (eds.) Proc. ODP, Scient. Results, 154: 83-99, College Station (TX).

Cande S.C.& Kent D.V. (1995) - Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic. *J. Geophys. Res.*, 100: 6093-6095, Berkeley.

Caruso A., Sprovieri M., Bonanno A. & Sprovieri R. (2002) - Astronomical calibration of the Serravallian/Tortonian Case Pelacani Section (Sicily, Italy). In: Iaccarino S.M. (ed.) - Integrated Stratigraphy and Paleoceanography of the Mediterranean Middle Miocene, *Riv. It. Paleont. Strat.*, 108: 297-306, Milano.

Di Stefano E., Bonomo S., Caruso A., Dinarés-Turell J., Foresi L., Salvatorini & Sprovieri R. (2002) - Calcareous plankton bio-events in the Miocene Case Pelacani section (Sicily, Italy). In: Iaccarino S.M. (ed.) - Integrated Stratigraphy and Paleoceanography of the Mediterranean Middle Miocene, *Riv. It. Paleont. Strat.*, 108: 307-323, Milano.

Foresi L.M, Bonomo S., Caruso A., Di Stefano A., Di Stefano E., Iaccarino S.M., Lirer F., Mazzei R., Salvatorini G. & Sprovieri R. (2002) - High resolution calcareous plankton biostratigraphy of the Serravallian succession of the Tremiti Islands (Adriatic Sea, Italy). In: Iaccarino S.M. (ed.) - Integrated Stratigraphy and Paleoceanography of the Mediterranean Middle Miocene, *Riv. It. Paleont. Strat.*, 108: 257-274, Milano.

Foresi L.M, Bonomo S., Caruso A., Di Stefano E., Salvatorini G. & Sprovieri R. (2002b) - Calcareous plankton high resolution biostratigraphy (foraminifera and nannofossils)of the uppermost Langhian-lower Serravallian Ras Il-Pellegrin section (Malta). In: Iaccarino S.M. (ed.) - Integrated Stratigraphy and Paleoceanography of the Mediterranean Middle Miocene, *Riv. It. Paleont. Strat.*, 108: 195-210, Milano.

Foresi L.M, Iaccarino S., Mazzei R. & Salvatorini G. (1998) - New data on middle to late Miocene calcareous plankton biostratigraphy in the Mediterranean area. *Riv. It. Paleont. Strat.*, 104: 95-114, Milano.

Foresi L.M, Iaccarino S., Mazzei R., Salvatorini G. & Bambini A. M. (in press) - Il plancton calcareo (foraminiferi e nannofossili) del Miocene delle isole Tremiti. *Palaeont. It.*, Pisa.

Fornaciari E. & Rio D. (1996) - Latest Oligocene to early middle Miocene quantitative calcareous nannofossil biostratigraphy in the Mediterranean region. *Micropaleontology*, 42: 1-36, New York.

Fornaciari E., Di Stefano A., Rio D. & Negri A. (1996) - Middle Miocene quantitative calcareous nannofossil biostratigraphy in the Mediterranean region. *Micropaleontology*, 42: 37-63, New York.

Giannelli L. & Salvatorini F. (1975) - I foraminiferi planctonici dei sedimenti terziari dell'Arcipelago maltese. II.

Biostratigrafia di: "Blue Clay", "Greensand" e "Upper Coralline Limestone". *Atti Soc. Tosc. Sc. Nat., Mem.*, Ser. A, 82: 1-24, Pisa.

Hedberg H. D. (1976) - International Stratigraphic Guide - A guide to stratigraphic classification, terminology and procedure. John Wiley and Sons, 200 p. New York.

Hilgen F.J., Krijgsman W., Raffi I., Turco E., & Zachariasse W.J. (2000) - Integrated stratigraphy and astronomical calibration of the Serravallian/Tortonian boundary section at Monte Gibliscemi (Sicily, Italy). *Mar. Micropaleont.*, 38: 181-211, Amsterdam.

Iaccarino S. (1985) - Mediterranean Miocene and Pliocene planktic foraminifera. In: Bolli H.M. et Al. - Plankton *Stratigraphy*, 1: 283-314, Cambridge University Press.

Iaccarino S. & Salvatorini G. (1982) - A framework of planktonic foraminiferal biostratigraphy for Early Miocene to Late Pliocene Mediterranean area. *Paleont. Stratigr. ed Evoluz.*, Quad. 2: 115-125, Roma.

Lirer F., Caruso A., Foresi L.M., Sprovieri M., Bonomo S., Di Stefano A., Di Stefano E., Iaccarino S. M.,Salvatorini G., Sprovieri R. & Mazzola S. (2002) - Astrochronolo-gical calibration of the upper Serravallian/lower Tortonian sedimentary sequence at Tremiti Islands (Adriatic Sea, Southern Italy). In Iaccarino S.M. (ed.) - Integrated Stratigraphy and Paleoceanography of the Mediterranean Middle Miocene, *Riv. It. Paleont. Strat.* 108: 241-256, Milano.

Maiorano P. (1995) - Biostratigrafia a nannofossili calcarei di successioni torbiditiche mioceniche nell'Appennino Meridionale e di successioni pelagiche (DSDP e ODP) Mediterranee ed extra Mediterranee. (Tesi di Dottorato) Università degli Studi di Bari.

Martini E. (1971) - Standard Tertiary and Quaternary calcareous nannoplankton zonation. In: Farinacci A: (Ed.), Proceeding II Planktonic Conference, Roma (1970), 2: 739-785, Roma.

Okada H. & Bukry D. (1980) - Supplementary modification and introduction of code numbers to the low latitude coccolith biostratigraphic zonation (Bukry D., 1973; 1975). *Mar. Micropaleont.*, 5: 321-325, Amsterdam.

Salvatorini G. & Cita M.B. (1979) - Miocene foraminiferal stratigraphy, DSDP Site 397 (Cape Bojador, North Atlantic). In Ryan, W.B.F. et Al., Init. Rep. Deep Sea Drill. Project, 47(1): 317-373, Washington.

Salvador A. (1994) - International Stratigraphic Guide - A guide to stratigraphic classification, terminology, and procedure. Second Edition. The Geological Society of America, 213 pp. Boulder, Colorado.

Sprovieri M., Caruso A., Foresi L., Bellanca A., Neri R., Mazzola S. & Sprovieri R. (2002) - Astronomical calibration of the upper Langhian/lower Serravallian record of the Ras-Il Pellegrin section (Malta Island, central Mediterranean). In Iaccarino S.M. (ed.) - Integrated Stratigraphy and Paleoceanography of the Mediterranean Middle Miocene, *Riv. It. Paleont. Strat.* 108: 183-194, Milano.

Theodoridis S. (1984) - Calcareous nannofossil biozonation of the Miocene and revision of the Helicoliths and Discoasters. *Utrecht Micropaleont. Bull.*, 32: 1-271, Utrecht.