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NEW DATA ON MIDDLE TO LATE MIOCENE CALCAREOUS PLANKTON BIOSTRATIGRAPHY IN THE MEDITERRANEAN AREA

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Riassunto. Sono state esaminate e/o riesaminate le associazioni a foraminiferi planctonici di sei sezioni mioceniche delle quali 5 nell' area mediterranea e una in Oceano Atlantico (Site 397). Lo scopo era quello di migliorare le conoscenze biostratigrafiche dell'intervallo Serravalliano-Tortoniano inferiore ed in particolare di controllare le distribuzioni stratigrafiche di *Neogloboquadrina acostaensis* (Blow) e *Paragloborotalia siakensis* (Le Roy) sulle quali secondo i dati bibliografici più recenti non esiste più un generale consenso. Lo studio delle associazioni ha permesso di riconoscere una successione di eventi in parte nuovi per l'area mediterranea ed in particolare di documentare un intervallo di concomitanza tra le distribuzioni di *P.lia siakensis* e *N. acostaensis*.

I nuovi dati hanno consentito di emendare lo schema zonale di Iaccarino e Salvatorini (1982) e Iaccarino (1985) relativo all'intervallo Serravalliano-Tortoniano. In particolare é stato accertato che la comparsa di *Neogloboquadrina acostaensis* (Blow) é un evento di età serravalliana, e che la scomparsa di *P.lia siakensis* (Le Roy) avviene dopo la comparsa di *N. acostaensis*.

La nuova zonazione é stata calibrata rispetto alla zonazione a nannofossili calcarei, alla scala cronostratigrafica e a quella geocronologica. Alla luce di questi nuovi dati é emerso che nella sezione tipo del Tortoniano gli eventi più prossimi alla sua base sono la LO di *P.lia siakensis*, la FCO di *N. acostaensis* e la FO di *Discoaster hamatus*. Pertanto si raccomanda di utilizzare questi eventi nella scelta del GSSP del limite Serravalliano-Tortoniano.

Abstract. Planktonic foraminifera from one Atlantic Ocean (Site 397) and five Mediterranean sequences of middle to late Miocene age were investigated. The aim of the research was to refine the biostratigraphy of the Serravallian to early Tortonian interval and, since the recent literature provides no general consensus, to check the range of *Neogloboquadrina acostaensis* (Blow) and *Paragloborotalia siakensis* (Le Roy).

Examination of planktonic foraminifera identified a succession of events which is, in part, new in the Mediterranean area, and documented an overlap in the distribution of *N. acostaensis* and *P.lia siakensis*.

Based on the new data, the zonal scheme for the Serravallian to early Tortonian interval proposed by Iaccarino and Salvatorini (1982) and Iaccarino (1985) was emended. In particular, it was ascertained that the first occurrence (FO) of *N. acostaensis* falls in the upper part of the Serravallian, well before the last occurrence (LO) of *P.lia siakensis*. The new zonation was calibrated with the calcareous nannofossil zonation and the geomagnetic polarity time scale. In light of these new data, the events closest to the base of the Rio Castellania-Rio Mazzapiedi-Tortonian type-section are the LO of *P.lia siakensis*, the first common occurrence (FCO) of *N. acostaensis*, and the FO of *Discoaster hamatus*.. Therefore, the use of these events in selecting the GSSP of the Serravallian/Tortonian boundary is recommended.

Fig. 1 - Geographic location of the sections investigated.

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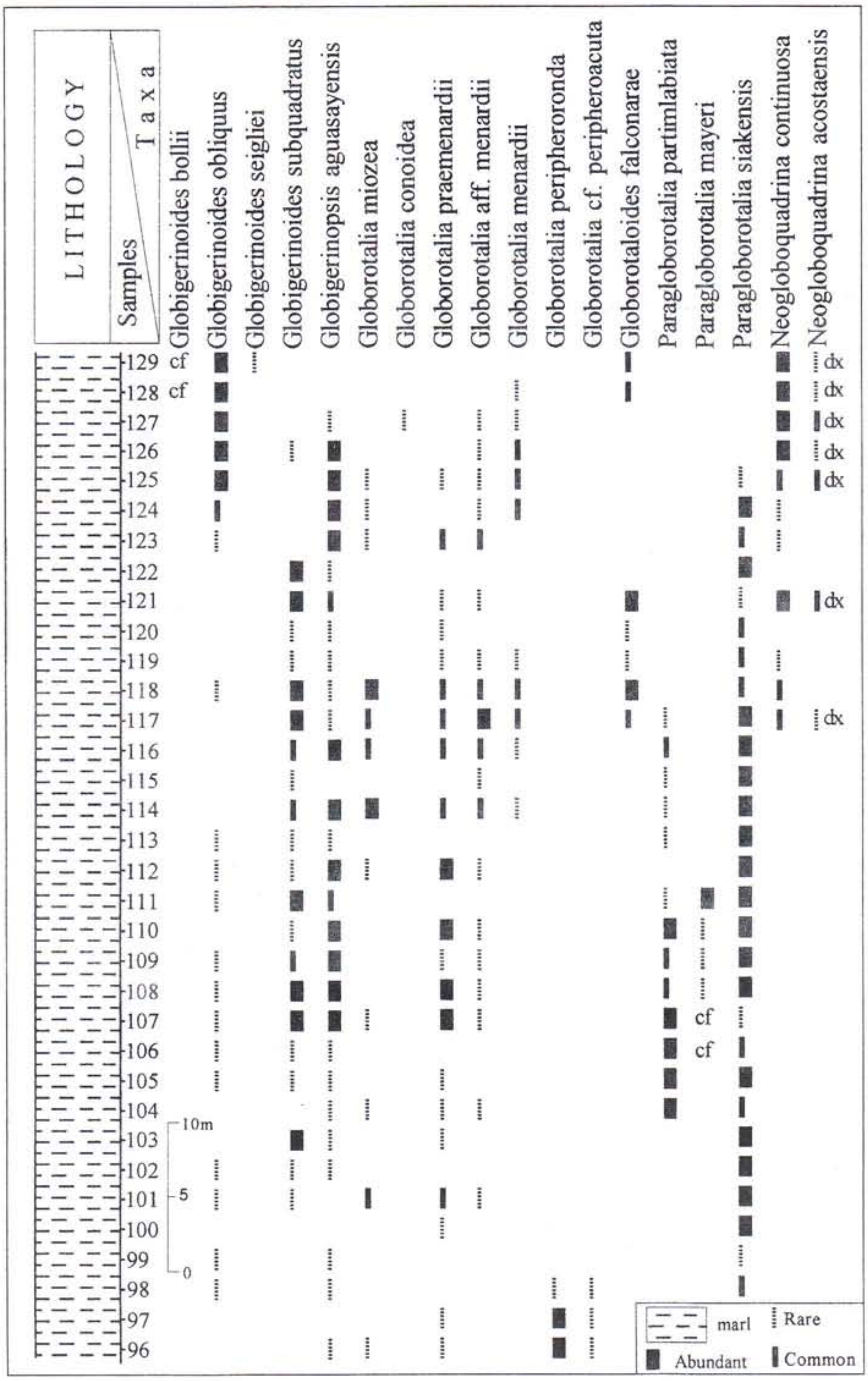


Tab. 1 - Distribution of selected planktonic foraminifera from Section 9 of Tremiti Islands; dx = dextral coiling.

Introduction.

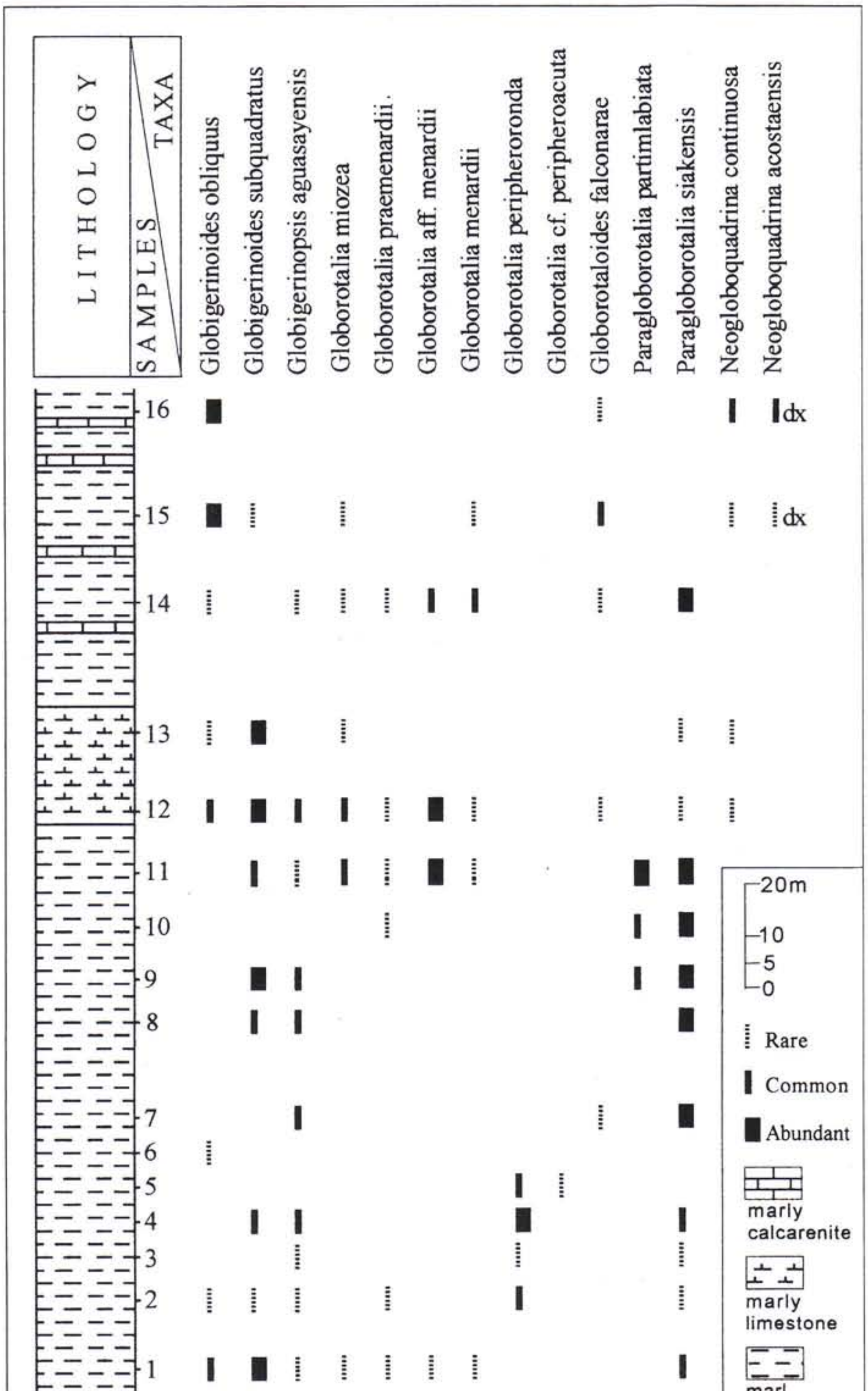
The presence of an interval (*Globorotalia menardii* Zone of Bolli, 1957 or Zone N15 of Blow, 1969) separating the last occurrence (LO) of *Paragloborotalia siakensis* (Le Roy) (= *Globorotalia mayeri* Cushman & Ellisor sensu Bolli, 1957; Bolli & Saunders, 1982, 1985) from the first occurrence (FO) of *Neogloboquadrina acostaensis* (Blow) is widely recorded throughout middle-late Miocene sedimentary sequences. In fact, it is believed that the former taxon disappears in the late Serravallian, whereas the latter appears in the early Tortonian, and many biostratigraphic zonations are based on these two events (Bolli, 1966; Blow, 1969; Bizon & Bizon, 1972; Borsetti et al., 1979; Bolli & Saunders, 1985; Iaccarino & Salvatorini, 1982; Iaccarino, 1985 among others).

According to Miller et al. (1985, 1991), the LO of *P.lia siakensis* and the FO of *N. acostaensis* are two events very close to each other at Sites 563, 558, and 608, and therefore the validity of Zone N15 of Blow (1969) and its equivalents is discussed here. Some authors (e.g. Cita et al., 1965; Huddleston, 1984; Mazza, 1985; Coccioni et al., 1992; Foresi, 1993) documented a partial overlap in the ranges of both taxa. The co-occurrence of *P.lia siakensis* and *N. acostaensis* was recorded also by Salvatorini & Cita (1979), Poore (1979), and Romeo & Sciuto (1987), but these authors attributed the overlap of *P.lia siakensis* to reworking.

Since this topic has great implications not only for the biostratigraphy but also for the chronostratigraphy of the Middle to Late Miocene interval, some Mediterranean and extra-Mediterranean sections encompassing this interval were examined or re-examined. The stratigraphic interval from the FO of *Globorotalia praemenardii* Cushman & Stainforth to the FO of *Globigerinoides extremus* Bolli & Bermudez is discussed to test the succession of bioevents and their reliability for a possible emendation of the Mediterranean planktonic foraminiferal zonal scheme of Iaccarino & Salvatorini (1982) and Iaccarino (1985), and consequently also those of Blow (1969, 1979) and Bolli & Saunders (1985).

Material.

Sequences from the Tremiti Islands in the Adriatic Sea, the M. Giammoia and Fiume Bianco sections in Sicily, Site 372 (DSDP Leg 42) in the Balearic Basin, and Site 397 (DSDP Leg 47A) at Cap Boja-



SAMPLES	Globigerinoides obliquus	Globigerinoides subquadratus	Globigerinopsis aguasayensis	Globorotalia miozea	Globorotalia praemenardii	Globorotalia aff. menardii	Globorotalia menardii	Globorotalia peripheroronda	Globorotalia cf. peripheroacuta	Globorotaloides falconarae	Paragloborotalia partimlabiata	Paragloborotalia siakensis	Neogloboquadrina continuosa	Neogloboquadrina acostaensis
16	Abundant									Rare			Common	Common dx
15	Abundant	Rare		Rare			Rare			Common			Rare	Rare dx
14	Rare		Rare	Rare	Rare	Common	Common			Rare		Abundant		
13	Rare	Abundant		Rare								Rare	Rare	
12	Common	Abundant	Common	Common	Rare	Abundant	Rare			Rare		Rare	Rare	
11		Common	Rare	Common	Rare	Abundant	Rare				Abundant	Abundant		
10					Rare						Common	Abundant		
9		Abundant	Common								Common	Abundant		
8		Common	Common									Abundant		
7			Common							Rare		Abundant		
6	Rare													
5								Common	Rare					
4		Common	Common					Abundant				Common		
3			Rare					Rare				Rare		
2	Rare	Rare	Rare		Rare			Common				Rare		
1	Common	Abundant	Rare	Rare	Rare	Rare	Rare					Common		

⁞ Rare
▮ Common
█ Abundant

Tab. 2 - Distribution of selected planktonic foraminifera from Bianco River section (Sicily); dx = dextral coiling.

dor in the Atlantic Ocean were studied (Fig. 1). Moreover, the lower portion of the Tortonian stratotype (Rio Mazzapiedi-Castellania Section in Piedmont) was re-examined. The range chart of selected taxa and their estimated abundance, obtained through semiquantitative analysis, are reported in Tables 1 to 6 for all investigated sequences. The taxonomy of Kennett & Srinivasan (1983) was followed.

Tremiti Islands (Adriatic Sea, Southern Italy).

The study of calcareous plankton from several Miocene sections cropping out on the Tremiti Islands is currently in progress. In the present paper, only the biostratigraphic results from Section 9 (Tab. 1), located in the NE of S. Nicola Island, close to the cemetery, are presented. Section 9 consists of 70 m of cyclically alternating whitish and gray marls (Cretaccio Formation of Selli, 1971). In the 34 samples investigated, the terrigenous fraction is absent and planktonic foraminifera are abundant and very well preserved.

Bianco River Section (Sicily).

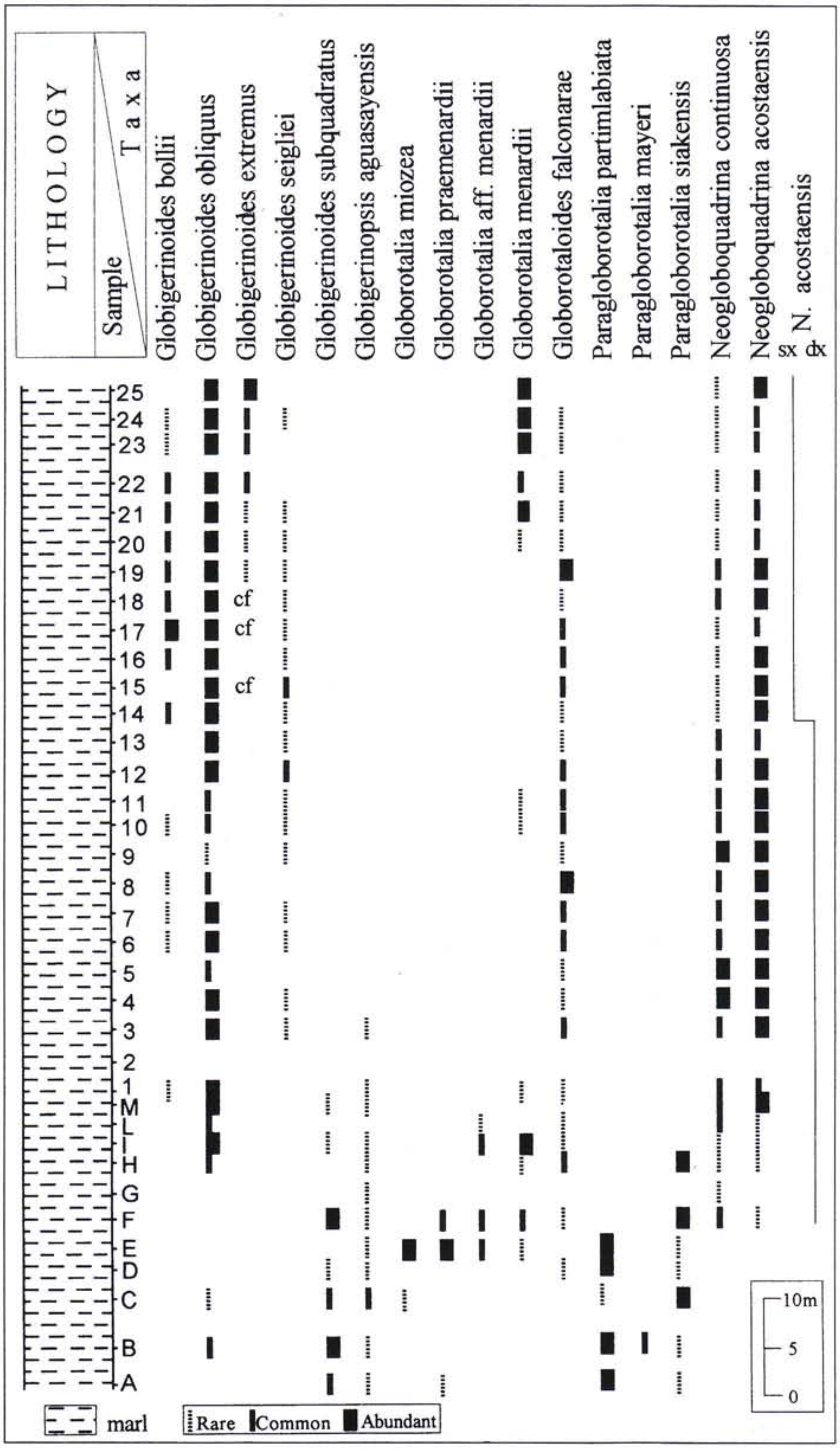
This section, 250 m thick, was sampled by Romeo & Sciuto (1989) along the Bianco River, left tributary of the Tellaro River (southern M. Iblei). It consists of marls and subordinated marly-limestones and marly-calcarenitic alternations belonging to the Tellaro Formation (Rigo & Barbieri, 1958). On the basis of planktonic foraminifera Romeo & Sciuto (1987), and subsequently Foresi (1993), referred the succession to the Serravallian-lower Tortonian interval and documented a hiatus in the basal part of the section. Both sets of samples, yielding abundant and well preserved foraminifera, were further examined in this work (Tab. 2).

M. Giammoia Section (Sicily).

The calcareous plankton of the Tortonian-Messinian interval from this section was studied by Romeo (1969), Colalongo et al. (1979), Zachariasse & Spaak (1983), Theodoridis (1984), Van der Zwaan & Gudjonsson (1986) and Miculan (1994). The lowest part of this section, investigated by Colalongo et al. (1979), up to sample 25, plus a set of samples (named A to M) underlying the base of Colalongo's sequence, were re-investigated in the present study (Tab. 3). The entire interval consists of alternating whitish and gray marls belonging to the "Globigerina Marls" or "Licata Formation" (Ogniben, 1954) and yielded rich and well preserved planktonic foraminiferal assemblages.

Site 372 (DSDP Leg 42, Balearic Basin).

This hole was drilled on the eastern side of the Menorca escarpment at a water depth of 2699 m. Planktonic foraminifera were studied by Bizon et al. (1978), Bizon & Glaçon (1972), Cita et al. (1978), Thunnell (1979), and Foresi (1993), while calcareous nannofossils were investigated by Müller (1978), Theodoridis (1984), and Negri (1988). All authors, except for Theodoridis (1984), recognised a hiatus in Core 9; the sediments above the hiatus were unanimously referred to the Messinian, while those below were referred either to the Serravallian (Cita et al., 1978) or to the Tortonian (Bizon, p. 80, in Shipboard Scientific Party, 1978). The Miocene sequence (Cores 9-24) below the hiatus, consisting of 150 m marly sediments, was investigated in the



Tab. 3 - Distribution of selected planktonic foraminifera from M. Giammoia section (Sicily); dx = dextral coiling; sx = sinistral coiling.

present study. In the 152 samples studied, the same as those examined by Cita et al. (1978) and Foresi (1993), the biogenic fraction consists mainly of generally well preserved planktonic foraminifera (Tab. 4).

Site 397 (DSDP Leg 47A, Eastern North Atlantic).

Hole 397 is located in the eastern part of the Atlantic Ocean, on the uppermost rise off Cap Bojador (south of the Canary Islands), and it was drilled at 2900 m water-depth. The Neogene calcareous plankton was studied previously by Salvatorini & Cita (1979), Cita & Colombo (1979), Mazzei et al. (1979), Cepek & Wind (1979), and Spaak (1983). The 78 samples from Cores 61-77 encompassing the Serravallian-Tortonian interval were re-examined in this study (Tab. 5). Lithologically, this interval consists of hemipelagic chalks to limestone with sandy beds. The hemipelagic sedimentation is disturbed by slumps, cross stratification, and graded beds. Planktonic foraminiferal assemblages are abundant and well preserved except for the lowest part of the interval where they are less abundant and only moderately preserved.

Comments on the bioevents.

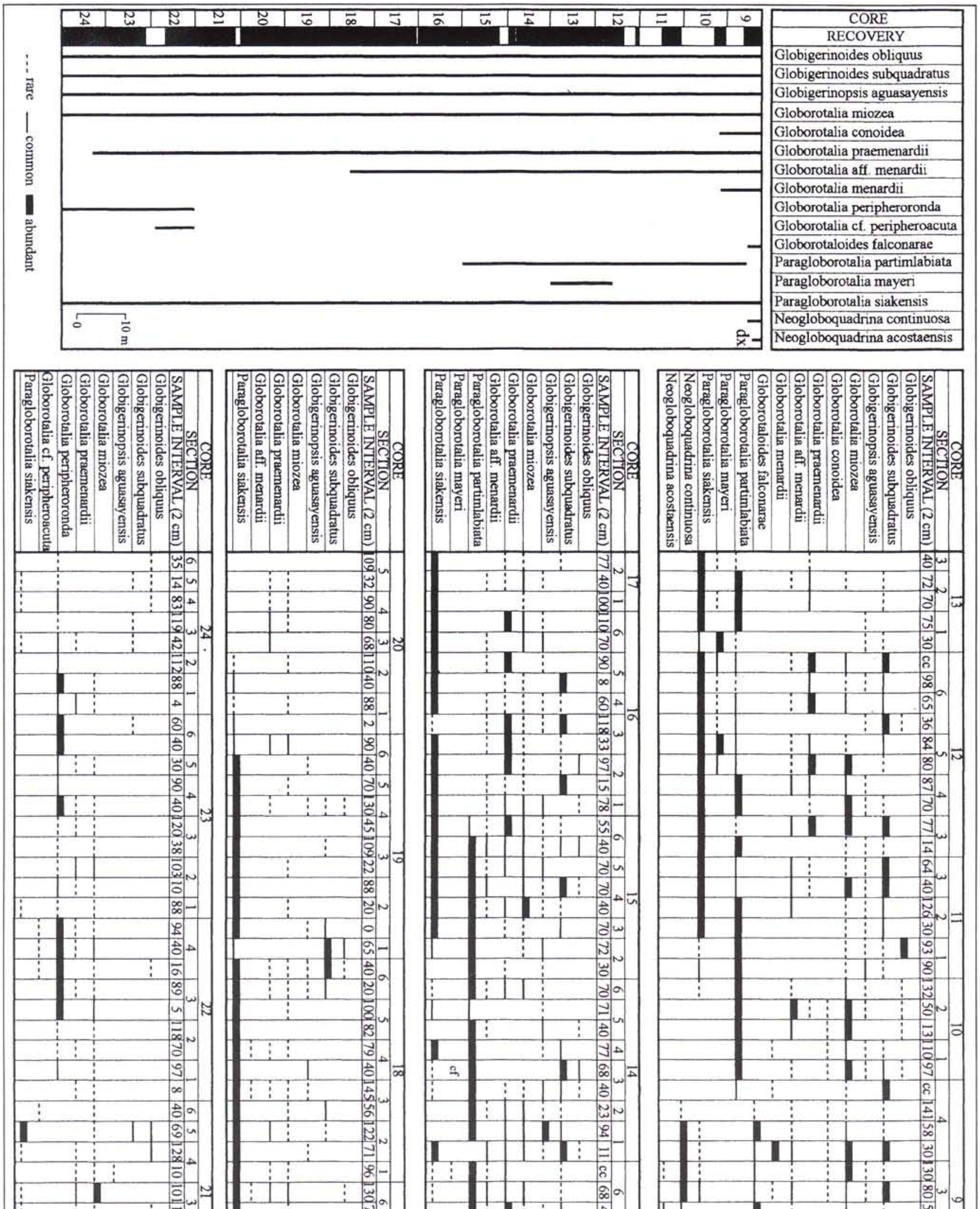
The positions of the most reliable planktonic foraminifera events recognised in the sections studied are indicated in Fig. 2. These events are correlated with calcareous nannofossil data obtained from the literature (Site 372, Negri, 1988; Site 397, cores 77-70, Mazzei et al., 1979) and direct observation (Section 9 of Tremiti Islands; M. Giammoia Section; Site 397, cores 71-61). The events are as follows (from bottom to top):

FO of *Globorotalia praemenardii.*

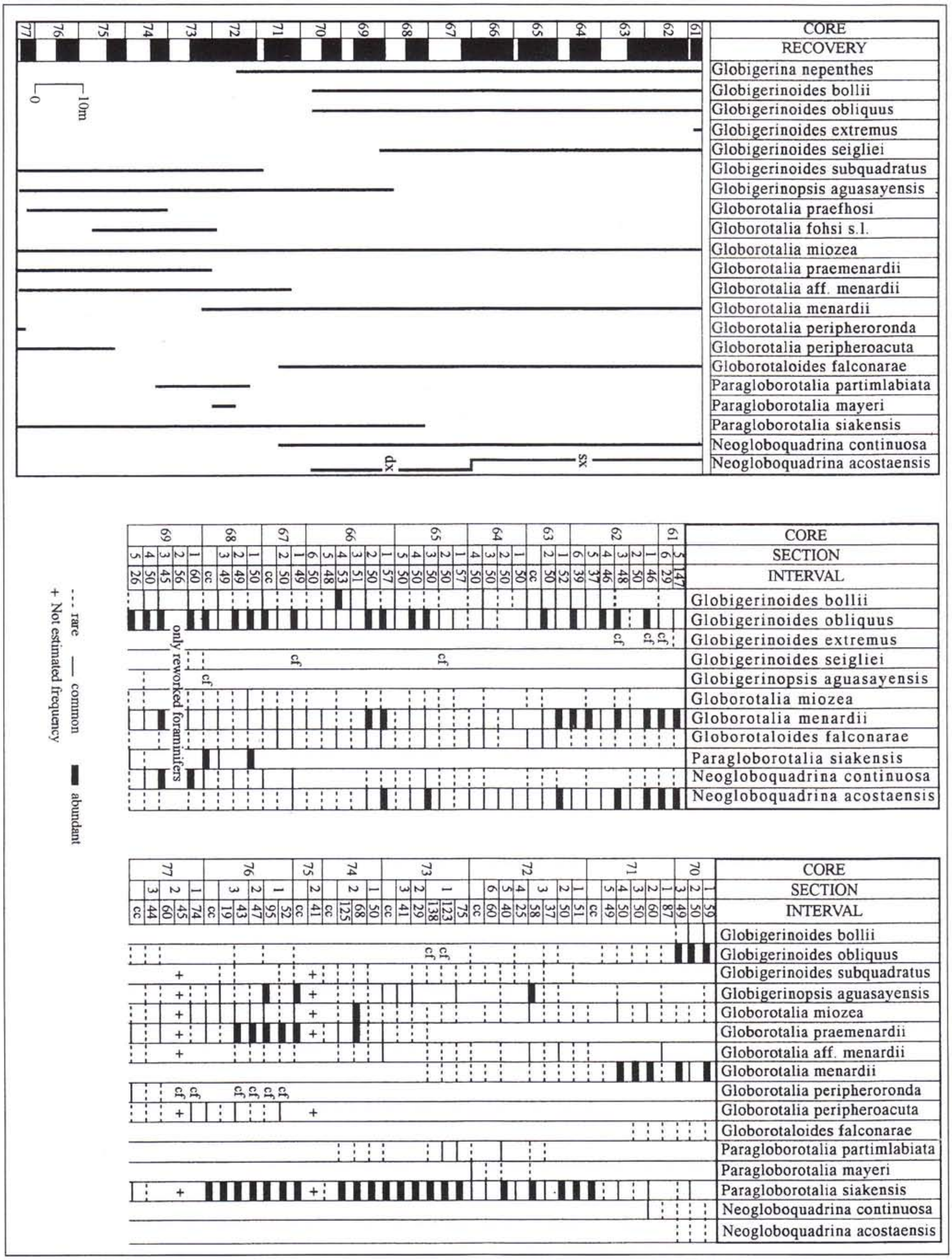
The species concept of Blow (1969) was rigorously followed for this taxon. Its FO was detected only at Site 372, in Core 24. The species ranges throughout the Serravallian but its abundance is very variable, becoming rare and discontinuous in the upper part of its range. Therefore, the LO of *Gl. praemenardii* is difficult to detect but is very close to the LO of *P.lia siakensis* (Fig. 2 and Tab. 1, 2, 3, 5, 6).

LO of *Globorotalia peripheroronda.*

The typical *Gl. peripheroronda* disappears just after the LO of *Sphenolithus heteromorphus* in the sections



Tab. 4 - Distribution of selected planktonic foraminifera of Site 372, Leg 42 (Balearic Basin); dx =dextral coiling.



Tab. 5 - Distribution of selected planktonic foraminifera at Site 397, Leg 47A (Northeastern Atlantic); dx= dextral coiling, sx= sinistral coiling.

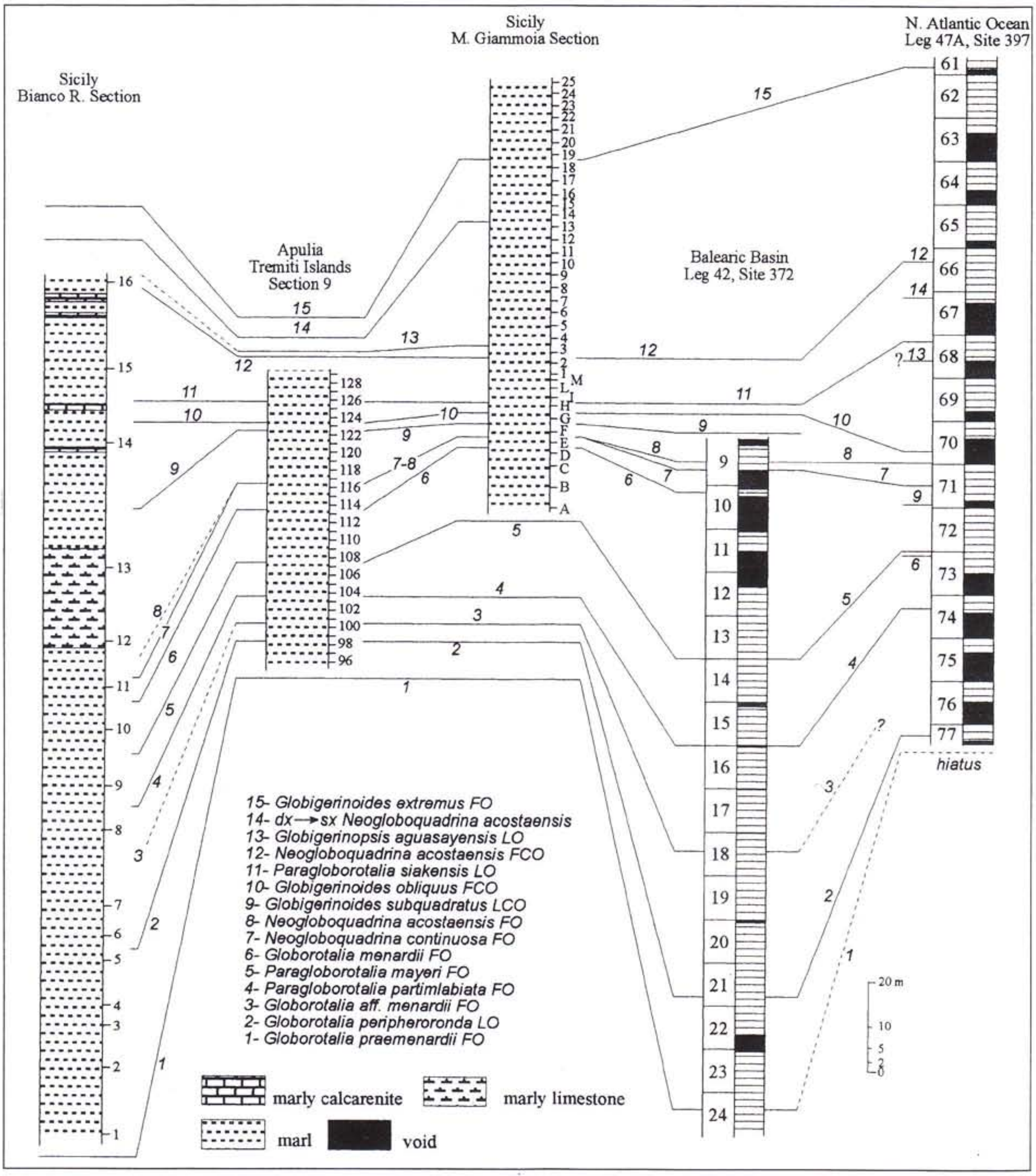


Fig. 2 - Correlation of the sections and holes based on the main biostratigraphic events; horizontal lines in DSDP stratigraphic logs indicate core section subdivisions.

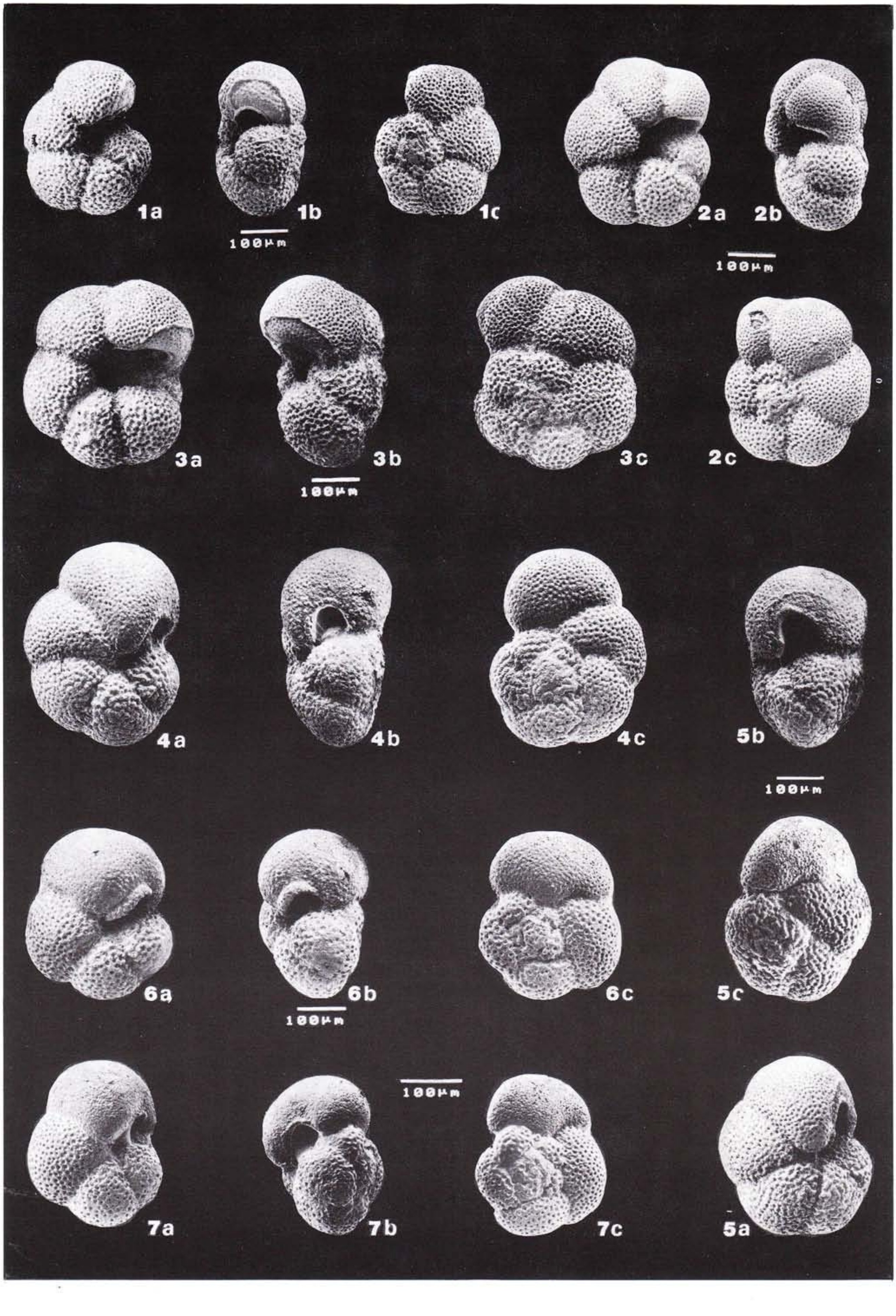
PLATE 1

Fig. 1-3 - *Paragloborotalia siakensis* (Le Roy); Sample TD-121;
a: umbilical view; b: lateral view; c: spiral view.

Fig. 4-5 - *Paragloborotalia mayeri* Cushman; Sample TD-111;
a: umbilical view; b: lateral view; c: spiral view.

Fig. 6 - *Paragloborotalia partimlabiata* Ruggieri and Sprovieri; Sample TD 105;
a: umbilical view; b: lateral view; c: spiral view.

Fig. 7 - *Paragloborotalia partimlabiata* Ruggieri and Sprovieri; Sample TD 104;
a: umbilical view; b: lateral view; c: spiral view.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examined, as already observed in other Mediterranean and extra-Mediterranean sequences (Giannelli & Salvatorini, 1975; Mazzei, 1980, 1985; Bizon et al., 1978; Müller, 1978; Cepek & Wind, 1979; Salvatorini & Cita, 1979; Bossio et al., 1991; Rio & Fornaciari, 1994). According to Berggren et al. (1985), Berggren (1993), and Aubry (1993) the LO of *Sphenolithus heteromorphus* slightly postdates the LO of *Gl. peripheroronda.*

It is worth mentioning that rare specimens, morphologically intermediate between *Gl. peripheroronda* and its descendant *Gl. peripheroacuta* occur at the Tremiti Islands (Section 9), in Sicily (F. Bianco Section), and at Site 372. This transitional form, here named *Gl.* cf. *peripheroacuta*, differs from the typical *Gl. peripheroacuta* mainly by a less angular peripheral margin (Tables 1, 2, 4) and was already recorded by Giannelli & Salvatorini (1975) and Martinotti (1981, *cum bibl.*).

FO of *Globorotalia* aff. *menardii.*

This taxon shows morphological features which are intermediate between *Gl. praemenardii* and *Gl. menardii.* It corresponds to the *Gl.* ex *cultrata* group of Cita et al. (1978) who described this taxon. At the Tremiti Islands and Site 372, the FO of this intermediate sinistral form, is well constrained between the LO of *Gl. peripheroronda* and the FO of *Paragloborotalia partimlabiata.* On the contrary, at Site 397 the first specimens of *Gl.* aff. *menardii* predate the LO of *Gl. peripheroronda.*

FO of *Paragloborotalia partimlabiata* (Pl. 1, fig. 6-7).

This taxon, common in the Mediterranean area (Ruggieri & Sprovieri, 1970; Giannelli & Salvatorini, 1976; Zachariasse & Spaak, 1983; Chamley et al., 1986), is not usually recorded in oceanic sequences (probably because it is considered a morphological variant of *P.lia mayeri/P.lia siakensis* or a senior synonym of *Gl. challengeri*, as suggested by Zachariasse, 1992). However, Salvatorini & Cita (1979) as well as Iaccarino & Salvatorini (1979) recorded this taxon in the Atlantic Ocean (Site 397 and Site 398, respectively) starting from Blow's Zone N12. According to Chamley et al. (1986), the arrival of *P.lia partimlabiata* is a cool-water migratory event from the Northern Atlantic, and the sudden spreading of this species in the Mediterranean and off north-east Africa resulted from the inflow of cool waters from higher latitudes. In fact, in Northwest Australia (Sites 361-362) *P.lia partimlabiata* arrives much later, just above the level with the last appearance of *P.lia mayeri* (=*siakensis*), strongly supporting its northern bioprovincial origin (Zachariasse, 1992). Therefore, the first appearance of *P.lia partimlabiata* is a time-transgressive event which takes place in the Mediterranean well before the last occurrence of *P.lia siakensis* (Fig. 2).

The entry level of *P.lia partimlabiata* is easily recognisable in all sections except at Site 397, where it is very rare in the lower part of its range, confirming the preference of this taxon for cooler water masses (Srinivasan & Kennett, 1981; Chamley et al., 1986). The FO of *P.lia partimlabiata* (Pl. 1, fig. 6-7) slightly postdates the FO of *Discoaster kugleri* in the sections examined. The succession of these two events was observed also in other Miocene sequences (i.e. Malta, Giannelli & Salvatorini, 1975; Mazzei, 1980, 1985). It is not documented by Rio & Fornaciari (1994) and Fornaciari et al. (1996) in the Mediterranean, since they define the NN6/NN7 boundary on the basis of the FCO of *D. kugleri* instead of its FO.

The LO of *P.lia partimlabiata* virtually coincides with the FO of *Neogloboquadrina continuosa* and *N. acostaensis* and it is very close to the FCO of *Globigerinoides obliquus.* At Site 397 (Tab. 5), the LO of *P.lia partimlabiata* predates the FO of both *N. continuosa* and *N. acostaensis.*

FO of *Paragloborotalia mayeri* (Pl. 1, fig. 4-5).

The species concept of Blow (1969), which is remarkably different from other authors' (Bizon & Bizon, 1972; Bolli & Saunders, 1982, 1985) who also includes

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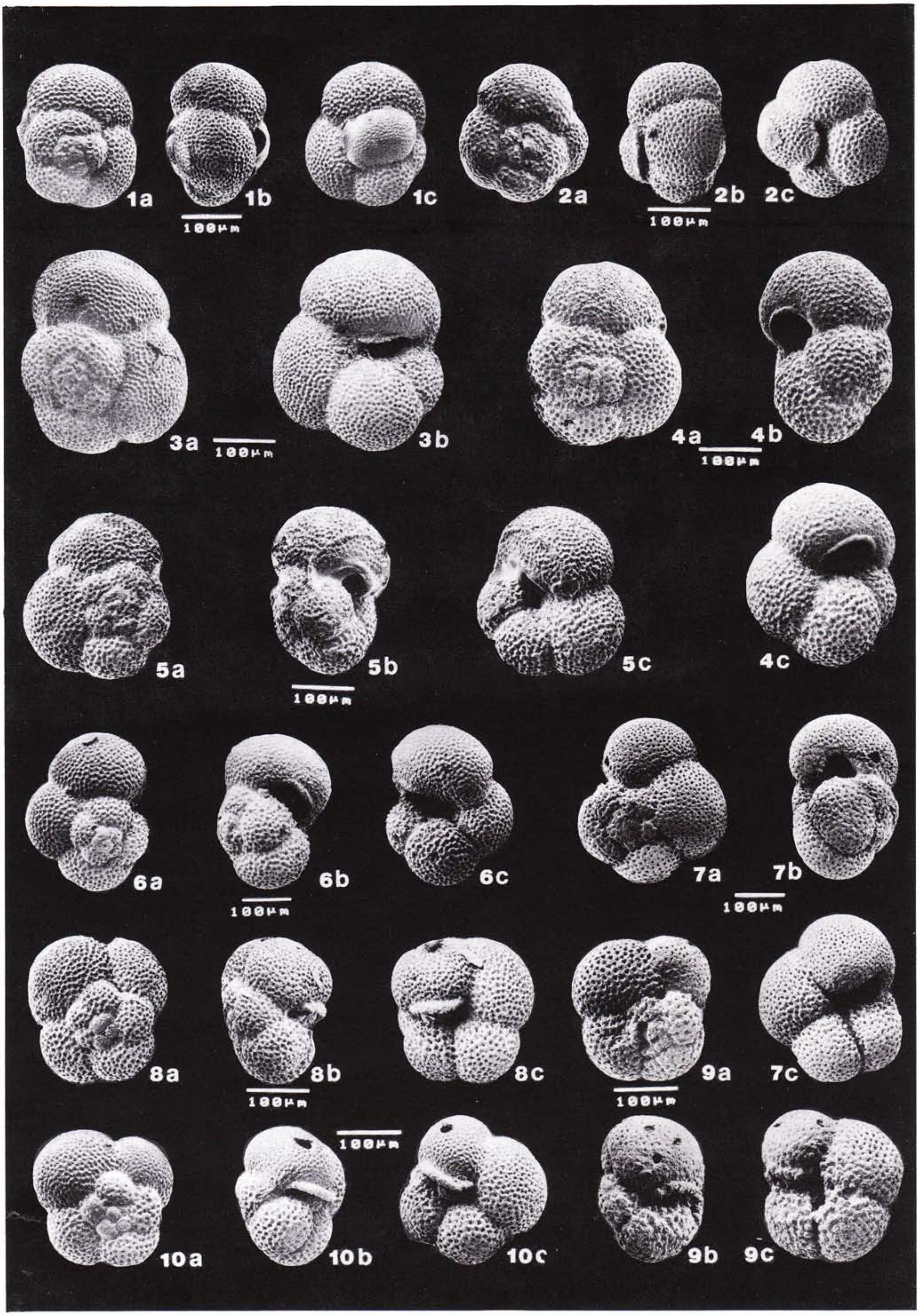
PLATE 2

Fig. 1-3 - *Globorotaloides falconarae* Giannelli and Salvatorini; Sample MG-16
a: spiral view; b: lateral view; c: umbilical view
Fig. 4 - *Globorotaloides falconarae/ Neogloboquadrina continuosa* transitional form; Sample TD-118
a: spiral view; b: lateral view; c: umbilical view
Fig. 5 - *Neogloboquadrina continuosa* (Blow); Sample TD-121
a: spiral view; b: lateral view; c: umbilical view
Fig. 6 - *Neogloboquadrina continuosa* (Blow); Sample TD-117
a: spiral view; b: lateral view; c: umbilical view
Fig. 7 - *Neogloboquadrina continuosa /Neogloboquadrina acostaensis* transitional form; Sample TD-121
a: spiral view; b: lateral view; c: umbilical view
Fig. 8,10 - *Neogloboquadrina acostaensis* (Blow); Sample TD-121
a: spiral view; b: lateral view; c: umbilical view
Fig. 9 - *Neogloboquadrina acostaensis* (Blow); Sample TD-117
a: spiral view; b: lateral view; c: umbilical view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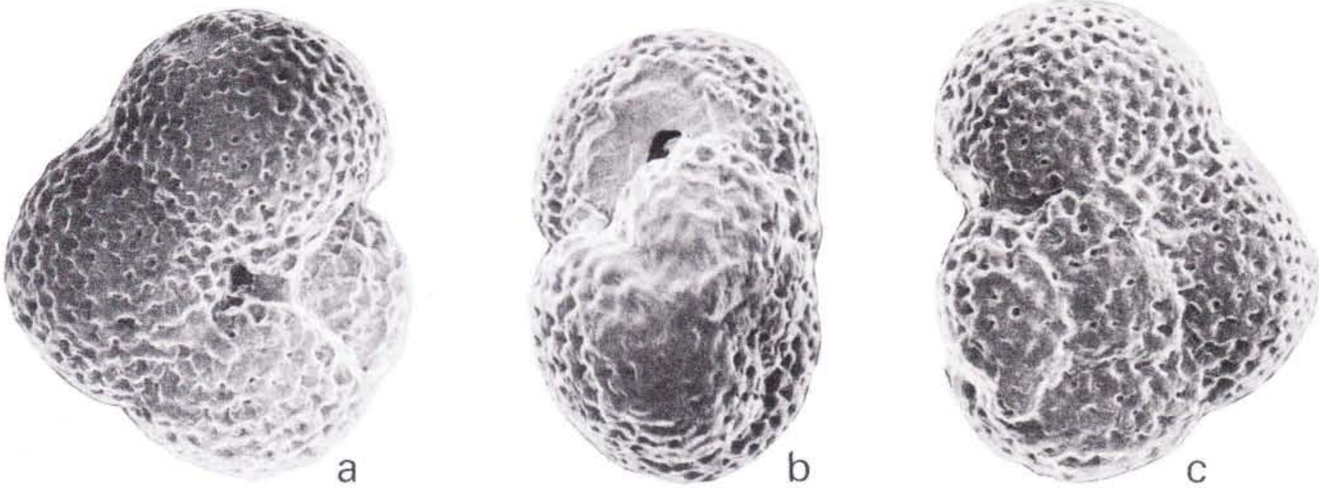


Fig. 3 - *Neogloboquadrina continuosa* (Blow), holotype, x 200; a: umbilical view; b: lateral view; c: spiral view.

in this taxon *Paragloborotalia siakensis*, is followed here. In our record (Tab. 1, 3, 4) the range of *P.lia mayeri* (Pl. 1, fig. 4-5) is very short and is observed between the FO of *P.lia partimlabiata* and the FO of *Gl. menardii*. The taxon was not recorded in the F. Bianco Section, probably because of low resolution sampling (Tab. 2).

FO of *Globorotalia menardii*.

Gl. menardii likely evolved from *Gl. praemenardii* via *Gl.* aff. *menardii*. This evolutionary trend was very slow and gradual and creates some difficulties in recognising the first appearance of typical *Gl. menardii*. In all the Mediterranean sections investigated, the FO of *Gl. menardii* falls between the LO of *P.lia mayeri* and the FO of *N. continuosa*. At Site 397 the FO of *Gl. menardii* occurs prior to the FO of *P.lia mayeri*. *Gl. menardii* is similar to *Gl. menardii* form 3 described by Zachariasse (1975) from the same stratigraphic levels.

FO of *Neogloboquadrina continuosa* (Pl. 2, fig. 5-6).

The specimens referred to *N. continuosa* correspond to the holotype as defined and described by Blow (1959, 1969). However, in contrast to Blow we suggest a younger first occurrence for this species. In agreement with Bolli (1985), we believe that the specimens recorded by most authors in the lower Miocene are 4 chambered morphotypes of *P.lia siakensis*. It is worth noting that the holotype was described from a level of the Pozon Formation (Eastern Falcon, Venezuela) belonging to Blow's Zone N14, that is almost coeval with the level we recognise the FO of *N. continuosa*.

The FO of *N. continuosa* is an easily detectable event both in Mediterranean and extra-Mediteranean areas. Zachariasse (1975), and Zachariasse & Spaak (1983) provided a similar range for this taxon from Southern Italy. Subsequently, Zachariasse (1992) considered the specimens labelled in 1975 as *Globorotalia continuosa* as a small phenotype of *Neogloboquadrina atlantica* and suggested that the latter taxon was the ancestor of *N. acostaensis*, rejecting *N. continuosa* as a valid taxon. The holotype of *N. continuosa* is illustrated in Fig. 3 (courtesy of B. Huber, Curator, Smithsonian Institution, Washington). Contrary to Zachariasse (1992) we believe that *N. continuosa* is still a valid taxon, and that the small phenotypes attributed by this author to *N. atlantica* are closer to *Globorotaloides falconarae*, a taxon occurring within the Langhian interval (Fornaciari et al., 1997). Therefore, intermediate *G. falconarae-N. continuosa* specimens (Pl. 2, fig. 4a, b, c) suggest *Gd. falconarae* as a possible ancestor of *N. continuosa*.

FO of *Neogloboquadrina acostaensis* (Pl. 2, fig. 8-10).

The FO of *N. acostaensis* was recognised at the same level as the FO of *N. continuosa*, or very close to it, in all sections investigated. However, *N. acostaensis* is rare and discontinuous at the beginning of its range, while it becomes consistently present and common (FCO) in higher levels (M. Giammoia section) (Tab. 3). The FO of *N. acostaensis* predates the LCO of *Gs. subquadratus*, the FCO of *Gs. obliquus*, and the LO of *P.lia siakensis* and falls within the upper part of the *Discoaster kugleri* Zone. The FCO of *N. acostaensis* postdates the FO of *Discoaster hamatus* (the lower boundary of the NN9 Zone). The coiling of *N. acostaensis* is mainly dextral in the lower part of its range and becomes predominantly sinistral just prior to the FO of *Gs. extremus*, within the *D. hamatus* Zone. Such a coiling range is consistent with that recorded by Zachariasse & Spaak (1983) in Sicily, but differs substantially from that reported by Coccioni et al. (1992, 1994) and Coccioni & Galeotti (1995) from the Marche region, the most striking discrepancy being that *N. acostaensis* is sinistrally coiled at the base of its range.

LCO of *Globigerinoides subquadratus.*

This taxon sharply decreases in abundance before the FCO of *Gs. obliquus* and only rare specimens are recorded in younger levels. This pattern occurs in all the sections examined, except at Site 397 where *Gs. subquadratus* is always very rare.

FCO of *Globigerinoides obliquus.*

This taxon occurs throughout the interval investigated, but becomes common from just prior to the LO of *P.lia siakensis* upwards in the Miocene sequence (see also Martinotti 1981, 1990; Zachariasse & Spaak, 1983). The increase in abundance of *Gs. obliquus* is considered here a biostratigraphically important event.

LO of *Paragloborotalia siakensis* (Pl. 1, fig. 1-3).

The extinction level of this taxon is an easily recognisable event because it is preceded by a sharp decrease in abundance. As mentioned above (see *N. acostaensis*) the LO of *P.lia siakensis* falls within the range of *N. acostaensis* but precedes its FCO. We believe that the LO of *P.lia siakensis* is an event that is correlated well in Mediterranean and extra-Mediterranean sequences (Berggren et al., 1985; Miller et al., 1985, 1991).

LO of *Globigerinopsis aguasayensis.*

Specimens referable to this species occur from the base of the interval investigated. *G. aguasayensis* becomes common in the middle part of the interval and disappears after the FO of *Gs. seigliei* (Tab. 3).

FO of *Globigerinoides extremus.*

This event was recorded in the M. Giammoia Section (Tab. 3) and at Site 397 (Tab. 5). In both sections, the evolutionary trend from *Gs. obliquus* is easily detectable. The FO of *Gs. extremus* falls within the *Discoaster calcaris* Zone.

Biostratigraphic implications.

The most important biostratigraphic implication of the observed succession of bioevents is the suppression of both the *Globorotalia menardii* Zone of Bolli (1966), Bizon & Bizon (1972), Borsetti et al. (1979), Iaccarino & Salvatorini (1982), Bolli & Saunders (1985), and Iaccarino (1985) and of its equivalent *Globorotalia (Neogloboquadrina) continuosa* Consecutive-Zone (N15) of Blow (1969), due to the co-occurrence of *N. acostaensis* and *P.lia siakensis.* In addition, the succession of bioevents described above implies some modifications in the zonal scheme proposed previously for the Mediterranean area (Iaccarino & Salvatorini, 1982 and emended by Iaccarino, 1985). These modifications improve the biostratigraphic resolution of the interval from the FO of *Gl. praemenardii* to the FO of *Gs. extremus.* The emended zonal scheme is presented in Fig. 3, while the correlation between the present zonal scheme and the

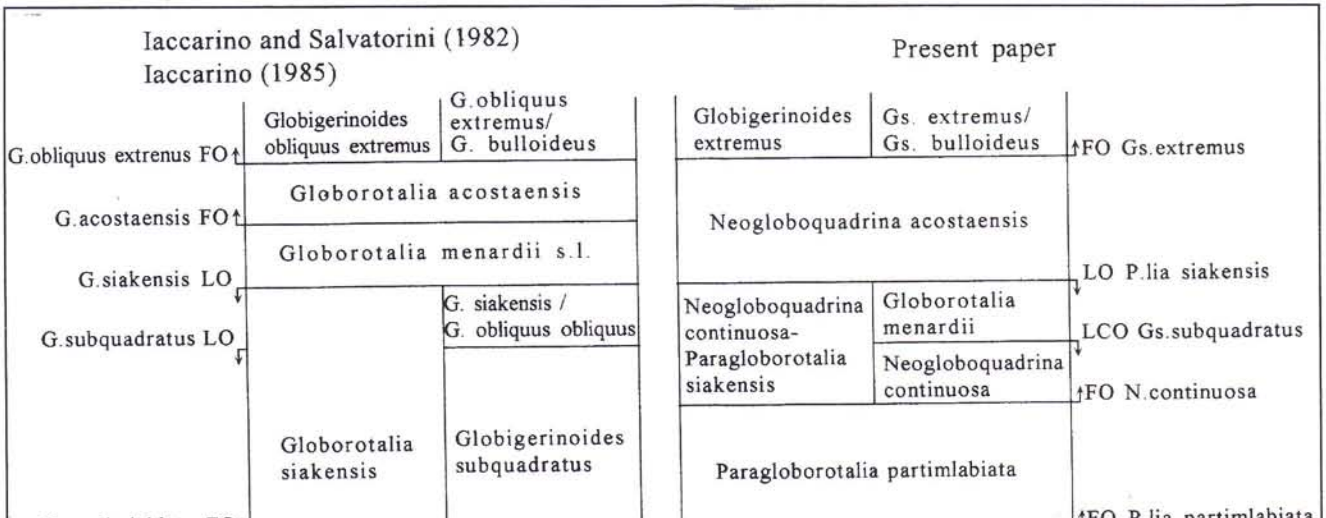


Fig. 4 - Comparison between the zonation of Iaccarino & Salvatorini (1982) and Iaccarino (1985) and that proposed here. FO=First Occurrence; LO=Last Occurrence; LCO=Last Common Occurrence

calcareous nannofossil zonation of Martini (1971), the geomagnetic polarity time scale of Cande & Kent (1995), and the chronologic ages of specific bioevents (i.e. *Sphenolitus heteromorphus* LO, *Discoaster hamatus* FO and LO) calibrated by Rio et al. (1994) and Fornaciari et al. (1996) is shown in Fig. 5.

Orbulina suturalis - Globorotalia peripheroronda Zone.

Category: concurrent range zone.

Author: Bizon & Bizon (1972).

Definition: interval from the FO of *O. suturalis* to the LO of *Gl. peripheroronda.*

Remarks: the zone was subdivided by Iaccarino & Salvatorini (1982) into three subzones; only the youngest subzone was considered in the present work.

Globorotalia praemenardii - Globorotalia peripheroronda Subzone.

Category: concurrent range subzone.

Author: Iaccarino & Salvatorini (1982).

Definition: interval from the FO of *Gl. praemenardii* to the LO of *Gl. peripheroronda.*

Remarks: the range of *Globorotalia* cf. *peripheroacuta* falls within the upper part of this subzone; the FO of *Globigerinopsis aguasayensis* occurs very close to the base of the subzone.

The lower boundary of this subzone was placed tentatively in the lower Chron 5ACn; the FO of *Gl. praemenardii* predates the LO of *Sphenolitus heteromorphus*, which falls within Chron 5A Br.

Dentoglobigerina altispira altispira zone.

Category: interval Zone.

Author: Iaccarino & Salvatorini (1982).

Definition: interval from the LO of *Gl. peripheroronda* to the FO of *Paragloborotalia partimlabiata.*

Remarks: in Iaccarino & Salvatorini (1982) and Iaccarino (1985) this interval is named *Globoquadrina altispira altispira* Subzone, the lowest subzone of the *P.lia siakensis* Zone. The FO of *Globorotalia* aff. *menardii* is recorded in this zone.

The lower boundary of the zone slightly postdates the LO of *S. heteromorphus*, and therefore was placed within C5A Br.

Paragloborotalia partimlabiata Zone.

Category: interval zone.

Author: Foresi et al. (this paper).

Definition: interval from the FO of *P. lia partimlabiata* to the FO of *Neogloboquadrina continuosa.*

Remarks: the total range of *Paragloborotalia mayeri* as well as the FO of *Globorotalia menardii*, and very likely, the FO of *Globigerina nepenthes* (Tab. 5) fall within this interval.

The FO of *P. lia partimlabiata* slightly postdates the FO of *Discoaster kugleri* which falls in the upper part of Chron 5An.2n (De Kaenel, personal communication). Consequently, the base of this zone is possibly close to the base of C5An.1r. Moreover, the FO of *P.lia. mayeri*, which postdates the FO of *P. lia partimlabiata*, should occur within Chron 5An.1n or in the lower part of C5r.

Neogloboquadrina continuosa-Paragloborotalia siakensis Zone.

Category: concurrent range zone.

Author: Foresi et al. (this paper).

Definition: interval from the FO of *N. continuosa* to the LO of *P. lia siakensis.*

Remarks: *N. continuosa* is consistently coiled dextrally in this zone. In addition, an abundance peak of *Globorotaloides falconarae* to *N. continuosa* transitional forms (Pl. 2, fig. 4) occurs very close to the FO of *N. continuosa.* Rare specimens of *N. acostaensis* make their first occurrence together with *N. continuosa. N. acostaensis* remains rare throughout the entire interval, whereas *N. continuosa* and *Gd. falconarae* become very common. All three taxa are absent or very rare in the upper part of the interval, where the sequences are more complete and the sampling is more closely spaced (Tab. 1, Tremiti Islands).

The FO of *N. continuosa* is an event that clearly predates the LO of *D. kugleri* which is recorded at the base of Chron 5n.2n. Therefore, the lower boundary of the zone and the FO of *N. acostaensis*, which is almost coeval with the FO of *N. continuosa*, probably falls in the middle part of Chron 5r.

Two subzones are distinguished within this interval on the basis of the LCO of *Gs. subquadratus.*

Neogloboquadrina continuosa Subzone.

Category: interval subzone.

Author: Foresi et al. (this paper).

Definition: interval from the FO of *N. continuosa* to the LCO of *Gs. subquadratus.*

Remarks: the FO of *Neogloboquadrina acostaensis* and the LO of *P. lia partimlabiata* are recorded at the base and in the upper part of the interval, respectively.

Globorotalia menardii Subzone.

Category: interval subzone.

Author: Iaccarino & Salvatorini (1982), emended.

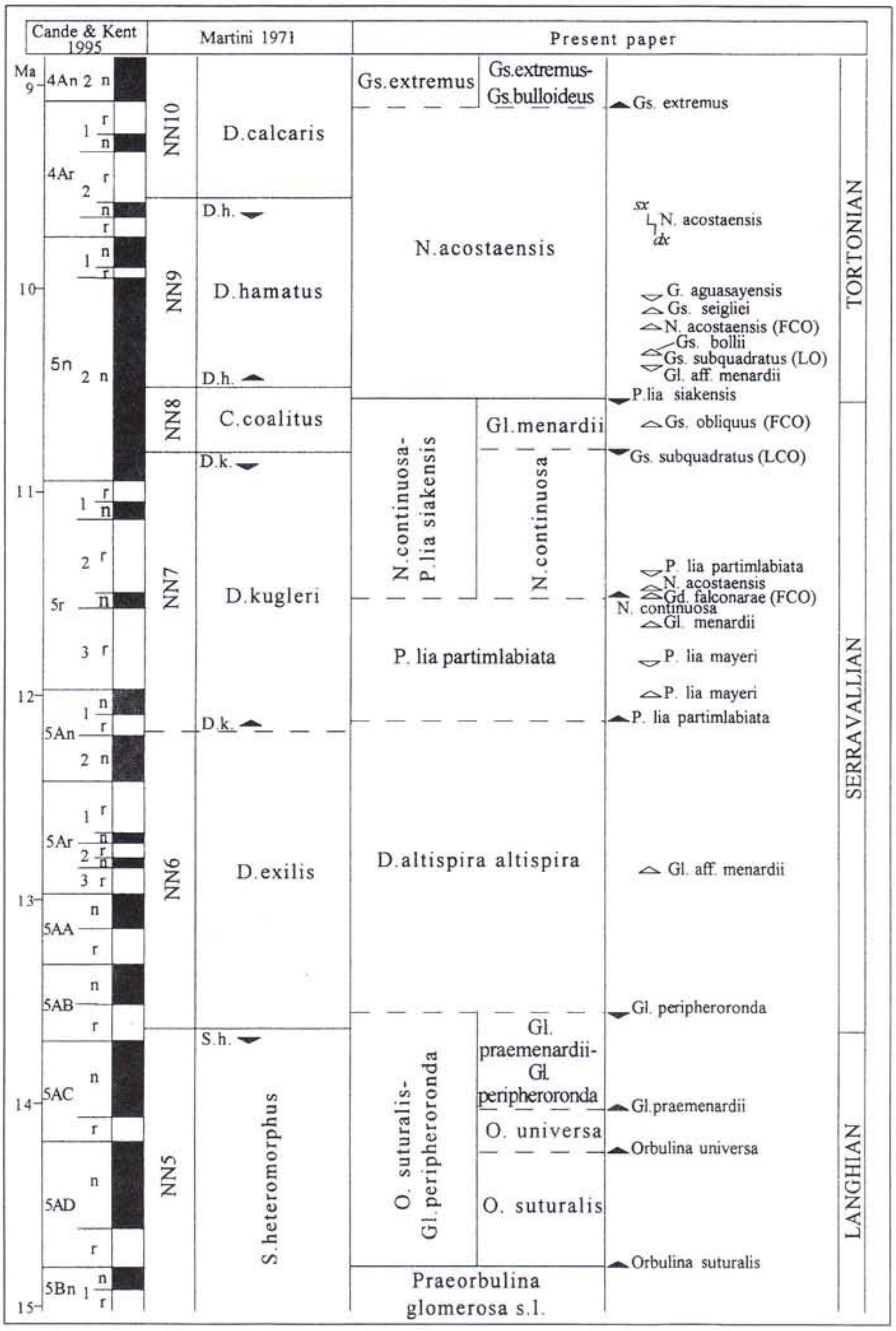


Fig. 5 - Correlation of the planktonic foraminiferal zonation of the present paper with the calcareous nannofossil zonation (Martini, 1971) and the geomagnetic polarity time scale of Cande & Kent (1995). Void triangles represent less reliable datum levels; dashed lines represent calibrations extrapolated from sedimentation rate calculated in Section 9 from Tremiti Islands. FCO = First Common Occurrence; LCO = Last Common Occurrence.

Definition: interval from the LCO of *Gs. subquadratus* to the LO of *P. lia siakensis*.

Remarks: This subzone is equivalent to the *Paragloborotalia siakensis-Globigerinoides obliquus obliquus* Subzone as defined by Iaccarino & Salvatorini (1982) and Iaccarino (1985). Within this subzone *Gs. obliquus* becomes common, *N. continuosa* goes from rare at the base of the subzone to very common in the upper part (Tab. 1), while *N. acostaensis* is generally rare.

The LCO of *Gs. subquadratus* slightly postdates the LO of *D. kugleri* and the FO of *Catinaster coalitus* indicating that the lower boundary of this subzone falls within the lower part of Chron 5n.2n.

The LCO of *Gs. subquadratus* corresponds to the upper boundary of the *Gs. subquadratus* Subzone of Iaccarino & Salvatorini (1982) and Iaccarino (1985), and the *Gs. ruber* Zone of Bolli & Saunders (1985).

Neogloboquadrina acostaensis Zone.

Category: interval zone.

Author: Iaccarino & Salvatorini (1982), emended.

Definition: interval from the LO of *P.lia siakensis* to the FO of *Gs. extremus.*

Remarks: the definition of this zone differs substantially not only from that of Blow (1969) and Bolli (1957) but also from the *Globorotalia acostaensis* Zone established for the Mediterranean region by Iaccarino & Salvatorini (1982) and Iaccarino (1985). In fact, the FO of *N. acostaensis* which characterises the lower boundary of their zone, occurs well below the base of the *N. acostaensis* Zone as defined here. The change from dextral to sinistral coiling in *N. acostaensis* is observed in the middle-upper part of the zone. Numerous other bioevents occur within the lower part of this zone, e.g. the LO's of *Gl. praemenardii*, *Gl.* aff. *menardii*, *Gs. subquadratus*, the FO of *Globigerinoides bollii* and *Gs. seigliei*, and the LO of *Globigerinopsis aguasayensis*, the FCO of *N. acostaensis*, the LO of *P.lia siakensis*, which defines the lower boundary of the zone, slightly precedes the FO of *D. hamatus*, recorded within the middle part of Chron 5n.2n.

Globigerinoides extremus Zone.

Category: interval zone.

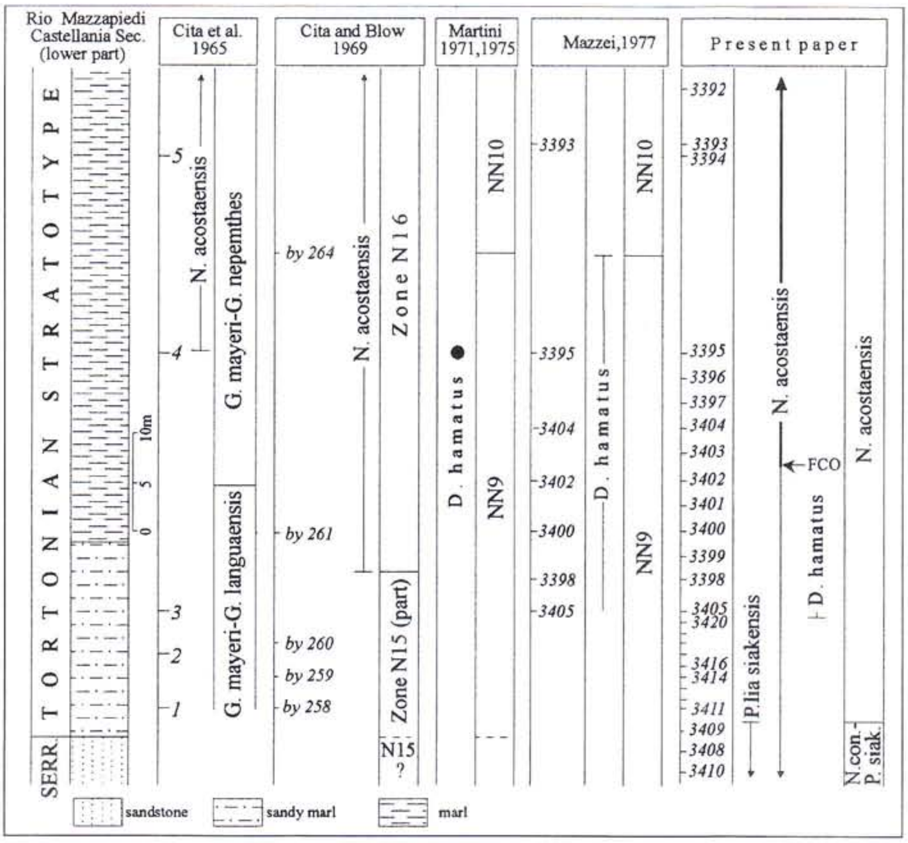


Fig. 6 - Comparison between calcareous plankton biohorizons within the lower part of the type-Tortonian Rio Mazzapiedi-Rio Castellania section as recorded by different authors; the numbers in italics represent the samples.

Author: Iaccarino & Salvatorini (1982).

Definition: interval from the FO of *Gs. extremus* to the FO of *Gl. conomiozea*.

Remarks: only the lower part of the zone is considered in this work (*Gs. extremus-Gs. bulloideus* Subzone).

The FO of *Gs. extremus* very likely occurs within the middle part of the *Discoaster calcaris* Zone; therefore, the lower boundary of the zone has been placed, temporarily, close to the C4Ar/C4An boundary.

Globigerinoides extremus/Globigerinoides bulloideus Subzone.

Category: interval subzone.

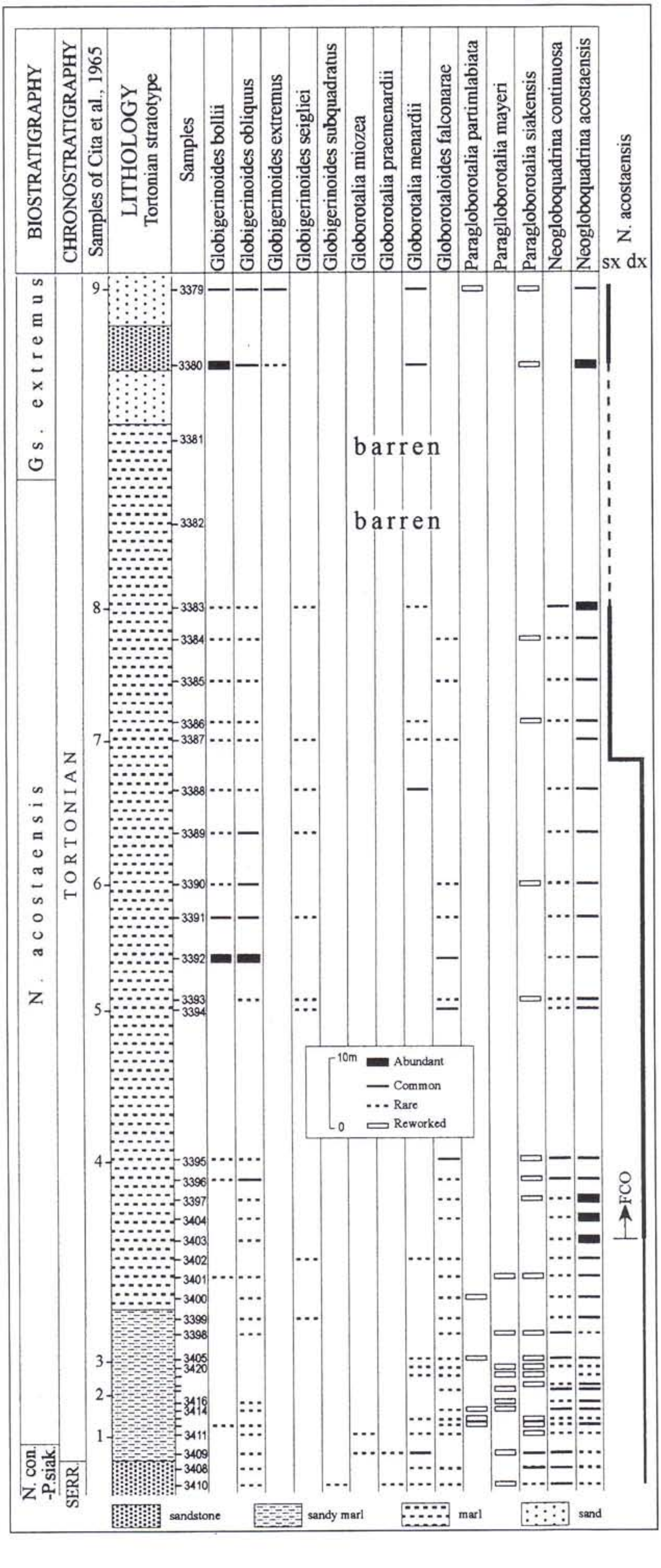
Author: D'Onofrio et al. (1975).

Definition: interval from the FO of *Gs. extremus* to the FO of *Globorotalia suterae*.

Chronostratigraphic implications.

We have emphasised that the FO of *N. acostaensis* falls within the upper part of the *Discoaster kugleri* Zone, a biozone that is documented well in the Serravallian stratotype (Müller, 1975; Rio & Fornaciari, 1994, Fornaciari et al., 1996). A Serravallian age for the entry of *N. acostaensis* was already suggested by Rio et al. (1990) and Rio & Fornaciari (1994). This hypothesis is consistent with the new data obtained from the reinvestigation of planktonic foraminiferal assemblages from the lower part of the Tortonian stratotype (Rio Mazzapiedi-Castellania Section). The same samples investigated by Mazzei (1977) and used in this study (Tab. 6) revealed that this portion of the section may be assigned to the interval extending from the uppermost part of *N. continuosa/P. lia siakensis* Zone to the lower part of the *Gs. extremus* Zone. Earlier Miocene reworked forms are recognised easily because they are poorly preserved. The distribution of taxa like *N. acostaensis*, *Globorotalia praemenardii*, *Globigerinoides bollii*, and *Gs. subquadratus* associated with the zonal markers is in agreement with this assignment. We stress that rare specimens of dextrally coiled *N. acostaensis* occur from the base of the section, well below the entry level recorded by Cita et al. (1965) and Cita & Blow (1969) (Fig. 6). The LO of *P. lia siakensis* falls very close to the base of the Tortonian type-section (sample 3409), and the occurrence of this taxon from sample 3411 to the top of the section (sample 3379) is attributed to reworking because it is found only rarely and discontinuously. The FCO of *N. acostaensis* occurs in sample 3403. Both events could be useful for the worldwide identification of the Serravallian/Tortonian boundary as it is defined traditionally.

The FO of *D. hamatus* is the calcareous nannofossil event that best approximates the Serravallian/Tortonian boundary. Martini (1971, 1975) recorded this taxon in the Tortonian stratotype only in sample 4 (Cita et al., 1965), and concluded that the NN8/NN9 boundary falls at the base of the Tortonian, and placed the NN9/NN10 boundary between samples 4 and 5. Müller (1975), who examined the Serravallian part of the Rio Mazzapiedi-Castellania section (except for the poorly exposed uppermost 40 m), recognised with certainty Zone NN7 and with some doubts Zone NN8. Müller does not exclude the possibility that also the lower part of Zone NN9 could be of Serravallian age. A Serravallian age for the FO of *D. hamatus*, as postulated by Müller, and a Tortonian age for the LO of the same taxon as postulated by Martini, was accepted also by Ryan



Tab. 6 - Distribution chart of selected planktonic foraminifera through the lower part of the Rio Castellania-Rio Mazzapiedi, stratotype of the Tortonian (Northern Italy); dx = dextral coiling, sx = sinistral coiling.

et al. (1974). The same conclusions were reached by Mazzei (1977), who referred the entire interval below level 4 of Cita et al. (1965) to the *D. hamatus* Zone, and more recently also by Rio & Fornaciari (1994) and Fornaciari et al. (1996).

From the correlation of the calcareous plankton events described, it appears that the FO of *D. hamatus* slightly postdates the LO of *P. lia siakensis*; consequently, the first specimens of *D. hamatus-bellus* recorded by Mazzei (1977) below sample 4 of Cita et al. (1965) are indicative of the base of Zone NN9. Therefore, the base of the Tortonian is better approximated by the FO of *D. hamatus* (15 m above the base) than by the LO of this taxon (Rio et al., 1990).

Conclusions.

Study of the calcareous plankton of five Mediterranean and one extra-Mediterranean sections encompassing the Serravallian-early Tortonian demonstrates a partial overlap of the ranges of *N. acostaensis* and *P. lia siakensis*; the time span of this overlap is estimated at 1 Ma. In fact, the FO of *N. acostaensis* falls within the upper part of *Discoaster kugleri* Zone (NN7) which is correlated with the middle part of Chron 5r of the geomagnetic polarity time scale (Cande & Kent, 1995), while the LO of *P. lia siakensis* is close to the top of the *Catinaster coalitus* Zone (NN8) that is correlated with the middle part of Chron 5n.2n. In the overlapping interval *N. acostaen-*

sis is mainly dextrally coiled, but is rare and discontinuous. From a biostratigraphic point of view, the zonal scheme of Iaccarino & Salvatorini (1982) and Iaccarino (1985) had to be emended. The zonal boundaries were redefined on the basis of the new succession of bioevents outlined in this paper. From a chronostratigraphic point of view, it is inferred that the base of the Tortonian cannot be defined by the FO of *N. acostaensis*, a bioevent which falls within the upper part of the Serravallian, well below the Serravallian/Tortonian boundary as defined in the Rio Mazzapiedi-Castellania type-section. The best events for approximating such a boundary are the LO of *P.lia siakensis* occurring in the lowest part of the Tortonian stratotype, the FCO of *N. acostaensis* and the FO of *D. hamatus*, which slightly postdates the LO of *P. lia siakensis*.

In summary, abiding to GSSP (Global Stratotype Section and Point) stage definition rules, it is recommended that the base of the Tortonian be placed at the LO of *P. lia siakensis*, or at the FCO of *N. acostaensis*, or at the FO of *D. hamatus*. The LO *Globorotalia praemenardii*, *Gl.* aff. *menardii*, *Globigerinoides subquadratus*, the FO of *Globigerinoides bollii*, and the FO of *Discoaster bellus* are considered as additional events that may be helpful in recognising the Serravallian/Tortonian boundary. All these bioevents suggest an age of about 10.5 Ma for this boundary.

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