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MEDITERRANEAN PLIOCENE BIOCHRONOLOGY: AN HIGH RESOLUTION RECORD BASED ON QUANTITATIVE PLANKTONIC FORAMINIFERA DISTRIBUTION

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Riassunto. L'analisi quantitativa di associazioni a Foraminiferi planctonici provenienti da successioni plioceniche mediterranee ha messo in evidenza numerose fluttuazioni di abbondanza, che si ripetono ciclicamente per 4 unità tassonomiche (*Globorotalia inflata* gruppo, *Globigerinoides ruber*, *Gd. obliquus* e *Gd. quadrilobatus*). La valutazione della periodicità di tali cicli tra livelli datati in base a dati paleomagnetici o biocronologici ha dimostrato che le fluttuazioni di abbondanza mostrano una periodicità di circa 20.000 anni nella parte bassa del Pliocene e di circa 40.000 anni nella parte alta del Pliocene. La periodicità delle fluttuazioni di abbondanza è pertanto rispettivamente ben correlabile con i cicli astronomici della precessione e della obliquità dell'eclittica. Sulla base di tali cicli è stato possibile ottenere una più precisa valutazione dell'età assoluta dei bioeventi. La comparazione di queste età con le età proposte per gli stessi eventi in aree dell'Oceano Atlantico settentrionale ha dimostrato che eventuali diacronie sono contenute in un massimo di 100.000 anni.

Un più dettagliato schema biostratigrafico a Foraminiferi planctonici per l'area mediterranea viene proposto, con la inclusione di quattro nuove subzone.

Abstract. Quantitative analysis of planktonic foraminiferal assemblages from Mediterranean Pliocene sections evidenced several fluctuations in abundance which for 4 taxonomic units (*Globorotalia inflata* group, *Globigerinoides ruber*, *Globigerinoides obliquus* and *Globigerinoides quadrilobatus*) occur cyclically. Estimate of cycle periodicity, using paleomagnetically or biochronologically absolute dated calibration points, proves that abundance fluctuations display a periodicity of about 20 kyr in the lower part of the Pliocene and of about 40 kyr in the upper part of the Pliocene, thus correlatable to the precession and obliquity astronomical cycles respectively. Based on the sequence of abundance fluctuations a precise age estimate was obtained for several biostratigraphic events. Comparison of the ages estimated of the Late Pliocene bio-events between the Mediterranean and North Atlantic regions shows that possible diacronies occur within a range not greater than 0.1 MA. A more detailed biostratigraphic scheme for the planktonic foraminifera, including four new subzones, is proposed for the Mediterranean area.

Introduction.

In the Mediterranean Pliocene stratigraphic record the calcareous plankton biostratigraphy is well established, based on well identified bio-events of planktonic

foraminifera (Cita, 1973, 1975; Colalongo & Sartoni, 1979; Spaak, 1983; Rio et al., 1984) and calcareous nannofossils (Raffi & Rio, 1979; Driever, 1988; Rio et al., 1990). A reliable magnetostratigraphy recently obtained in the Mediterranean Plio-Pleistocene record (Tauxe et al., 1983; Zijderveld et al., 1986; Hilgen & Langereis, 1988; Channell et al., 1988; Channell et al., 1990; Zachariasse et al., 1989; Zachariasse et al., 1990; Channell, Di Stefano & Sprovieri, in press) allows to correlate the biostratigraphic datums to the Geomagnetic Reversal Time Scale (GRTS), with a resulting biochronological framework to which geological and oceanographic events of this time interval may be referred. Nevertheless, high detailed stratigraphic resolution is yet not possible within a single biostratigraphic zone which, in some instances, covers a relatively long time span. The integrated calcareous plankton biostratigraphy of the Mediterranean Pliocene-Pleistocene record (Rio et al., 1984; Rio & Sprovieri, 1986; Glaçon et al., 1990) improves the resolution of the longer intervals identified on the base of either planktonic foraminifera or calcareous nannofossils, but it does not offer the high refinement which sometime is requested for scaling and ranking the several geological, sedimentological, paleoclimatic and oceanographic events which occurred at a very frequent rate during the Pliocene.

Biostratigraphic events are seldom coincident with paleomagnetic reversals, and their absolute ages are estimated by interpolation on the assumption that sediment accumulation rate between the calibration points remained constant. A constant sediment accumulation rate is well-known to be unrealistic, especially if considered through a relatively long time interval. Therefore the age estimates of the biostratigraphic events may be more or less strongly approximated. The introduction of more frequent calibration points which subdivide long sequences into shorter intervals decreases the possible error derived from irregularities in the sediment accumulation rate. It is the only possibility to further improve the age estimates of the various events.

In the Southern Mediterranean Lower Pliocene land-sections (Calabria and Sicily) carbonate-rich carbonate-poor couplets are cyclically repeated in the lithological record (Zijderveld et al., 1986; Hilgen, 1987; Channell et al., 1988; Zachariasse et al., 1990). Comparison of the number of couplets with absolute dated calibration points estimated on the base of paleomagnetic data in the same sections resulted in the recognition of a mean duration of about 21,000 years for the deposition of each couplet, a value that well corresponds to the periodicity of the astronomical precession cycles (Berger, 1984). The stratigraphic resolution of this interval was therefore strongly improved and several stratigraphic events, such as the Miocene-Pliocene boundary and the *Gt. margaritae* and *Gt. puncticulata* Mediterranean first and last occurrences (FO, LO) (Zijderveld et al., 1986; Hilgen & Langereis, 1988; Zachariasse et al., 1989, 1990; Langereis & Hilgen, 1990; Channell, Di Stefano & Sprovieri, in press) could be well calibrated. Nevertheless, beside the difficulty to single out every couplet, that can be surely identified only in well exposed outcrops, this lithological feature is not visually

recognizable everywhere in the Mediterranean Pliocene lithological record. For instance, in the deep sea Tyrrhenian sequences (ODP, Leg 107) such an alternation in lithology was not recognized; in the more terrigenous Lower Pliocene sequences from Northern Italy it is difficult to detect and in the Mediterranean Upper Pliocene sequences it is generally not present at all. A more general, inter-regional tool must therefore be adopted in order to obtain an higher resolution of the stratigraphic record and an accurate correlation of the discrete events in different areas and in different geological or sedimentological setting.

Several papers (Parker, 1958; Bé & Tolderlund, 1971; Cifelli & Smith, 1974; Kipp, 1976; Bé & Hutson, 1977; Thunell, 1978; Coulbourn et al., 1980; Herman, 1981; Loubere, 1981; among others) proved that the abundance of different planktonic foraminiferal taxonomic groups fluctuates in response to climatic changes. Planktonic foraminifera generally represent a major component of the faunal assemblages in a wide variety of sedimentary and latitudinal settings. Since the climatically induced fluctuations in abundance of selected taxonomic units may be recognized in a wide range of environments and since the origin of these fluctuations is a general and independent "external factor" to sedimentation, these abundance peaks may be correlated over a wide area. Abundance fluctuations in planktonic foraminiferal assemblages are generally used to monitor different climatic intervals of the more recent geologic record or, in modern oceans, different water masses. Even if the climatic inference on the planktonic foraminifera population represents today the rationale on which the here adopted methodology is settled, abundance peaks have significance *per se* and not for the climatic significance they reflect. With this concept in mind, "cold", "cool" or "warm" fluctuations are equally useful to point out peculiar stratigraphic levels. Since the same peak event may be considered originated by the same climatic fluctuation, it is isochronous and offers the possibility for a detailed correlation of the lithological layer in which it was detected. The comparison of the sequence of peaks to the GRTS in several different sequences will not only check their actual synchronicity, but will also offer several other absolute dated calibration points in the geologic record which can be detected by the simple, practically un-expensive and easily available micro-paleontological investigation.

In the following sections it will be proved that abundance fluctuations of planktonic foraminiferal assemblage from several Mediterranean Pliocene sections are isochronous. They may be inter-regionally used to compare and correlate, between "classical" biostratigraphic boundaries, different events belonging to the same stratigraphic interval. It also allows a greater refinement of the absolute ages estimate of the calcareous plankton events. It will be also remarked that during the Pliocene time interval the cyclicity of the abundance fluctuations of the planktonic foraminifera assemblage have a period well comparable with the precession and obliquity astronomical cycles.

Methods.

The results are based on quantitative data from the planktonic foraminiferal assemblages. All the studied samples were disaggregated in normal water and washed on a 63 microns sieve. From the split dried residues greater than 125 microns at least 300 specimens of planktonic foraminifera were counted and the obtained quantitative data were normalized to 100. Countings of planktonic foraminiferal assemblages were based on 18 taxonomic units (TU). The component members of each category are reported below. Abbreviations used to label the curves plotted in the figures are reported in brackets.

- *Globigerina bulloides* (G. bul).
- *Globigerinoides obliquus* (G. obl): *Gd. obliquus obliquus*, *Gd. obliquus extremus* and *Globigerina apertura*.
- *Globigerinoides quadrilobatus* (G. quad): *Gd. quadrilobatus* (well developed four chambers in the last whorl) and *Gd. sacculifer* (sac-like last chamber) are included in this unit.
- *Globigerinoides ruber* (G. rub): *Gd. ruber*, more rare *Gd. elongatus* and *Gd. conglomeratus*.
- *Globorotalia inflata* (G. inf): the three stratigraphically discrete taxa of *Gt. puncticulata*, *Gt. bononiensis* and *Gt. inflata* s.s. are included in this unit.
- *Globorotalia acostaensis* (G. aco): *Gt. acostaensis* and *Gt. planispira* have been included in this taxonomic unit.
- *Globorotalia crassaformis* (G. cras): *Gt. crassaformis* keeled and not keeled forms and *Gt. crassaformis aemiliana* are included.
- *Globorotalia margaritae* (G. marg).
- *Sphaeroidinellopsis* spp. (Sphaer).
- *Orbulina* spp. (Orbul).
- *Neogloboquadrina pachyderma* (N. pac): both right and left coiled specimens are included.
- *Neogloboquadrina atlantica* (N. atl): only left coiled specimens.
- *Globigerina quinqueloba* (G. qui).
- *Globigerinita glutinata* (G. glut).
- *Globorotalia scitula* (G. sci).
- *Neogloboquadrina dutertrei* (N. dut).
- *Hastigerina siphonifera* (not plotted in the Figs., since always rare to very rare or absent in the samples).

Throughout the text each taxonomic unit will be indicated by the name of its main component member.

Fig. 1 - Adopted Mediterranean Plio-Pleistocene calcareous plankton biostratigraphic scheme (modified from Thunell et al., 1991). FCO) First Common Occurrence; LCO) Last Common Occurrence; S1) LO of *H. sellii*; S2) FO of *Gephyrocapsa* sp. 3 (sensu Rio et al., 1990).

For all the considered sections the planktonic foraminifera abundance raw data have been elaborated by Q-mode factor analysis using the Cabfac program and the loadings of the retained varimax factors have been plotted. By using the Fourier transform procedure, with subtraction of the mean, periodograms have been obtained for biostratigraphic intervals of Hole 653A (ODP, Leg 107), Capo Spartivento and Monte S. Nicola sections using the factor loadings as time series data. The estimated frequency spectrum allows to decompose the variance of the data into contributions over a range of frequencies. Since the time series are nonstationary, as data do not have a fixed mean, the differences between consecutive values rather than the original data were analyzed. The squared amplitudes of the sinusoids are plotted on the ordinates.

The biostratigraphic scheme of Cita (1973, 1975) for the planktonic foraminifera, amended by Rio et al. (1984) has been adopted; the nannofossil biostratigraphic scheme is from Rio et al. (1990). The biostratigraphic boundaries are traced coincident with the sample in which the defining biostratigraphic event is recorded. The adopted biostratigraphic schemes are reported in Fig. 1 and compared with the Geomagnetic Reversed Time Scale (GRTS) (Berggren et al., 1985) and the Global Standard Time Scale (GSTS).

As far as the adopted planktonic foraminifera biostratigraphic scheme, according to data derived from several deep-sea and land sections in the Mediterranean region, the definition of top of MPI 3 has been reconsidered in this paper.

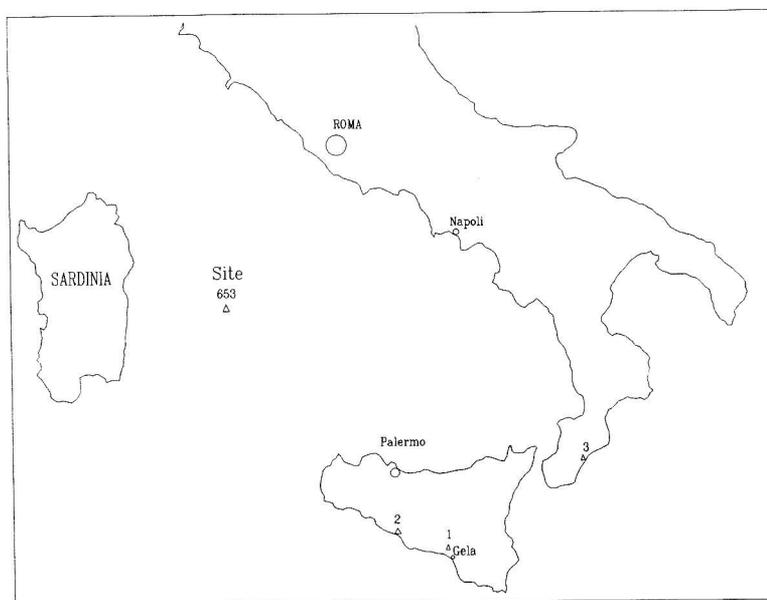


Fig. 2 - Location of the sections and ODP Site 653 discussed in the paper. 1) Monte S. Nicola; 2) Capo Rossello and Punta Piccola; 3) Capo Spartivento.

At Site 653 *Gt. margaritae* enters the countings up to 159.50 MBSF (Fig. 5). It is then discontinuously present with rare specimens up to 153.26 MBSF, where Glaçon et al. (1990) identified the MPI 3-MPI 4 boundary. This level is above the LO of *Reticulofenestra pseudoumbilicus*, which occurs at 156.50 MBSF (Rio et al., 1990).

At Site 654 *Gt. margaritae* is common up to about 174.50 MBSF, just below an unrecovered interval. Above this level it is rare and scattered up to 166.50 MBSF, when it disappears, again above the LO of *D. pseudoumbilicus*, recognized at 169.95 MBSF (Glaçon et al., 1990).

At Site 652 *Gt. margaritae* is frequent up to 133.55 MBSF; it is then again rare and scattered up to 126.47 MBSF, above the LO of *R. pseudoumbilicus*, recorded at 132.20 MBSF (Glaçon et al., 1990).

In Bianco and Monte S. Nicola sections the last occurrence of *Gt. margaritae* is abrupt and recorded below the last occurrence of *R. pseudoumbilicus* (Rio et al., 1989; Channell, Di Stefano & Sprovieri, in press). Zachariasse et al. (1989) reported that the LO of *Gt. margaritae* in the Capo Rossello area is well below the Gilbert/Gauss boundary. The same distribution has been recognized in the Monte S. Nicola section (Channell, Di Stefano & Sprovieri, in press), where the last occurrence of *Gt. margaritae* is also below the Gilbert/Gauss boundary.

It is difficult to evaluate the significance of the rare specimens of *Gt. margaritae* in the three ODP Sites above the level from where the species is present rare and scattered. They may represent scattered incursions into the Mediterranean of rare specimens of a species no more present in the Mediterranean but still living in the oceans, where it disappears at about 3.40 MA (Berggren et al., 1985). For biostratigraphic purpose the rare and scattered specimens above the interval during which *Gt. margaritae* constantly enters the countings are considered meaningless and difficult to be detected in a routine analysis.

Therefore the top of the *Gt. margaritae*-*Gt. puncticulata* biozone (MPI 3) is proposed in coincidence of the last common occurrence (LCO) of the *Gt. margaritae*. In agreement with the results from the Capo Rossello area (Langereis & Hilgen, 1990) an absolute age of 3.71 MA is ascribed to this biostratigraphic event, even if an error of about 0.15 MA is possible in its evaluation depending on the identification of its last common occurrence or of its actual last occurrence which, according to Langereis & Hilgen (1990) is estimated at about 3.57 MA. Extrapolation on the curve of sediment accumulation rate in Hole 653A between the *Gt. bononiensis* FO, at 3.16 MA, and the *Gt. puncticulata* LO, at 3.38 MA, produces absolute ages of 3.71 MA and 3.57 MA respectively for these two events (Fig. 3).

Material.

The fluctuations in abundance of planktonic foraminifera have been studied in 5 Mediterranean sections. The sequence of Hole A at ODP Site 653 (Leg 107) has been considered as main reference section. Four other Mediterranean, closely spaced

4.65	4.15	3.88	3.69	3.71	2.65	2.37	2.00	1.81	1.58	ABSOLUTE AGE (MA)		
EARLY PLIOCENE					LATE PLIOCENE					PLIEST	CHRONO	
M Pl 1	M Pl 2	M Pl 3	M Pl 4	M Pl 5	M Pl 6	FORAMS						
<i>Amaurolithus tricorniculatus</i>	<i>Ceratolit. rugosus</i>	<i>Ret. pseud.</i>	<i>Discoaster tamalis</i>	<i>Disc. pent.</i>	<i>Disc.</i>	<i>Dic. productus brouweri</i>	NANNO					
							<i>C. maritima</i>	MBSF recovery				
210	200	190	180	170	160	150	140	130	120	110	100	90

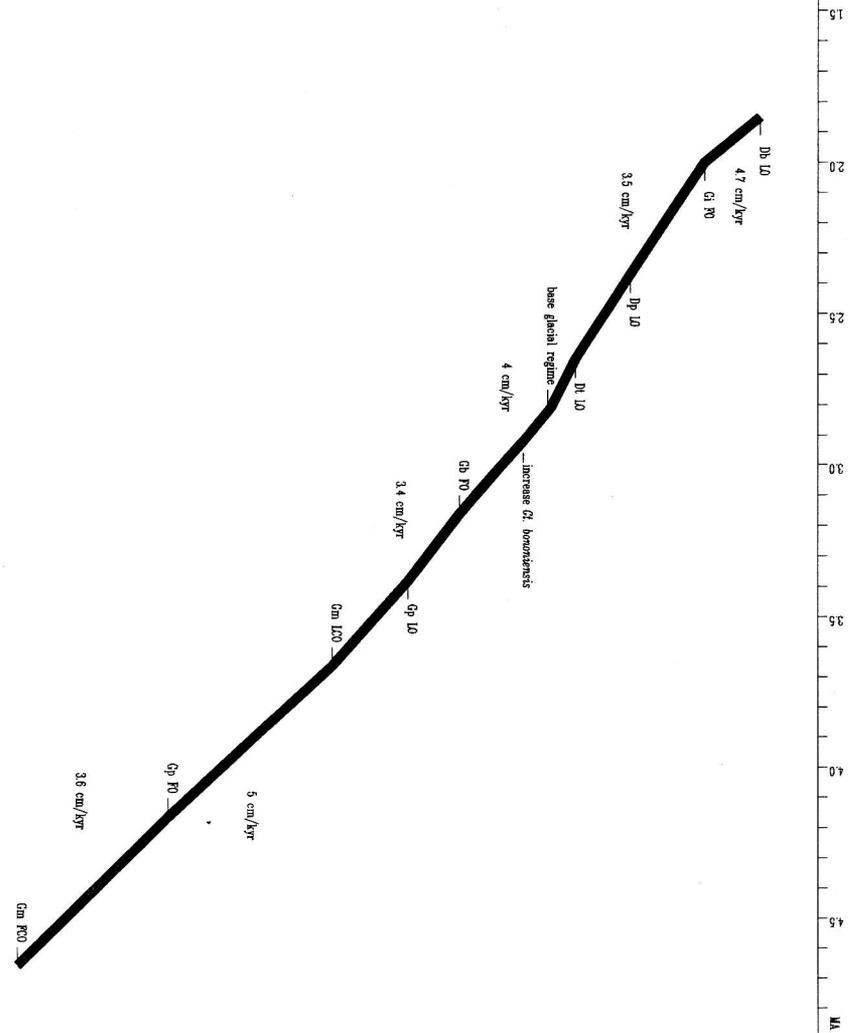


Fig. 3 - Curve of sediment accumulation rate at ODP Hole 653A. Note the hiatus at 86 MBSF, marked by a wavy line. Db) *D. brouweri*; Gi) *Gt. inflata*; Dp) *D. pentaradiatus*; Dt) *D. tamalis*; Gb) *Gt. bononiensis*; Gp) *Gt. puncticulata*; Gm) *Gt. margaritae*. Calcareous nannofossil biostratigraphy is from Rio et al. (1990).

sampled sequences outcropping in Southern Sicily and in Calabria (Fig. 2), spanning more or less long Pliocene intervals, have been studied to cover the stratigraphic intervals which are badly or not represented in the covered sequence of Hole 653A.

ODP Site 653.

One of the primary objective of ODP Leg 107 was the recovery of a continuous, undisturbed Plio-Pleistocene sedimentary sequence to represent a "deep-sea type section" for biostratigraphic and palaeoenvironmental studies in the Mediterranean Pliocene. This was achieved at Site 653, located on the edge of the Cornaglia Terrace in the western Tyrrhenian basin, less than 1 kilometer north-east of DSDP Site 132 (Leg 13), at 2817 m water depth. Two holes (653A and 653B) were cored at this Site by advanced piston corer (APC) and extended core barrel (XCB) systems. Recovery was good, with an average of 100% during APC coring and 88% during XCB coring (Kastens et al., 1987). Hole 653A did not yield magnetostratigraphy due to poor magnetic signals of the sedimentary sequence (Channell et al., 1990) but a good calcareous plankton biostratigraphy was established for this site by Glaçon et al. (1990) and Rio et al. (1990).

At Site 653 one stratigraphic hiatus, in the otherwise continuous sequence, was detected at the top of the Pliocene across the Pliocene-Pleistocene boundary. Apart from the relatively long unrecovered interval in core 15 (base of MPI 5 biozone), short unrecovered intervals are present essentially in the lower part of the sequence. Generally 4 samples per section were studied, with a total of 548 samples (Sprovieri, 1991). The relative abundance of the taxonomic units present in the Pliocene and Pleistocene interval are plotted against depth and biostratigraphic schemes in Fig. 4, 5 and 6. The palaeoenvironmental analysis of the Pliocene-Pleistocene sequence at Site 653, also based on stable oxygen and carbon isotope analyses (Thunell et al., 1990; Vergnaud

Fig. 4 - Relative abundance (%) of planktonic foraminifera (5 TUs) in the Pliocene-Pleistocene interval at ODP Hole 653A. Note the hiatus at 86 MBSF, marked by a wavy line. G. bull) *G. bulloides*; G. obl) *Gd. obliquus*; G. quad) *Gd. quadrilobatus*; G. rub) *Gd. ruber*; G. inf) *Gt. inflata* group; black vertical bars) recovered intervals. Calcareous nannofossil stratigraphy is from Rio et al. (1990).

Fig. 5 - Relative abundance (%) of planktonic foraminifera in the Pliocene-Pleistocene interval at ODP Hole 653A. Note the hiatus at 86 MBSF, marked by a wavy line. Sphaer) *Sphaeroidinellopsis* spp.; G. marg.) *Gt. margaritae*; G. aco) *Gt. acostaensis*; G. scit) *Gt. scitula*; G. cras) *Gt. crassaformis*; G. trun) *Gt. truncatulinoides*; black vertical bars) recovered intervals. Calcareous nannofossil stratigraphy is from Rio et al. (1990).

Fig. 6 - Relative abundance (%) of planktonic foraminifera in the Pliocene-Pleistocene interval of ODP Hole 653A. Note the hiatus at 86 MBSF, marked by a wavy line. Orbul) *Orbulina* spp.; N. atl) *N. atlantica*, left coiled specimens; G. qui) *G. quinqueloba*; N. pac) *N. pachyderma*, right and left coiled specimens; N. dut) *N. dutertrei*; G. glut) *G. glutinata*; black vertical bars) recovered intervals. Calcareous nannofossil stratigraphy is from Rio et al. (1990).

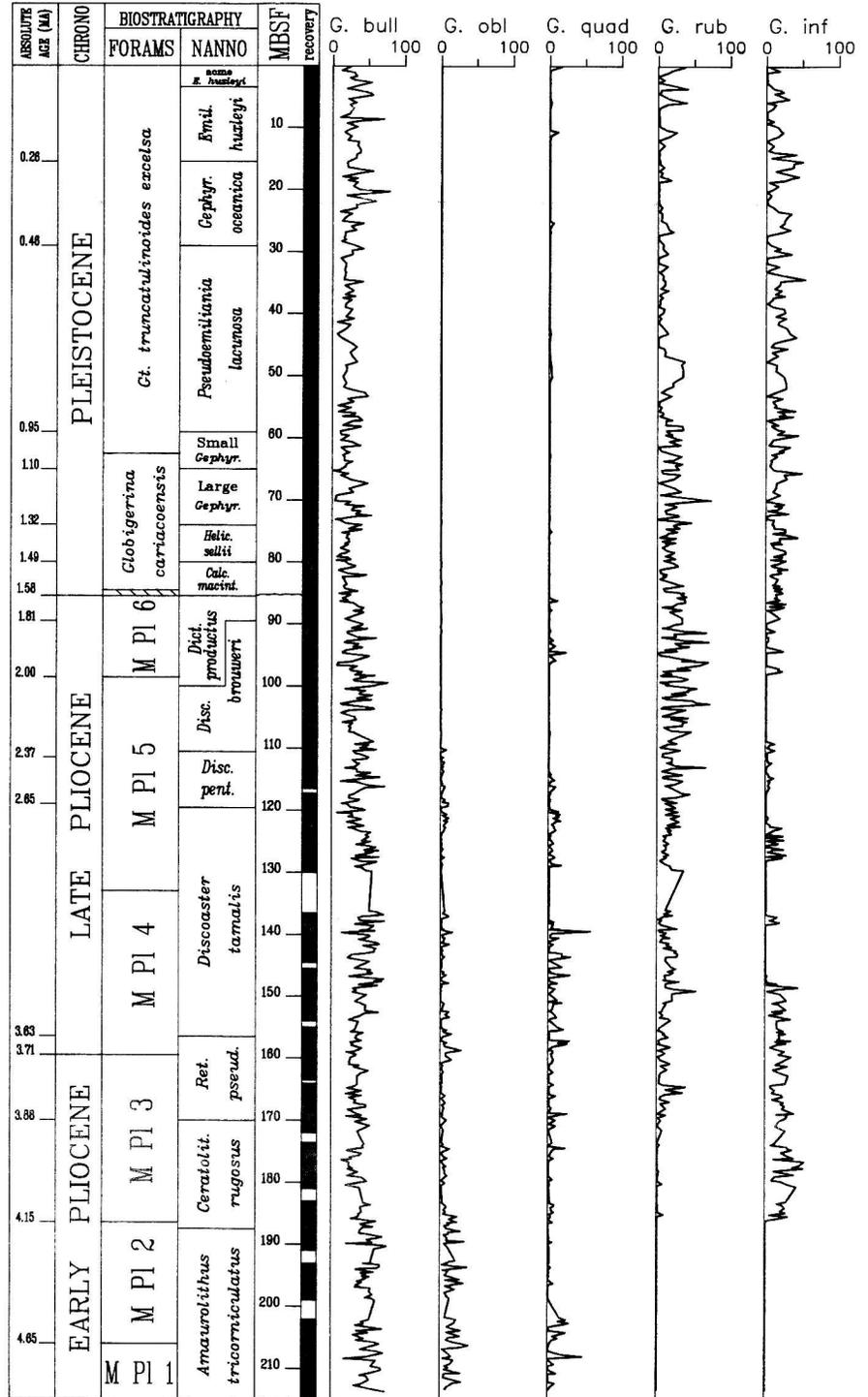


Fig. 4

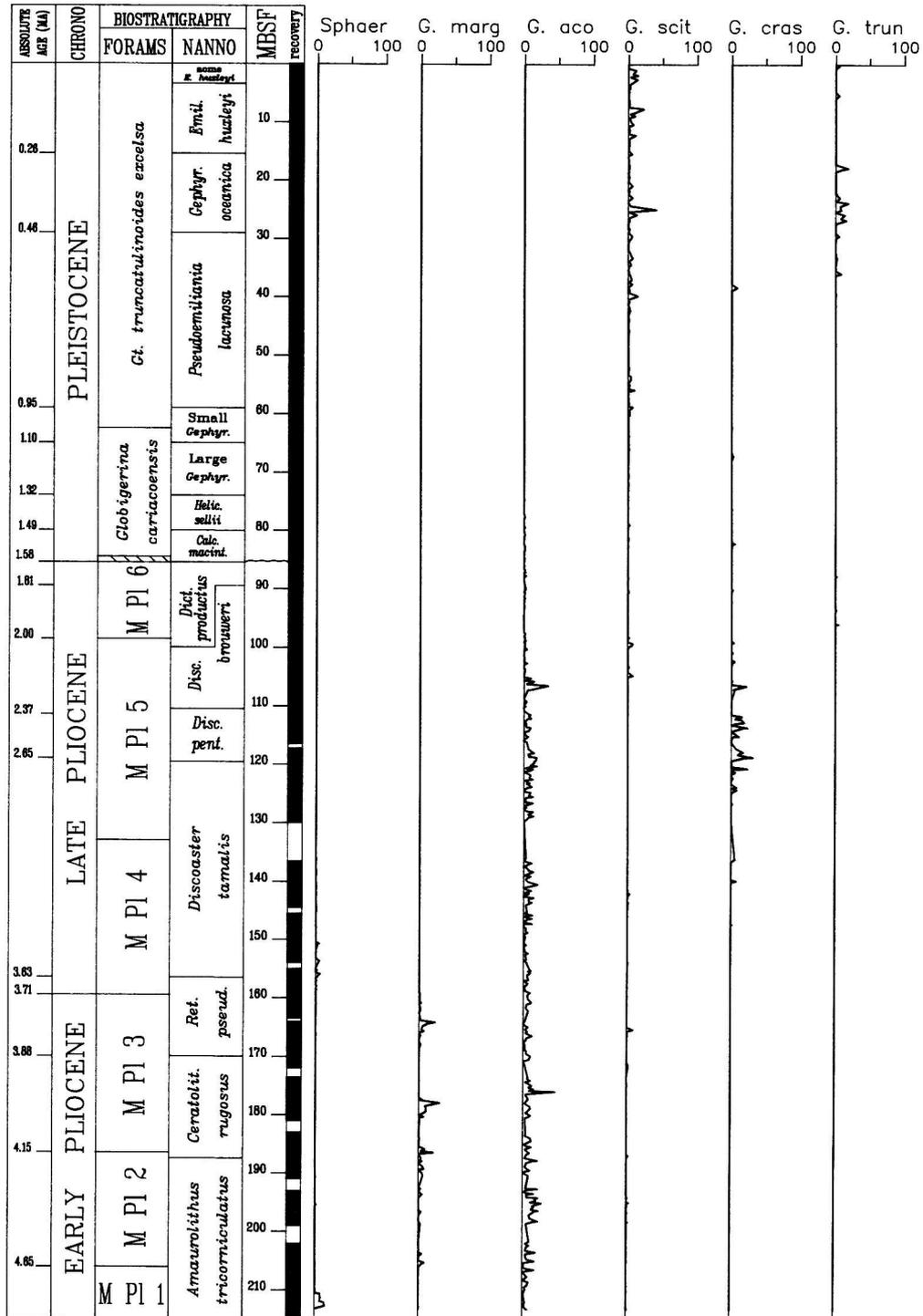


Fig. 5

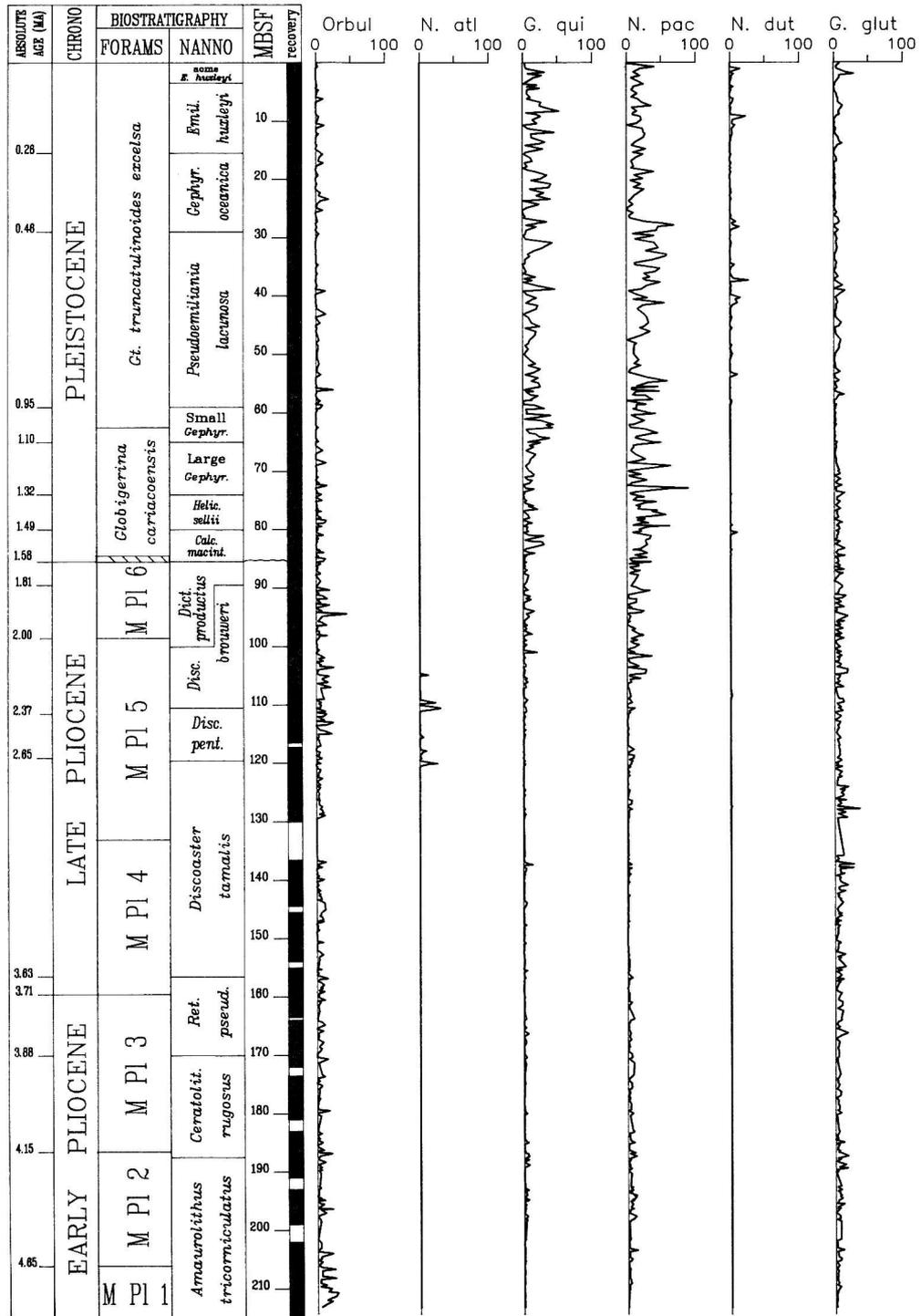


Fig. 6

Grazzini et al., 1990), is reported in Rio et al. (1990). The paleoclimatic interpretation based on quantitative data of planktonic foraminifera is reported in Sprovieri (1991). In Fig. 7 the loadings of the 6 Factors retained from varimax rotation of the Q-mode factor analysis of the planktonic foraminifera raw abundance data (ODP Hole 653A)

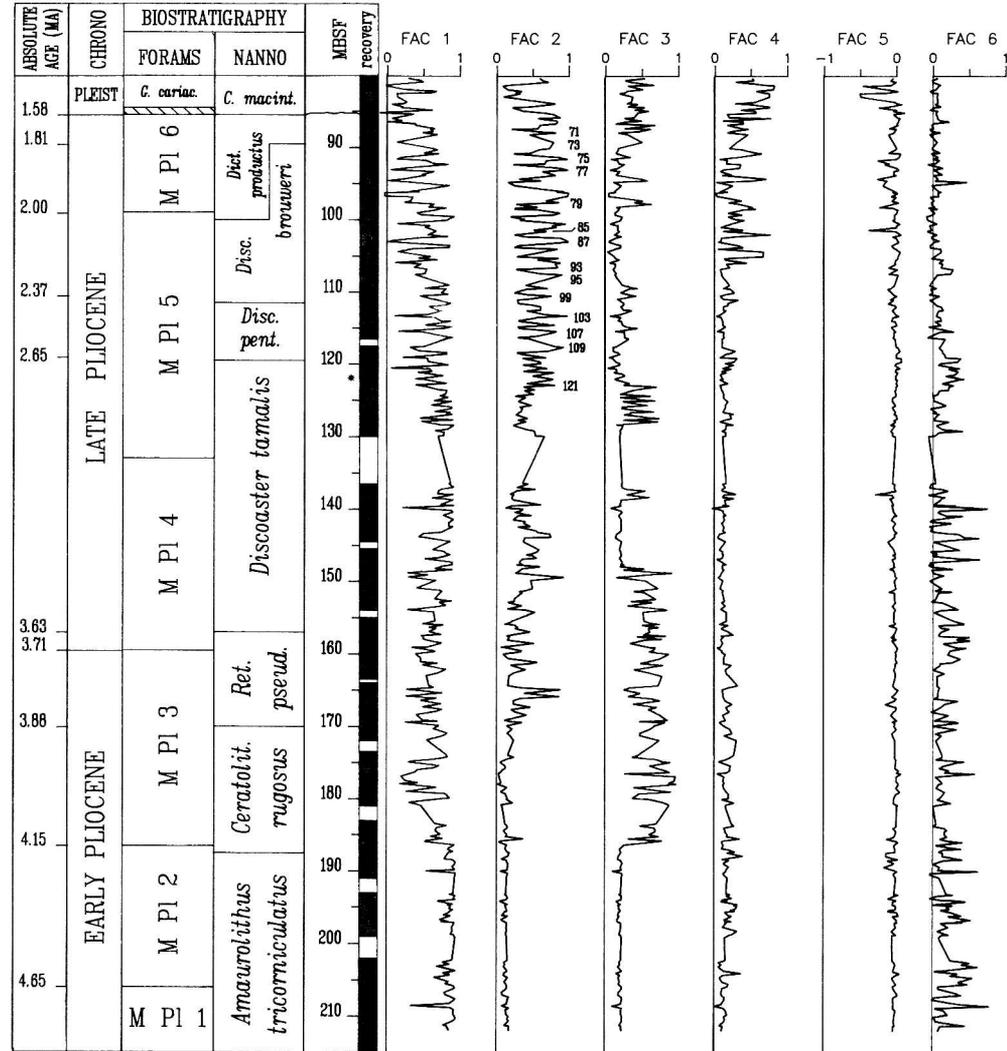


Fig. 7 - Distribution of Factor loadings in the Pliocene-lowermost Pleistocene interval at ODP Hole 653A. Asterisk indicates the first entrance of left coiled *N. atlantica*. Some "warm" fluctuations of Factor 2 are numbered according to those proposed by Raymo et al. (1989) for oxygen isotopic stages. Factor 1 is dominated by *G. bulloides* TU, Factor 2 by *Gd. ruber* TU, Factor 3 by *Gt. inflata* TU, Factor 4 by *N. pachyderma* TU, Factor 5 by *G. quinqueloba* TU and Factor 6 by *Gd. quadrilobatus* TU. Black vertical bars) recovered intervals. Calcareous nannofossil stratigraphy is from Rio et al. (1990).

	1	2	3	4	5	6
<i>G. bulloides</i>	3.9632	0.6447	0.9795	0.4904	- 0.1641	- 0.4999
<i>N. pachyderma</i>	- 0.4106	- 0.0517	- 0.2104	4.1192	0.7760	0.3163
<i>Gd. obliquus</i>	0.4619	- 0.3455	0.0464	- 0.0966	0.2193	2.3463
<i>Gd. quadrilobatus</i>	- 0.0608	0.1623	0.0794	- 0.2799	- 0.2520	2.7961
<i>Gd. ruber</i>	- 0.6816	4.1265	0.0231	- 0.0369	0.1465	0.0304
<i>Gt. acostaensis</i>	0.4975	- 0.0207	- 0.0323	- 0.0830	0.3389	1.7761
<i>Gt. crassaformis</i>	0.0639	0.1596	- 0.1139	- 0.0180	0.0155	0.1648
<i>Gt. inflata</i>	- 0.9657	- 0.1900	4.1093	0.1096	0.0993	0.0336
<i>Gt. margaritae</i>	0.0940	- 0.0498	0.0485	- 0.0189	0.0630	0.0339
<i>Gt. scitula</i>	0.0148	- 0.0352	0.0782	0.0961	- 0.2943	- 0.1021
<i>Gt. truncatula</i>	- 0.0295	0.0114	0.1182	- 0.0091	- 0.0071	- 0.0751
<i>Orbulina</i> spp.	0.2107	0.4152	0.2129	- 0.1160	- 0.1711	0.9279
<i>Sphaeroidinellopsis</i> spp.	0.0070	-0.0132	0.0097	- 0.0170	0.0043	0.0670
<i>H. siphonifera</i>	0.0357	0.1061	0.1019	- 0.0530	0.0450	0.1087
<i>N. atlantica</i>	0.0342	0.1020	- 0.0645	0.0353	0.0644	0.0056
<i>G. quinqueloba</i>	- 0.2463	0.0393	0.0064	0.7372	- 4.1100	0.1210
<i>G. glutinata</i>	0.3744	0.3818	- 0.0656	0.2881	- 0.2807	0.4823
<i>N. dutertrei</i>	- 0.0145	- 0.0215	0.0011	0.1724	- 0.1279	- 0.0271
Variance	35.559	18.579	18.360	15.445	3.546	2.863

Tab. 1 - Scaled varimax factor scores matrix and variances of planktonic foraminifera in ODP Hole 653A.

are reported for the Pliocene and lowermost Pleistocene interval. Varimax factor scores and variances for all the Pliocene-Pleistocene sequence of Hole 653A are reported in Tab. 1. Factor 1 is dominated by *Globigerina bulloides* TU, Factor 2 by *Globigerinoides ruber* TU, Factor 3 by *Globorotalia inflata* TU, Factor 4 by *Neoglobobulimina pachyderma* TU, Factor 5 by *Globigerina quinqueloba* and Factor 6 by *Globigerinoides obliquus* TU and *Globigerinoides quadrilobatus* TU. The paleoclimatic interpretation of the Factors is reported in Sprovieri (1991).

Capo Rossello section.

In order to cover the very base of the Pliocene, corresponding to MPI 1 biozone, not completely represented in the available samples from Hole 653A (Glaçon et al., 1990), the basal 16 meters of the Capo Rossello section (Cita & Gartner, 1973) have been studied, at a sampling rate of 40 cm (Fig. 8).

The presence of rare specimens of *Gt. margaritae* in samples from just above the base of the sequence induced Sprovieri (1978) to report that the MPI 1 biozone is missing at the base of the Capo Rossello section. In several of the new samples studied for this paper between about 2 and 10 meters above the base of the section rare specimens of *Gt. margaritae* have been found again, but the species is common only from 11.20 upward. Therefore the presence of MPI 1 biozone is now recognized at the

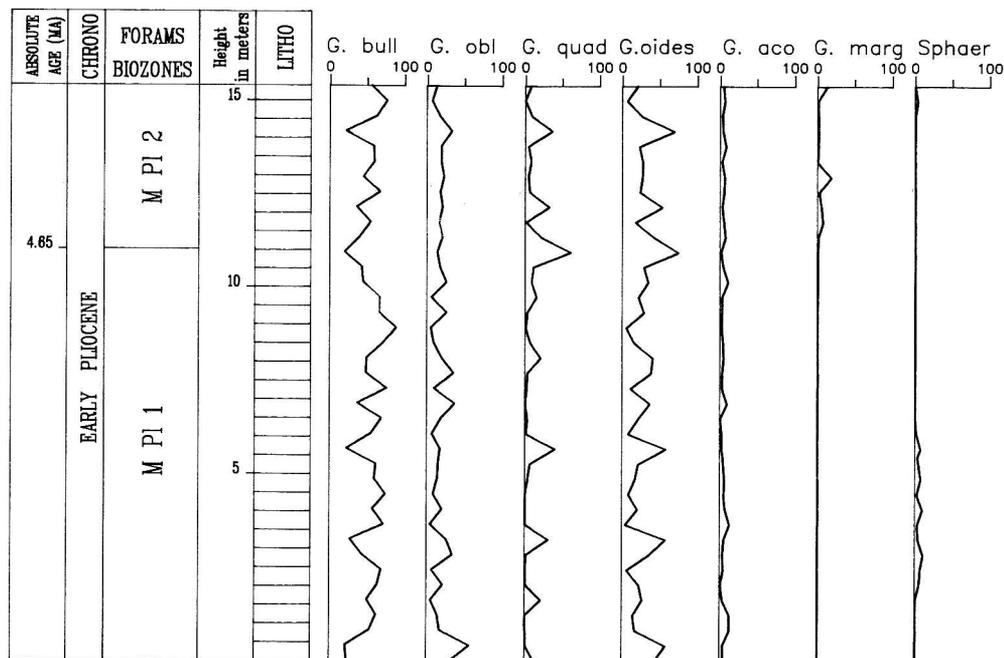


Fig. 8 - Relative abundance (%) of planktonic foraminifera in the MPI 1 interval (Early Pliocene) in the Capo Rossello section. See Fig. 4 and 5 for labels.

base of the Capo Rossello section, which is considered complete of its basal part. In the level sampled 15 meters above the base of the Pliocene, coincident with an abundance peak of the *Gd. obliquus* taxonomic unit, common specimens of *Gt. limbata* are present. No nannofossil biostratigraphy is available from this new set of samples, but according to Rio et al. (1984) the basal 30 meters of the Capo Rossello section are referable to the *Amaurolithus tricorniculatus* nannofossil biozone. The relative abundance of the most important taxonomic units recognized along this segment is reported in Fig. 8, in which also the sum of percentage values of *Globigerinoides obliquus* TU and *Globigerinoides quadrilobatus* TU is reported (*G. oides*).

Monte S. Nicola section.

This section outcrops about 10 km north-west of Gela, near the southern coast of Sicily. It covers the Upper Pliocene-Lower Pleistocene stratigraphic interval, from just below the *Gt. margaritae* LO to just above the *Gephyrocapsa oceanica* s.l. FO. It is 161 meters thick, with the basal 36 meters represented by the "Trubi" marly limestones and the following 125 meters represented by the marls of the Monte Narbone Formation. Detailed litho-, bio- and magneto-stratigraphy, and the paleoclimatic history of the section have been published by Channell, Di Stefano & Sprovieri (in press). A syn-sedimentary tectonic activity gave origin, essentially in correspondence

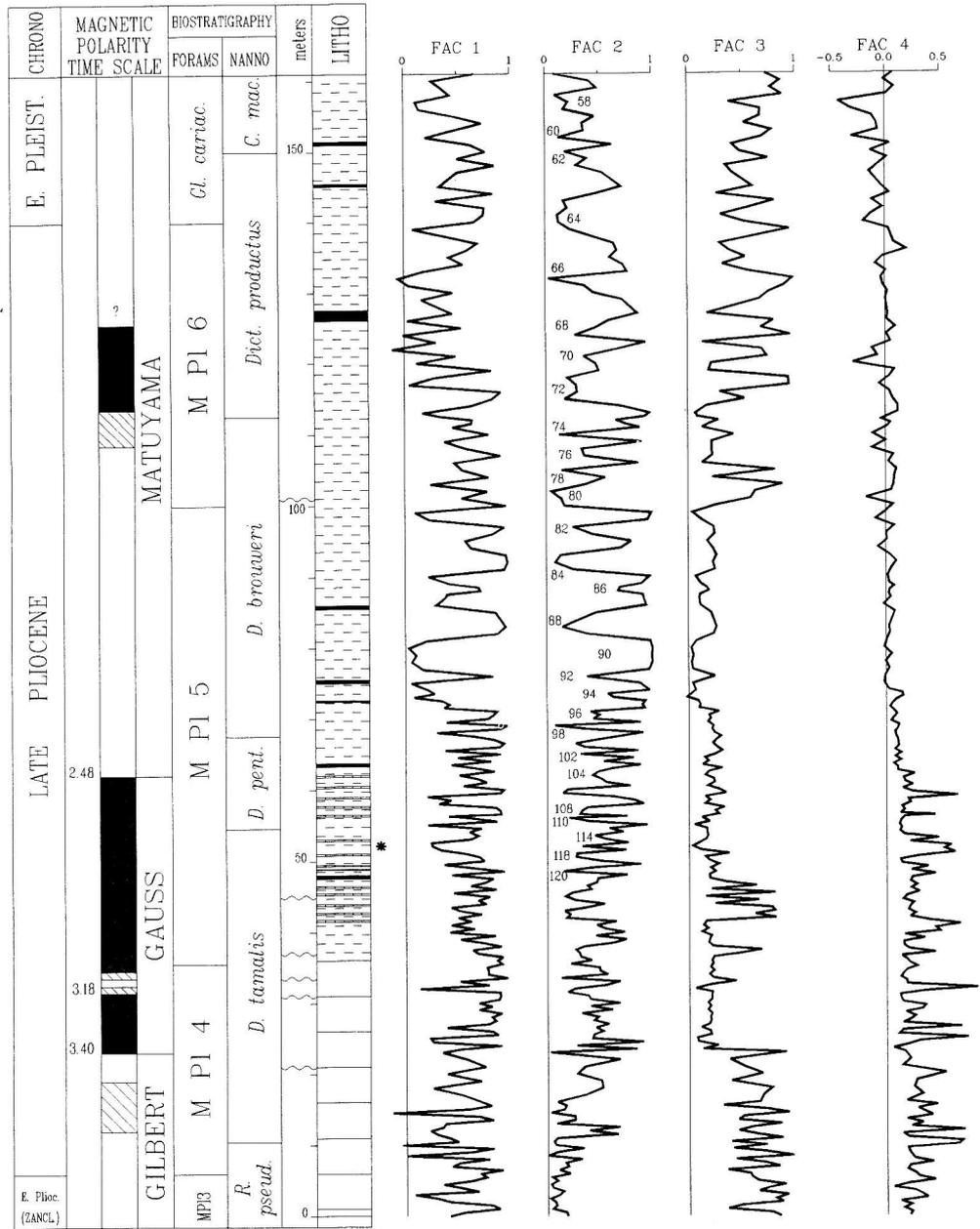


Fig. 9 - Distribution of Factor loadings in the Pliocene-lowermost Pleistocene interval in the Monte S. Nicola section. Horizontal black bars) laminites; dashed bars) manganesiferous levels. Asterisk indicates the first entrance of left coiled *N. atlantica*. Some "cold" fluctuations of Factor 2 are numbered according to those proposed by Raymo et al. (1989) for oxygen isotope stages. Wavy lines indicate hiatuses. Factor 1 is dominated by *G. bulloides* TU, Factor 2 by *Gd. ruber* TU, Factor 3 by *Gt. inflata* TU and Factor 4 by *Gd. quadrilobatus* TU on the positive values and by *N. pachyderma* on the negative values.

	1	2	3	4
<i>G. bulloides</i>	3.6001	- 0.1832	0.7735	0.3968
<i>N. pachyderma</i>	0.1642	- 0.2528	0.8178	- 1.5935
<i>Gd. obliquus</i>	0.0512	0.0305	0.2251	0.9392
<i>Gd. quadrilobatus</i>	- 0.2843	- 0.1594	0.0412	3.0192
<i>Gd. ruber</i>	- 0.2286	- 3.6985	0.0155	- 0.0651
<i>Gt. acostaensis</i>	0.1262	- 0.1473	0.0641	0.5051
<i>Gt. crassaformis</i>	0.1122	- 0.1551	- 0.1814	0.3632
<i>Gt. inflata</i>	- 0.8574	0.1117	3.5289	0.3024
<i>Gt. margaritae</i>	0.0283	0.0360	0.0358	0.0153
<i>Orbulina</i> spp.	0.1099	- 0.3277	0.0230	0.0161
<i>Sphaeroidinellopsis</i> spp.	0.0119	0.0232	0.0635	0.1109
<i>N. atlantica</i>	- 0.0147	- 0.0966	- 0.0478	0.1171
<i>G. quinqueloba</i>	0.2395	0.0123	0.4175	- 0.8929
<i>G. glutinata</i>	0.2050	- 0.1430	0.0876	- 0.0237
Variance	37.961	29.297	20.761	5.311

Tab. 2 - Scaled varimax factor scores matrix and variances of planktonic foraminifera in Monte S. Nicola section.

of the upper part of MPI 4 and lower part of MPI 5 biozones, to several reversed faults with east-west direction. The entity of displacements is generally small, but they produced the obliteration of several lithologic levels with the consequence that in some intervals the complete sequence of quantitative fluctuations of the considered taxonomic units cannot be followed. In Fig. 9 the loadings of the 4 varimax Factors retained from varimax rotation in the Q-mode factor analysis of the planktonic foraminifera raw abundance data are plotted. In Tab. 2 the varimax factor scores and the variances are reported. Factor 1 is dominated by *Globigerina bulloides* TU, Factor 2 by *Globigerinoides ruber* TU, Factor 3 by *Globorotalia inflata* TU and Factor 4 by *Globigerinoides quadrilobatus* TU on the positive values and by *N. pachyderma* TU on the negative values. The paleoclimatic interpretation of the Factors is discussed in Channell, Di Stefano & Sprovieri (in press).

Punta Piccola section.

This well-known section (Brolsma, 1978; Sprovieri & Barone, 1982; Spaak, 1983; Rio et al., 1984; Zachariasse et al., 1989, 1990; Channell, Di Stefano & Sprovieri, in press), outcropping 4 km east of Capo Rossello, along the southern coast of Sicily, covers the lithological transition from the "Trubi" marly limestones (below) to the gray marls of the Monte Narbone Formation (above), from the upper part of the MPI 4 to the lower part of the MPI 5 biozones. It therefore covers the stratigraphic interval in correspondence of the unrecovered interval at the base of core 15 at Site 653. At Monte S. Nicola several hiatuses are present in the same stratigraphic interval due to

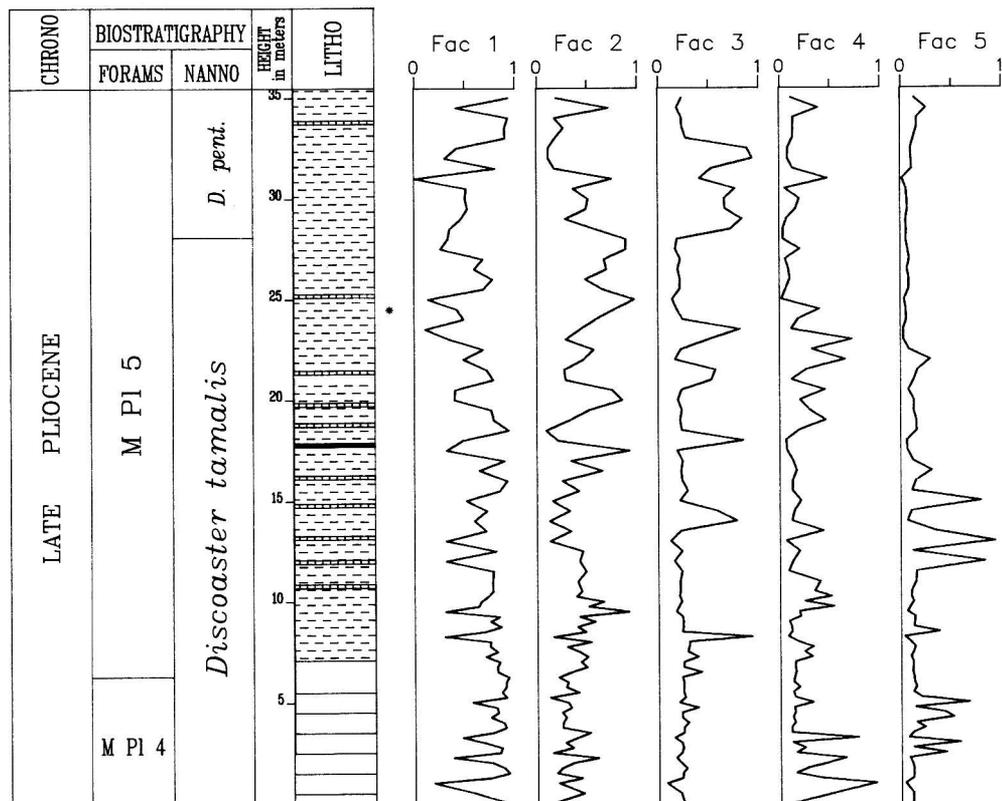


Fig. 10 - Distribution of Factor loadings in the Punta Piccola section. Black bar) laminite; dashed bars) manganeseiferous levels. Asterisk indicates the first entrance of left coiled *N. atlantica*. Factor 1 is dominated by *G. bulloides* TU, Factor 2 by *Gd. ruber* TU, Factor 3 by *Gt. crassaformis* TU, Factor 4 by *Gt. inflata* TU (*Gt. bononiensis*), Factor 5 by *Gd. quadrilobatus* TU.

	1	2	3	4	5
<i>G. bulloides</i>	3.4573	0.0772	0.7854	0.4298	0.4243
<i>N. pachyderma</i>	0.0131	0.0947	-0.0122	0.0188	-0.0216
<i>Gd. obliquus</i>	0.0197	0.3230	0.2868	0.3768	0.3360
<i>Gd. quadrilobatus</i>	-0.4386	0.2407	-0.0847	3.5459	-0.0929
<i>Gd. ruber</i>	-0.1830	3.2942	0.3597	-0.2659	0.0916
<i>Gt. acostaensis</i>	0.0648	1.2601	-0.0262	-0.1412	-0.2165
<i>Gt. bononiensis</i>	-0.4525	-0.0545	0.0270	0.0041	3.5502
<i>Gt. crassaformis</i>	-0.7681	-0.3812	3.4837	-0.0164	-0.1606
<i>Orbulina</i> spp.	0.0289	0.3402	0.0043	0.0431	0.0483
<i>Sphaeroidinellopsis</i> spp.	0.0318	-0.0187	-0.0137	-0.0021	0.0274
<i>N. atlantica</i>	-0.0724	0.1536	0.1461	-0.0117	-0.0613
<i>G. quinqueloba</i>	0.0320	0.0472	0.0303	-0.0033	0.0286
<i>G. glutinata</i>	0.1151	0.3046	0.0660	0.0824	-0.0690
Variance	47.639	21.472	14.202	8.197	5.501

Tab. 3 - Scaled varimax factor scores matrix and variances of planktonic foraminifera in Punta Piccola section.

several, small reversed faults. In Fig. 10, in which the lithology and the calcareous plankton biostratigraphic schemes are reported, the loadings of the 5 Factors retained from varimax rotation in the Q-mode factor analysis of the planktonic foraminifera raw abundance data are plotted. In Tab. 3 the varimax factor scores and the variances

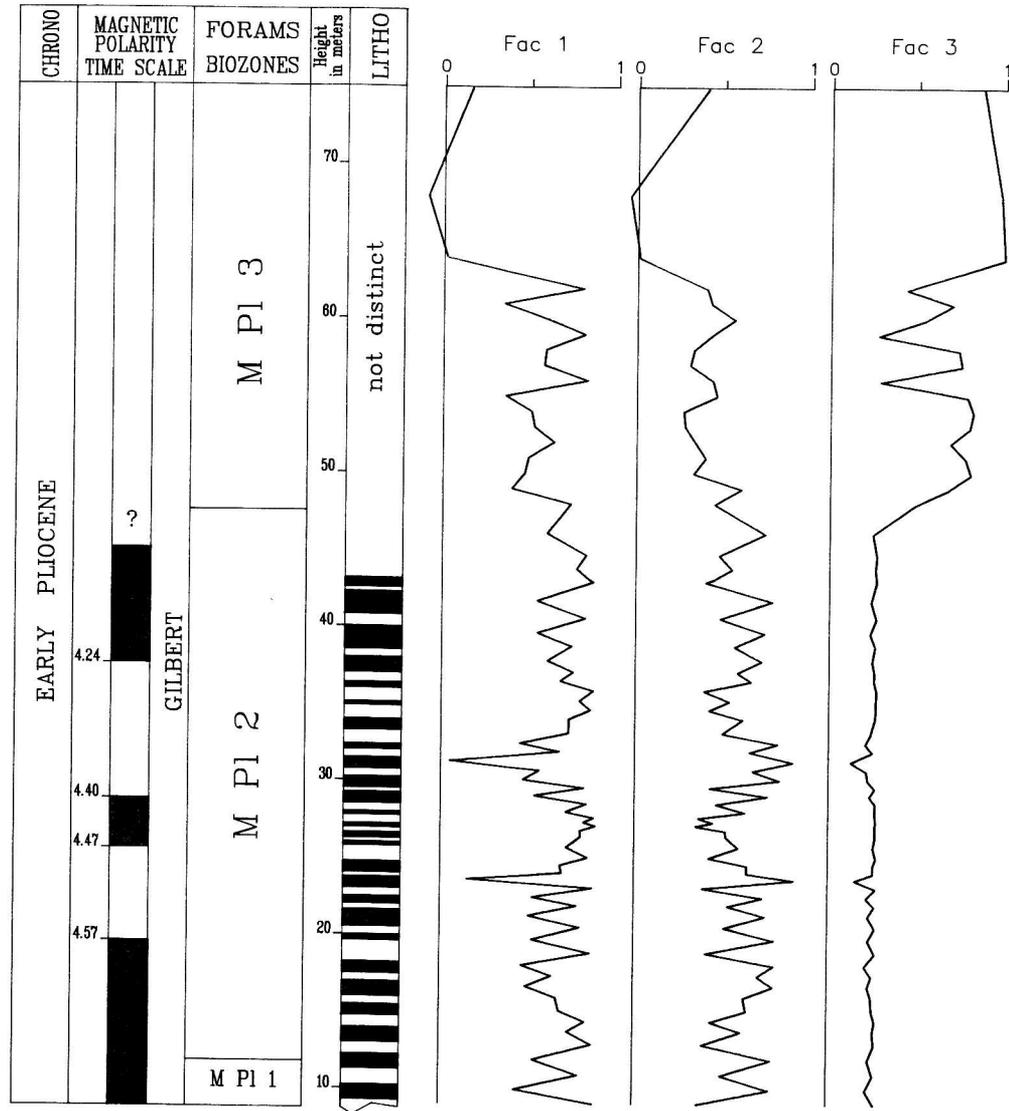


Fig. 11 - Distribution of Factor loadings in the Capo Spartivento section. Black bars) carbonate-poor intervals; white bars) carbonate-rich intervals. Factor 1 is dominated by *G. bulloides* TU, Factor 2 by *Gd. obliquus* TU and *Gd. quadrilobatus* TU, Factor 3 by *Gt. inflata* TU (*Gt. puncticulata*). Magnetics are from Channell et al. (1988).

are reported. Factor 1 is dominated by *Globigerina bulloides* TU, Factor 2 by *Globigerinoides ruber* TU, Factor 3 by *Globorotalia crassaformis* TU, Factor 4 by *Globigerinoides quadrilobatus* TU and Factor 5 by *Globorotalia inflata* TU (*Gt. bononiensis*).

<i>G. bulloides</i>	3.5803	0.9424	1.0621
<i>G. nepenthes</i>	0.0346	0.0019	- 0.0169
<i>N. pachyderma</i>	- 0.0261	0.3431	- 0.0237
<i>Gd. obliquus</i>	- 0.7455	2.8704	- 0.0192
<i>Gd. quadrilobatus</i>	- 0.5315	1.4132	0.0303
<i>Gd. ruber</i>	- 0.0393	0.0179	0.1183
<i>Gt. acostaensis</i>	- 0.4551	1.7294	0.1341
<i>Gt. margaritae</i>	- 0.1777	0.5416	0.0671
<i>Gt. puncticulata</i>	- 0.9959	- 0.3365	3.7184
<i>Gt. scitula</i>	- 0.0169	0.0501	0.0096
<i>Orbulina</i> spp.	0.3021	0.3686	- 0.0405
<i>Sphaeroidinellopsis</i>	0.1076	- 0.0171	- 0.0425
<i>H. siphonifera</i>	- 0.0173	0.0458	- 0.0008
<i>G. quinqueloba</i>	- 0.0463	0.1603	0.0564
<i>G. glutinata</i>	- 0.0583	0.4398	0.0116
Variance	48.142	31.551	14.459

Tab. 4 - Scaled varimax factor scores matrix and variances of planktonic foraminifera in Capo Spartivento section.

Capo Spartivento section.

The magnetostratigraphy and lithology of this section, outcropping along the Ionian coast of Calabria, were published by Channell et al. (1988). The same samples studied by these Authors were used for this study. They have been collected with at least one sample per each carbonate-rich carbonate-poor interbeds, for a total of 98 samples. The 76 m thick section is referable to the MPI 1 up to 12.73 m above the base, where *Gt. margaritae* FCO (First Common Occurrence) is recorded, to the MPI 2 biozone from 12.73 to 47.50 m above the base and to the MPI 3 biozone from 47.50 m up to the top of the sequence.

The end of the *Sphaeroidinellopsis* acme interval is recorded at 4.68 m above the base, in coincidence with a thick, indurated carbonate level, corresponding to the carbonate unit 6 of Zijderveld et al. (1986). In some levels of the MPI 1 biozone rare specimens of *Gt. margaritae* have been found. At 18 and 19 m above the base frequent specimens of *Globorotalia limbata* are present.

Quantitative data have been performed only in the interval from above the *Gt. margaritae* FCO. In Fig. 11, in which the calcareous plankton biostratigraphy and the magnetostratigraphic results are reported, the varimax Factors retained from varimax rotation in the Q-mode factor analysis of the raw abundance data of the planktonic foraminifera taxonomic units are plotted. In Tab. 4 the varimax factor scores and

variances are included. Factor 1 is dominated by *Globigerina bulloides*, Factor 2 by *Globigerinoides obliquus* TU and *Globigerinoides quadrilobatus* TU and Factor 3 by *Globorotalia inflata* TU (*Gt. puncticulata*).

	MA		MA
<i>Gt. margaritae</i> FCO	4.65	<i>Sphaeroidinellopsis</i> LO	3.06
<i>Gt. puncticulata</i> FO	4.15	<i>D. tamalis</i> LO	2.65
<i>D. asymmetricus</i> FCO	3.87-3.88	<i>D. pentaradiatus</i> LO	2.37
<i>Gt. margaritae</i> LCO	3.71	<i>Gt. bononiensis</i> LO	2.32
<i>R. pseudoumbilicus</i> LO	3.63	<i>N. atlantica</i> (left) LO	2.25
<i>Sphenolithus</i> spp. LO	3.53	<i>Gt. inflata</i> FO	2.00-1.99
<i>Gt. puncticulata</i> LO	3.38	<i>D. browneri</i> LO	1.81-1.83
<i>Gt. bononiensis</i> FO	3.16	<i>G. oceanica</i> s.l. FO	1.58-1.59

Tab. 5 - Proposed calcareous plankton biochronology in the Mediterranean Pliocene interval.

Biochronology.

Only in the recent past good magnetostratigraphic data on Mediterranean Pliocene sequences were published. Tauxe et al. (1983) provided a good magnetostratigraphy from the N/Q stratotype boundary Vrica section; Zijderveld et al. (1986) obtained high quality magnetostratigraphy from the Lower Pliocene Singa composite section and Channell et al. (1988) obtained good results from the Capo Spartivento sequence, both in Calabria (Southern Italy). Hilgen & Langereis (1988), Zachariasse et al. (1989) and Zachariasse et al. (1990) published important magnetostratigraphic data from the Capo Rossello area. The ODP Leg 107 Site 653, in the Tyrrhenian basin, did not yield magnetostratigraphy due to the poor magnetic signals at this site, but several magnetostratigraphic reversals were recognized in the Pliocene interval at Sites 652 and 654 and in the Pleistocene interval of Sites 650 and 651 (Channell et al., 1990). Nevertheless, frequent unrecovered segments and many syn-sedimentary gaps make the recognition of some of these reversal boundaries inconsistent or doubtful. Finally, Channell, Di Stefano & Sprovieri (in press) published good paleomagnetic data from the Monte S. Nicola section, in which the Gilbert/Gauss boundary, the base of Mammoth and the Gauss/Matuyama boundary have been identified. All these data improved the accuracy of the calibrations of several biostratigraphic events, essentially in the Lower Pliocene stratigraphic record (Zijderveld et al., 1986; Hilgen & Langereis, 1988; Channell et al., 1988; Zachariasse et al., 1989, 1990; Langereis & Hilgen, 1990). These biochronological estimates were used as tie-points to obtain the curve of the sediment accumulation rate at Site 653 (Fig. 3) with the results that several other intervening bio-events, essentially belonging to the calcareous nannofossil assemblage, were also calibrated with good accuracy (Tab. 5).

In the MPI 5 interval reliable paleomagnetostratigraphic data have been published from Punta Piccola (Zachariasse et al., 1989, 1990) and Monte S. Nicola (Channell, Di Stefano & Sprovieri, in press) sections. Due to hiatuses and/or change in sediment accumulation rate in this interval of the Monte S. Nicola and Punta Piccola sections (Fig. 9 and Fig. 12) the curve of the sediment accumulation rate in the two sequences cannot provide a refined age of the bio-events. The absolute ages of other control points between the *Sphaeroidinellopsis* LO and the *D. pentaradiatus* LO have been inferred by cross-correlation of these two sections with the sequence at Site 653. The following correlations have been considered:

1) In the Punta Piccola section the sharp increase in abundance of *Gt. bononiensis* (Factor 5 in Fig. 10) at 12 mab (meters above the base) is coincident with the second manganeseiferous level. This level, coincident with the top of the Kaena subchron (Zachariasse et al., 1989), has an absolute age of 2.92 MA. At Site 653 the same sharp increase of *Gt. bononiensis* (Fig. 4 and Factor 3 in Fig. 7) is recorded at 127.80

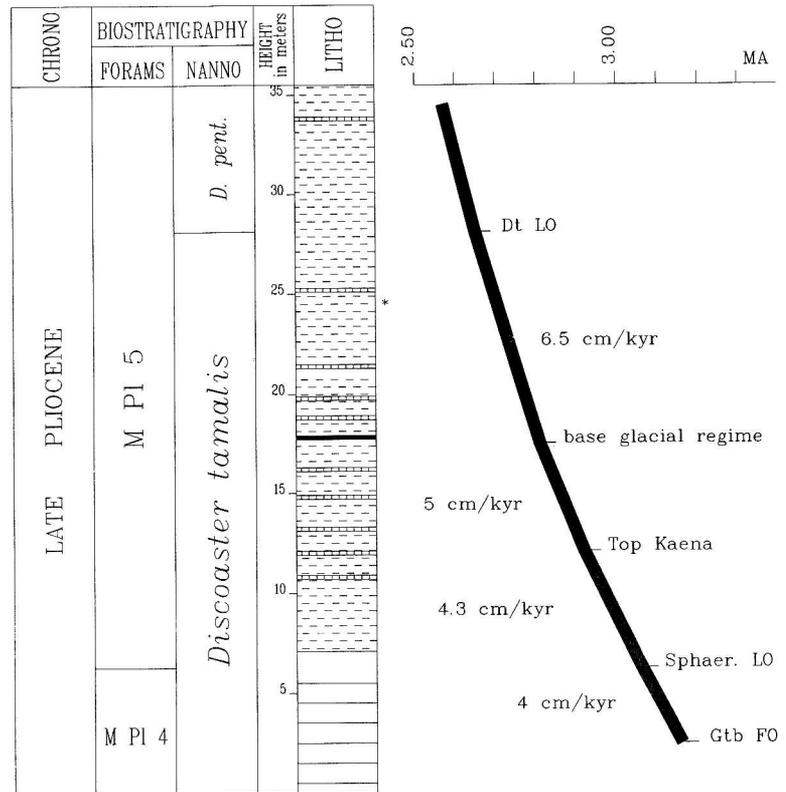


Fig. 12 - Curve of sediment accumulation rate in the analyzed Punta Piccola section. See Fig. 10 for lithology. Dt) *D. tamalis*; Sphaer.) *Sphaeroidinellopsis* spp.; Gtb) *Gt. bononiensis*. Position of the top of Kaena is from Zachariasse et al. (1989).

MBSF. An absolute age of 2.92 MA is therefore ascribed to this level.

2) By extrapolation of the curve of the sediment accumulation rate at Site 653 between this level and the *Gt. bononiensis* FO (at 138.36 MBSF; Glaçon et al., 1990), with an absolute age of 3.16 MA (Zachariasse et al., 1989), an absolute age of 2.81 MA can be inferred for the level at 122.80 MBSF, in coincidence of a strong increase in the *Gd. ruber* taxonomic unit (Factor 2 in Fig. 7).

3) In the Monte S. Nicola section the same sharp increase of the *Gd. ruber* taxonomic unit is recognized at 48 mab (Factor 2 in Fig. 9). This level has therefore an absolute age of 2.81 MA.

4) In the Monte S. Nicola section the Gauss/Matuyama boundary has been recognized at 62 mab (Channell, Di Stefano & Sprovieri, in press). The curve of the sediment accumulation rate between this level (at 2.48 MA) and the level at 48 mab (with an absolute age of 2.81 MA) allows to interpolate an absolute age of 2.65 MA for the *D. tamalis* LO, which occurs at 54.50 mab (Fig. 9; Channell, Di Stefano & Sprovieri, in press).

5) Seven abundance fluctuations of Factor 2 are present in the *D. pentaradiatus* biozone in Monte S. Nicola section and in Hole 653 A sequence. In the Monte S. Nicola section the Gauss/Matuyama boundary (which, by comparison of the manganeseiferous and laminated levels in the two sections, occurs in the same position as reported by Zachariasse et al. (1990) in the extended Punta Piccola section) falls between fluctuations 4 and 5 above the *D. tamalis* LO or between fluctuations 2 and 3 below the *D. pentaradiatus* LO. Therefore this paleomagnetic boundary is coincident at Site 653 with the level at 113.95 MBSF, for which an absolute age of 2.48 MA can be evaluated.

6) By extrapolation of the curve of the sediment accumulation rate between this level and the level corresponding to the *D. tamalis* LO (at 2.65 MA) an absolute age of 2.37 MA can be obtained for the *D. pentaradiatus* LO.

7) By interpolation on the same curve of the sediment accumulation rate between the *D. tamalis* LO and the level at 2.81 MA (increase of Factor 2) an absolute age of 2.71 MA may be obtained for the first (Mediterranean) occurrence of left coiled *N. atlantica*, which is recognized at Site 653 at 120.46 MBSF, just below the *D. tamalis* LO (Glaçon et al., 1990). The same event is recognized at Punta Piccola in the same biostratigraphic position (just below the *D. tamalis* LO) at 24.50 mab (Fig. 10) and the same absolute age may be obtained, as discussed below.

The age evaluation of the Pliocene biostratigraphic events occurring above the *D. pentaradiatus* LO will be discussed in the following paragraph.

Results.

MPI 1 biozone (4.85-4.65 MA).

The abundance fluctuations of the planktonic foraminiferal assemblage have been obtained from a short segment at the base of the Capo Rossello section. Ten

fluctuations of *Globigerinoides* spp. (*G. oides* in Fig. 8) are present between the base of the Pliocene, with an absolute age of 4.85-4.86 MA (Zijderveld et al., 1986) and the top of the MPI 1, coincident with the *Gt. margaritae* FCO, at 4.65 MA (Fig. 8). They have a mean periodicity of about 20 kyr, which is well comparable with the periodicity of the precession astronomical cycles (Berger, 1984).

MPI 2 biozone (4.65-4.15 MA).

Recent papers by Zijderveld et al. (1986) and Channell et al. (1988) proved that in the interval between the Mediterranean *Gt. margaritae* FCO and the *Gt. puncticulata* FO, at 4.15 MA, 25 lithological cycles identified by the sequence of carbonate-rich carbonate-poor couplets can be recognized, at a mean time interval of about 20 kyr. In the Capo Spartivento section 25 fluctuations of the loadings of Factor 2, dominated by *Gd. quadrilobatus* and *Gd. obliquus* TUs, can be recognized in the same interval (Fig. 11 and Fig. 13), in perfect agreement with the lithological alternations. At Site 653 in the MPI 2 biozone only 18-19 cycles of Factor 6 (= Factor 2 in the Capo Spartivento section) can be counted on the base of the available samples (Fig. 7 and Fig. 14). Nevertheless in the unrecovered intervals between 202.20 and 199.12 and between 193.06 and 190.85 MBSF other fluctuations may be considered. In this part of the sequence the fluctuations of Factor 6 are spaced at a mean interval of about 66 cm. Since the two unrecovered intervals are respectively 3.08 and 2.21 meters thick, 4 and 3 cycles may be respectively supposed in the two unrecovered intervals, which may account for the difference compared with the Capo Spartivento section. The fluctuations of Factor 6 effectively recognized in the MPI 2 interval at Site 653 have a periodicity of about 26 kyr, but it is surely over-estimated and a value close to 20 kyr can be considered, in agreement with the periodicity of the lithological couplets and the faunal abundance fluctuations at Capo Spartivento, which have the same periodicity of the precession astronomical cycles.

MPI 3 biozone (4.15-3.71 MA).

In the interval corresponding to the MPI 3 biozone, 20-21 cycles of Factor 3 are recognized (Fig. 7 and Fig. 15) at Site 653. Again this number is surely under-estimated, since another fluctuation may be supposed in the unrecovered interval between 183.35 and 180.90 MBSF. On the base of the recognizable cycles, their periodicity along the MPI 3 segment at Site 653 is of about 21-22 kyr; even if it is slightly over-estimated, the periodicity is again well comparable with the periodicity of the precession astronomical cycles.

Base MPI 4 - Base glacial regime (3.71-2.81 MA).

Between the *Gt. margaritae* LCO and the *Gt. bononiensis* FO, at 3.16 MA (Zachariasse et al., 1989), 24 cycles of Factor 6 are recognized at Site 653 (Fig. 7 and Fig. 16), but in the unrecovered intervals between 155.36 and 154.10 MBSF and at

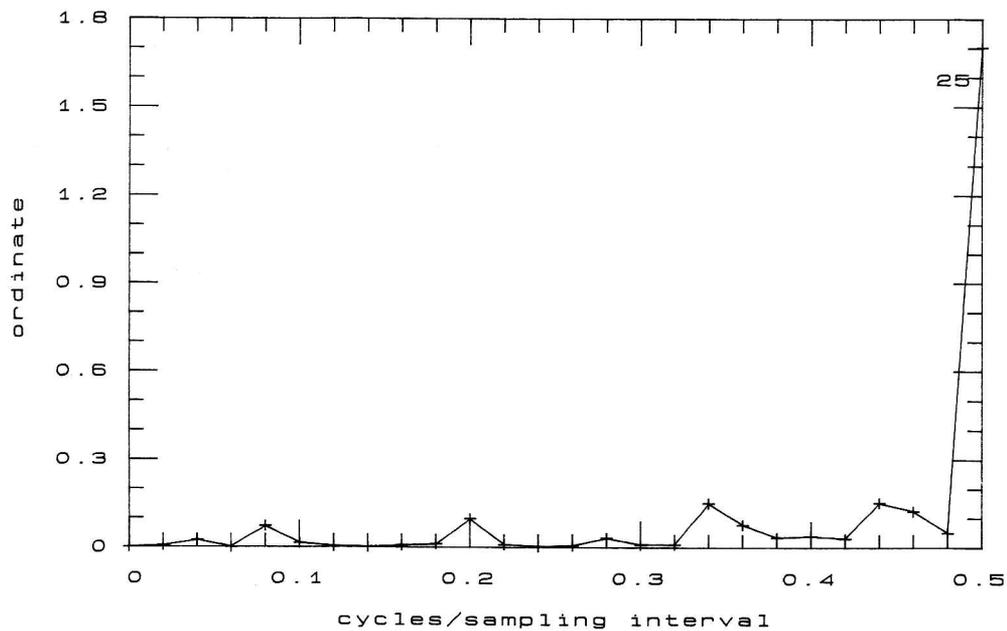


Fig. 13 - Periodogram of the MPI 2 interval of the Capo Spartivento section. Band frequency 0.02. Number of samples=51. Squared amplitudes of the sinusoids are plotted on the ordinate.

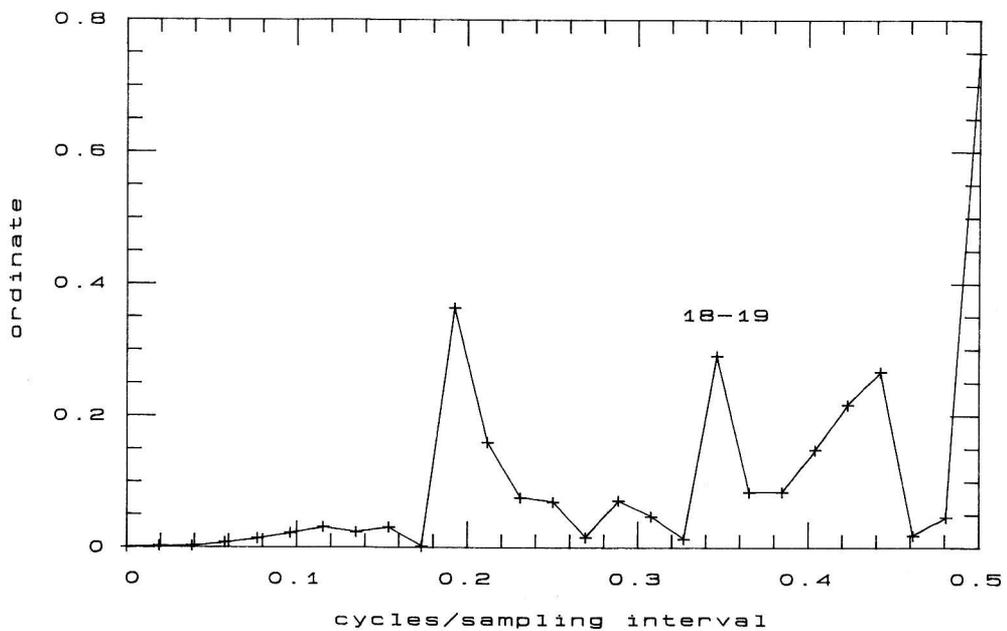


Fig. 14 - Periodogram of the MPI 2 interval of the ODP Hole 653A. Band frequency 0.01923. Number of samples=53. Squared amplitudes of the sinusoids are plotted on the ordinate.

about 145 MBSF and in the short not sampled interval between 159 and 158.45 MBSF 3 other cycles may be supposed. No quantitative data are available at present in correspondence of this stratigraphic segment from land-sections. The 24 cycles of Factor 6 in this interval of 0.55 MA have a periodicity of about 23 kyr, but this value is again over-estimated since 3 other cycles may be present and therefore a periodicity again well comparable with the period of the precession orbital cycles can be estimated.

The unrecovered segment between 136 and 130 MBSF at Site 653 prevents any analysis. Cyclicity of the quantitative data between the *Gt. bononiensis* LO and the *D. tamalis* LO was estimated in the complete, continuous section of Punta Piccola. Between the *Gt. bononiensis* FO and the second manganeseiferous level at 12 mab, which is coincident with the top of Kaena, at 2.92 MA, 12 fluctuations of Factor 2 are present (Fig. 10), with a mean periodicity of 20 kyr. Between the second manganeseiferous level and the strong increase of Factor 2 at 17.5 mab, which has an absolute age of 2.81 MA and represents the beginning of the glacial-interglacial climatic regime (Sprovieri, 1991; Channell, Di Stefano & Sprovieri, in press), five fluctuations of Factor 2 are present (Fig. 10), again with a periodicity of about 20 kyr. Therefore the precession astronomical cycles still dominate these two stratigraphic intervals. In the upper part of the Punta Piccola section the *D. tamalis* LO is recognized at 28 mab (Fig. 10; Channell, Di Stefano & Sprovieri, in press). This level has therefore an absolute age of 2.65 MA. In the segment between this level and the strong increase of Factor 2 at 17.5 mab (Fig. 10), corresponding to a time interval of 0.16 MA, 4 cycles of Factor 2 are present, regularly spaced. These fluctuations have therefore a mean periodicity of about 40 kyr, well comparable with the period of the obliquity astronomical cycles. According to Raymo et al. (1989) obliquity astronomical cycles dominate during glacial-interglacial climatic regimes in the mid-high latitudes.

Above 17.5 mab the fluctuations of Factor 2 in the Punta Piccola section clearly occur at more spaced intervals (Fig. 10). Along this segment marked changes in lithology are not recognizable and therefore this feature, more than to a relevant increase in sediment accumulation rate (Zachariasse et al., 1989) which only shows a small increase upward (Fig. 12), is ascribed to a change in time periodicity of the abundance fluctuations. The base of this change is coincident with the beginning of a strong climatic instability, in agreement with a glacial-interglacial model (Sprovieri, 1991; Channell, Di Stefano & Sprovieri, in press).

Base glacial regime - Pliocene/Pleistocene boundary (2.81-1.64 MA).

The sequences of Site 653 and Monte S. Nicola are the reference sections for the upper part of the Pliocene, after the beginning of the glacial regime. At Site 653 25 cycles of Factor 2 are present between the base of the glacial regime, at 122.80 MBSF, and the *D. brouweri* LO, at 88.70 MBSF (Fig. 7 and Fig. 17). In the 0.16 MA interval up to the *D. tamalis* LO 4 cycles are present, 7 cycles occur in the 0.28 MA interval of the *D. pentaradiatus* zone (with therefore a 41 kyr periodicity in both intervals), and 14 cycles in the *D. brouweri* zone (Fig. 7). The *Gt. inflata* FO occurs 9 cycles of Factor

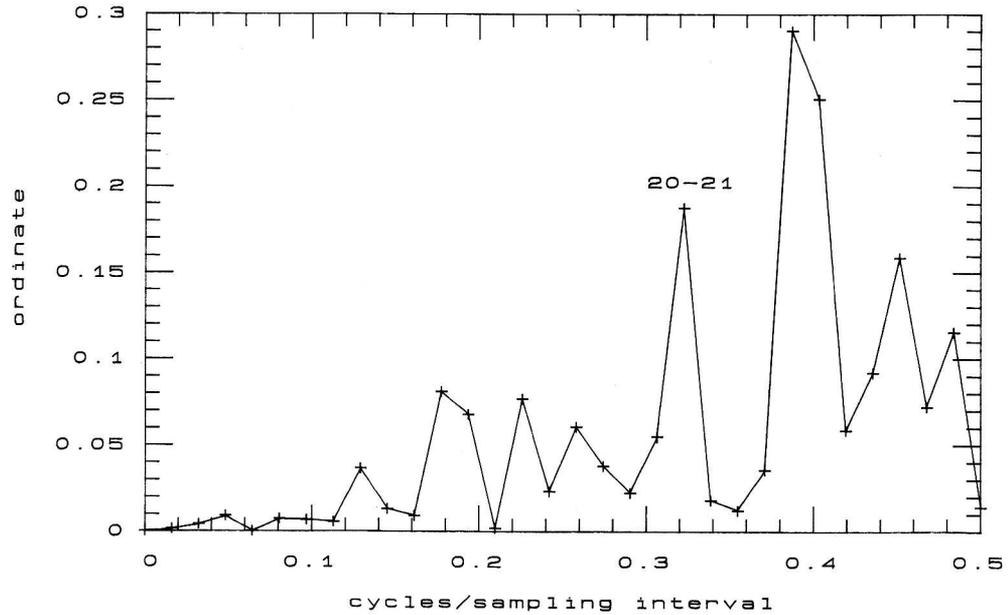


Fig. 15 - Periodogram of the MPI 3 interval of the ODP Hole 653A. Band frequency 0.01613. Number of samples=53. Squared amplitudes of the sinusoids are plotted on the ordinate.

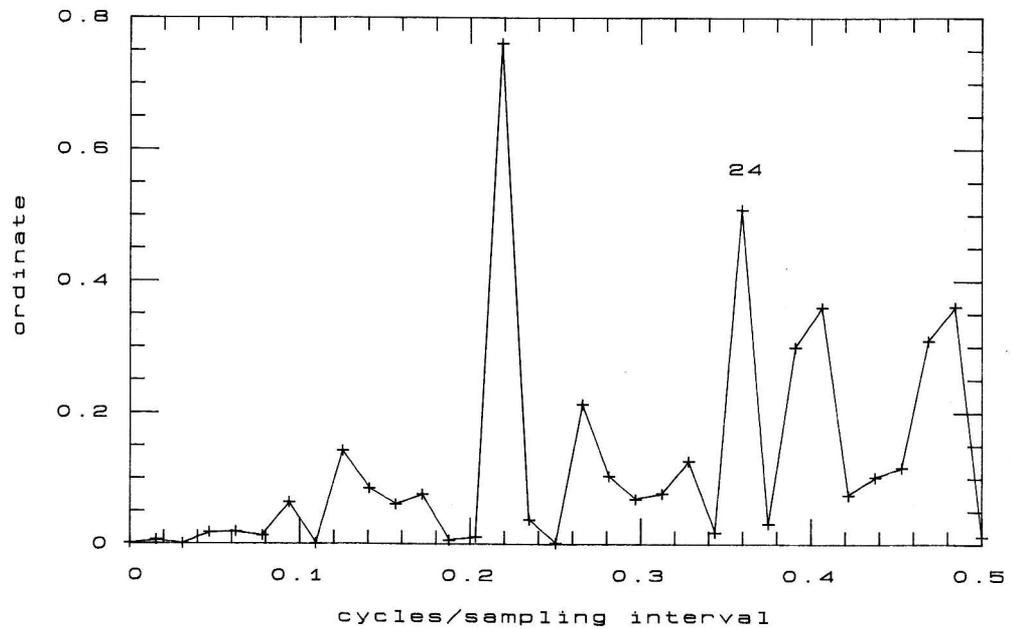


Fig. 16 - Periodogram of the interval between the *Gt. margaritae* LCO and the *Gt. bononiensis* FO of the ODP Hole 653A. Band frequency 0.01563. Number of samples 66. Squared amplitudes of the sinusoids are plotted on the ordinate.

2 above the *D. pentaradiatus* LO.

The interpretation of the fluctuations of Factor 2 at Monte S. Nicola is reported in Fig. 9. As at Site 653, between the base of the glacial regime at 48 mab and the *D. tamalis* LO 4 cycles are present, 7 cycles are present in the *D. pentaradiatus* zone, and 14 cycles can be counted in the *D. brouweri* zone. The *Gt. inflata* FO occurs 9 cycles above the *D. pentaradiatus* LO, as at Site 653, and again 4 cycles are present between the *Gt. inflata* FO and the *D. brouweri* LO. The first occurrence of *Gt. truncatulinoides*, recorded at 107 mab and at 93.82 MBSF respectively at Monte S. Nicola and Site 653 (Glaçon et al., 1990; Channell, Di Stefano & Sprovieri, in press), occurs in both sections 2 cycles below the *D. brouweri* LO. At Monte S. Nicola between the base of the Pleistocene and the *D. brouweri* LO 4 cycles are clearly present (Fig. 9) and the *G. oceanica* s.l. FO occurs just below the second fluctuation above the base of the Pleistocene (Fig. 9), with 5 complete cycles between the *D. brouweri* LO and the *G. oceanica* s.l. FO (Fig. 9 and 18). In conclusion, in the interval of 1.17 MA between the base of the glacial Pliocene at 2.81 MA and the base of the Pleistocene at 1.64 MA 28 cycles of Factor 2 are included, which have a mean periodicity of 41 kyr.

The cycles recognized in this interval can be used for extrapolating the age of poorly constrained bio-events. In particular, in the Monte S. Nicola section *G. oceanica* s.l. first occurs at 150 mab (Channell, Di Stefano & Sprovieri, in press), just below the second fluctuation of Factor 2 which follows the Pliocene-Pleistocene boundary. An absolute age of 1.58-1.59 MA is therefore estimated for this bio-event.

At Site 653 *Gt. inflata* first occurs at 98.40 MBSF (Glaçon et al., 1990), just above 9 fluctuations of Factor 2 following the *D. pentaradiatus* LO. Then the absolute age of the *Gt. inflata* FO can be estimated 0.36-0.37 MA younger than the age of the *D. pentaradiatus* LO. An absolute age of 1.99-2.00 MA is suggested for the first Mediterranean occurrence of *Gt. inflata*. In the same sequence the last occurrence of *D. brouweri* is recorded at about 88.70 MBSF (Rio et al., 1990), that is 4 cycles of Factor 2 above the *Gt. inflata* FO. An absolute age of 1.81-1.83 MA is proposed for the last occurrence of *D. brouweri* in the Mediterranean basin. An absolute age of 1.89-1.91 MA is obtained for the first appearance of *Gt. truncatulinoides*, which at Site 653 and the Monte S. Nicola section occurs in coincidence of the second fluctuation of Factor 2 below the *D. brouweri* LO. At both sites *N. atlantica* is represented by only left coiling specimens up to 75 mab and 105.20 MBSF respectively. This event occurs in coincidence of the third fluctuation of Factor 2 following the *D. pentaradiatus* LO and an absolute age of about 2.25 MA is estimated. Above this level *N. atlantica* is present up to the lowermost Pleistocene, but it is represented by essentially right coiling specimens. The first occurrence of left coiled *N. atlantica* is recorded, at Monte S. Nicola and Punta Piccola, between the second and third fluctuation of Factor 2 above the base of the glacial regime. Therefore the age of this event in the two sequences may be estimated at about 2.71 MA, as also obtained on the curve of the sediment accumulation rate at Site 653 (Fig. 3). An absolute age of 2.31-2.32 MA is evaluated for the *Gt. bononiensis* LO, which is recognized above the first fluctuation of Factor 2 following

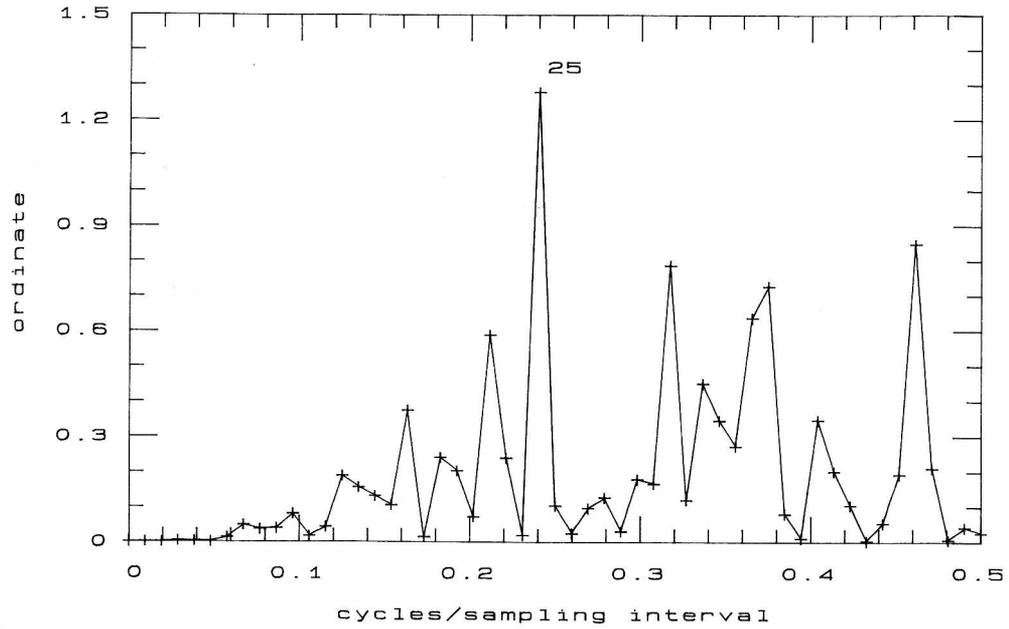


Fig. 17 - Periodogram of the interval between the base of the glacial regime and the *D. brouweri* LO of ODP Hole 653A. Band frequency 0.00962. Number of samples=105. Squared amplitudes of the sinusoids are plotted on the ordinate.

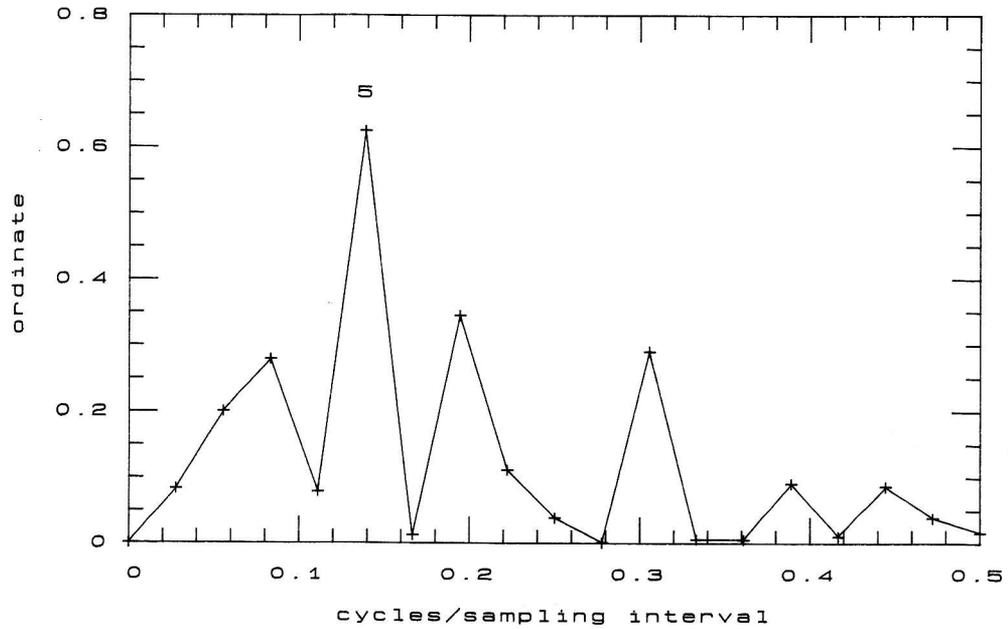


Fig. 18 - Periodogram of the interval between the *D. brouweri* LO and the *G. oceanica* s.l. FO in the Monte S. Nicola section. Band frequency 0.01064. Number of samples=65. Squared amplitudes of the sinusoids are plotted on the ordinate.

the *D. pentaradiatus* LO both at Site 653 and at Monte S. Nicola.

As far as the age estimates of calcareous nannofossil events in the Early and early Late Pliocene, during which fluctuations have a periodicity of 20 kyr, the FCO of *Discoaster asymmetricus*, which in Hole 653A occurs at 169.90 \pm 0.37 MBSF (Rio et al., 1990) and about 9 fluctuations of Factor 3 below the LCO of *Gt. margaritae* (Fig. 7), has an estimated age of 3.87-3.88 MA.

At Monte S. Nicola *Reticulofenestra pseudoumbilicus* (forms larger than 7-8 mm) disappears 10.50 meters above the base (Channell, Di Stefano & Sprovieri, in press) and just above 4 fluctuations of Factor 3 above the LCO of *Gt. margaritae* (Fig. 9). In Hole 653A the same event is recorded at 156.60 \pm 0.27 MBSF (Rio et al., 1990), again just above 4 fluctuations of Factor 3 above the *Gt. margaritae* LCO (Fig. 7). An age of 3.63 MA is estimated for the extinction level of *R. pseudoumbilicus* (forms larger than 7-8 mm).

Sphenolithus spp. disappear at Monte S. Nicola 18 meters above the base (Channell, Di Stefano & Sprovieri, in press) and just above 9 fluctuations of Factor 3 above the *Gt. margaritae* LCO (Fig. 9). In Hole 653A the same event is recorded at 152 \pm 0.17 MBSF (Rio et al., 1990), again just above 9 fluctuations of Factor 3 above the *Gt. margaritae* LCO (Fig. 7). An age of 3.53 MA is estimated for the extinction level of *Sphenolithus* spp.

The age estimates of the main Pliocene biostratigraphic events proposed in this paper are reported in Tab. 5.

Discussion.

In the previous section it was proved that the abundance fluctuations of various taxonomic units do not occur at random, but their number is constant within a specific stratigraphic interval. Therefore abundance fluctuations of taxonomic units provide a means to further subdivide the biostratigraphic zones based on the calcareous plankton datum planes, to recognize possible short sedimentary gaps in otherwise considered continuous sections and to precisely quantify the duration of gaps or unrecovered intervals.

Raymo et al. (1989) formalized oxygen isotopic stages down to stage 116, at 2.70 MA, and proved that in the North Atlantic ocean variations in the oxygen isotopic record were dominated by the 41 kyr component of the orbital obliquity in the interval between 2.70 and 1.60 MA. Comparing several bio-events to this high resolution record they also proposed a detailed biochronology for these events.

In the interval between 2.81 MA, coincident with the proposed base of glacial regime, and about 1.60 MA at Site 653 and in Monte S. Nicola section the fluctuations of Factor 2 are dominated by the 41 kyr periodicity of the obliquity astronomical cycles. These fluctuations can be compared with the high resolution oxygen isotope records recognized by Raymo et al. (1989) in the North Atlantic sites. In particular, the same number of cycles are present in the same time-interval. Therefore the two

comparable high resolution records can be used to correlate in detail the first and last occurrence of bio-events in the Mediterranean and North Atlantic regions during the Late Pliocene. If the sequence of numbers used by Raymo et al. (1989) is adopted and number 104 is ascribed to the fluctuation of Factor 2 coincident in the Monte S. Nicola section with the Gauss/Matuyama boundary (this same level is correlated at Site 653 with the level at 113.95 MBSF) the following results are obtained (Fig. 7 and Fig. 9).

The increase of left coiled *N. pachyderma*, which at Site 607 is recorded in coincidence of the isotopic stage 64, at the top of Olduvai subchron, at Monte S. Nicola is coincident with the same fluctuation 64. Therefore this event has the same absolute age in the Mediterranean basin, where it is recorded in the Vrica section above the top of Olduvai (Tauxe et al., 1983; Aguirre & Pasini, 1985).

The *D. brouweri* LO, which occurs between isotopic stages 72 and 71 at Site 607, is recorded in coincidence of fluctuation 73 in the Mediterranean sequences (Fig. 9). Therefore this event is slightly older in the Mediterranean basin than at Site 607.

The *Gt. inflata* FO is coincident with the isotopic stage 78 at Site 607, but it is just above fluctuation 81 at Site 653 and at Monte S. Nicola. Therefore in the Mediterranean basin this event predates the same event at Site 607 of about 50 kyr.

The last occurrence of left coiled specimens of *N. atlantica* at Site 607 is recorded in the upper part of the isotopic stage 96; it is just below stage 94 in Hole 609 (and 609A) and between stages 94 and 95 in Hole 552A. In the Mediterranean sequences the last occurrence of dominant *N. atlantica* left coiled specimens is recorded in coincidence of fluctuation 93. It slightly postdates the same event in Hole 552A and at Site 607, but it is comparable in Hole 609.

The *Gt. puncticulata* LO in the Atlantic ocean (equal to the *Gt. bononiensis* LO in the Mediterranean basin) is recorded in the upper part of stage 96, just below the *N. atlantica* LO, at Site 607, just below stage 96 in Hole 609 and in coincidence of stage 97 in Hole 552A. In the Mediterranean sequences *Gt. bononiensis* disappears in coincidence of fluctuation 96, in good agreement with its last occurrence at Site 607 and in Hole 609.

The *D. pentaradiatus* LO is coincident with fluctuation 99 in the two Mediterranean sequences. At Site 607 it occurs between stage 100 and 99, in Hole 609 in coincidence of stage 101 and in Hole 552A in coincidence of stage 100. A good correlation is therefore recognizable with Site 607.

The oldest bio-event calibrated by Raymo et al. (1989) is the *D. tamalis* LO, which is coincident with stage 111 at Site 607, and with the upper part of stage 114 in Hole 609. In the three studied Mediterranean sequences this event is recorded on fluctuation 113, therefore it is older than at Site 607, but slightly younger than in Hole 609.

In conclusion, the absolute age of the above discussed calcareous plankton events are well comparable between the Mediterranean and the North Atlantic regions, if diachroneities within a range of about 0.1 MA are considered negligible.

Proposal of new subzones for the Mediterranean Pliocene.

Two planktonic foraminifera biostratigraphic events, the *Gt. puncticulata* LO and the *Gt. bononiensis* LO, appear to be useful for increasing the biostratigraphic resolution of the Mediterranean Pliocene. They are always recorded at the same stratigraphic level, as proved by their occurrence in coincidence of the same abundance fluctuations and their absolute age are now well calibrated at 3.38 MA and 2.32 MA respectively. Therefore the planktonic foraminifera scheme of Cita (1973, 1975), amended by Rio et al. (1984) may be improved to include four new biostratigraphic subzones. These biostratigraphic events here used to define the boundaries of the proposed subzones have already been adopted by Spaak (1983) in his biostratigraphic scheme.

The proposed subzones have essentially a regional, Mediterranean value. They are defined as follows (Fig. 19). The MPI 4 biozone is divided into two subzones:

Globorotalia puncticulata subzone (MPI 4a).

Interval from the last common occurrence of *Gt. margaritae*, at 3.71 MA to the extinction level of *Gt. puncticulata*, at 3.38 MA, with a total duration of 0.33 MA. Two very short intervals, characterized by *Gt. crassaformis* and *Gt. bononiensis* respectively, also occur in this biozone. They may be detected only by a very detailed sampling.

Globorotalia planispira subzone (MPI 4b).

Interval from the extinction level of *Gt. puncticulata* (at 3.38 MA) to the extinction level of *Sphaeroidinellopsis* spp., at 3.06 MA, with a total duration of 0.32 MA. The lower part of this subzone is characterized by a high abundance of the *Gd. quadrilobatus* TU. The cooling event, world-wide recognized at 3.2-3.1 MA, whose base coincides with the first occurrence of *Gt. bononiensis* is detectable in the middle part of this subzone.

The MPI 5 biozone is divided into two subzones.

Globorotalia bononiensis subzone (MPI 5a).

Interval from the extinction level of *Sphaeroidinellopsis* spp. (3.06 MA) to the extinction level of *Gt. bononiensis*, at about 2.32 MA, with a duration of about 0.74 MA. The nominal marker is generally well represented in this interval. *Gt. crassaformis* is frequently present and its abundance increases in the samples in which *Gt. bononiensis* is rare to absent. The first occurrence of left coiled *N. atlantica* in the Mediterranean is recorded in the middle part of this subzone, at 2.71 MA, but the occurrence of this species is poorly consistent and it cannot be used as zonal marker to separate another subzone in the basal part of MPI 5.

Globorotalia incisa subzone (MPI 5b).

Interval from the extinction level of *Gt. bononiensis* (2.32 MA) to the *Gt. inflata* FO, at 2.00 MA, with a duration of about 0.32 MA. In the Mediterranean sequences the nominal taxon appears just below the base of this subzone and disappears in the lower part of the *Globigerina cariacensis* biozone. It is generally present, even if never abundant.

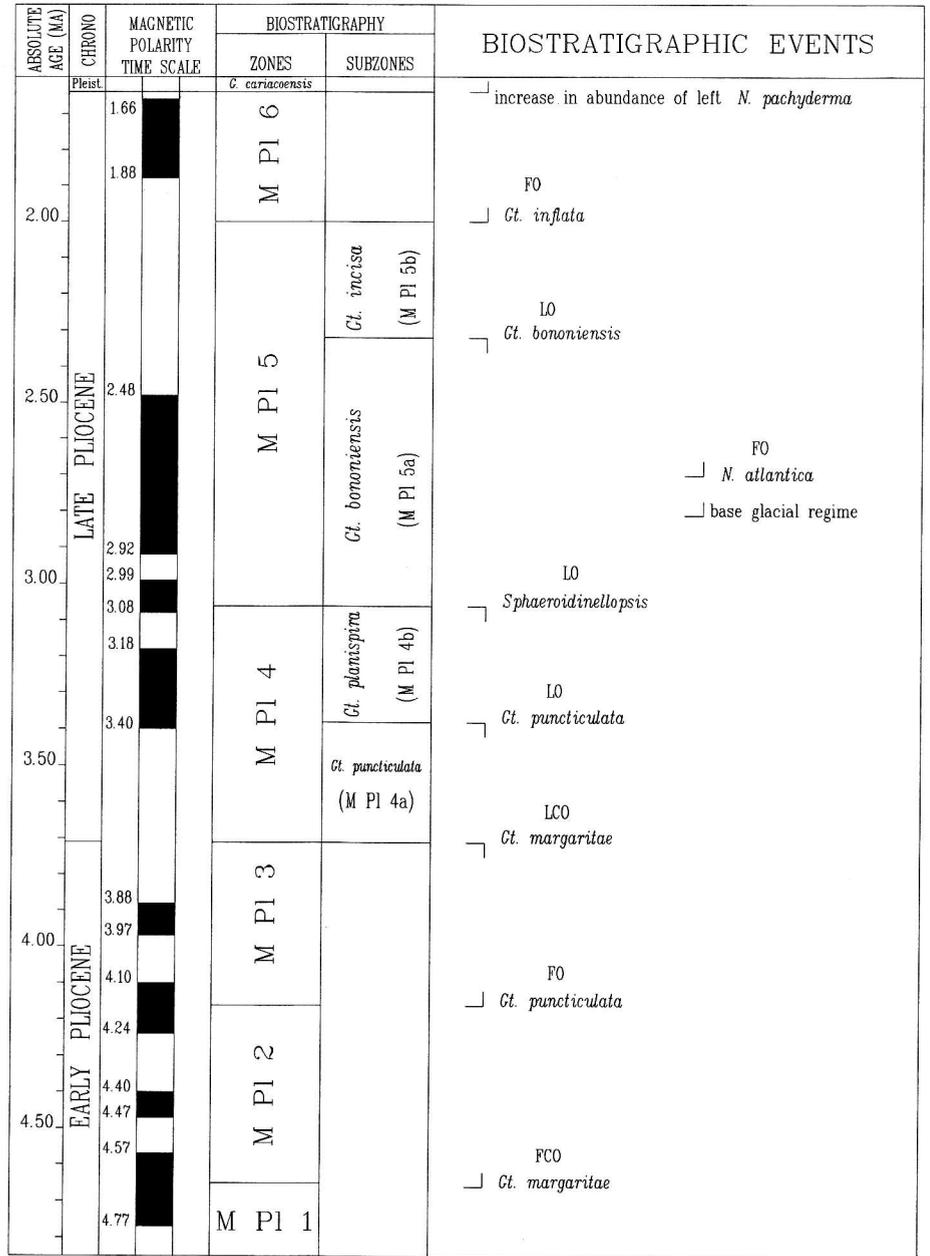


Fig. 19 - Proposed biostratigraphic scheme of the Mediterranean Pliocene based on planktonic foraminiferal bio-events. Note the four new subzones in zones MPI 4 and MPI 5.

Conclusions.

Quantitative analysis carried out on the planktonic foraminifera assemblages recovered from several more or less long and complete Mediterranean Pliocene sections evidenced that a sequence of strictly and regularly spaced fluctuations in abundance occurs in this stratigraphic interval. They occur at a periodicity of about 20 kyr in the portion of Pliocene prior to the base of the glacial-interglacial regime, dated at 2.81 MA and at a periodicity of about 41 kyr from the latter level to the N/Q boundary, well comparable to the precession and obliquity astronomical cycles respectively.

The identification of 130 cycles of known periodicity within the time span of 3.20 MA allows us to estimate or extrapolate more reliable absolute age of numerous bio-events and to estimate their synchronicity or diachroneity with those detected outside the Mediterranean area.

Gt. margaritae is present from the base of the Pliocene, but it is common only from a level whose absolute age is estimated at 4.65 MA. The *Gt. margaritae* last common occurrence is recorded at 3.71 MA, and it predates the disappearance of this species in the oceans, where this event is calibrated at about 3.40 MA. The *Gt. puncticulata* LO is estimated at 3.38 MA. This event is not well identified in the open ocean, where *Gt. puncticulata* is lumped together with *Gt. bononiensis*. In the Mediterranean region these two species are considered as discrete taxa, with *Gt. bononiensis* which appears at 3.16 MA. The disappearance of this species is at 2.32 MA, just above the *D. pentaradiatus* LO, in good agreement with the age of the same event calibrated in the Atlantic ocean. The *Sphaeroidinellopsis* LO is estimated at 3.06 MA. *Gt. inflata* appears at 2.00 MA, slightly predating the same event in the Atlantic ocean. In the MPI 6 biozone a short interval with *Gt. truncatulinoides truncatulinoides* and *Gt. tosaensis* is present. Its base is estimated at 1.89 MA, well below the N/Q boundary as defined in the Vrica section, at 1.64 MA. *N. atlantica* first occurs, with an high abundance peak, at 2.71 MA and disappears at about 2.25 MA.

As far as calcareous nannofossils age evaluations, the *D. asymmetricus* FCO is at 3.87-3.88 MA. The *R. pseudoumbilicus* LO is at 3.63 MA and *Sphenolithus* spp. disappear at 3.53 MA. The absolute age of the LOs of *D. tamalis* and *D. pentaradiatus* are estimated at 2.65 and 2.37 MA respectively. The *D. brouweri* LO is at 1.81 MA. The *G. oceanica* s.l. FO is estimated at 1.58 MA. The absolute age estimates of several bio-events in the Late Pliocene between about 2.80 and 1.60 MA are well comparable with the age calibrations obtained for the same events by comparison with the oxygen isotope record by Raymo et al. (1989) in the Atlantic ocean.

The planktonic foraminifera biostratigraphic scheme of Cita (1973, 1975), amended by Rio et al. (1984) has been integrated by 4 new subzones. Namely, the MPI 4 biozone has been divided into 2 subzones, a lower subzone named *Gt. puncticulata* (MPI 4a) and the upper subzone named *Gt. planispira* (MPI 4b). The biostratigraphic boundary between these two subzones is defined by the extinction level of *Gt. puncticulata*, at 3.38 MA. The MPI 5 biozone is divided into 2 subzones, a lower subzone named *Gt. bononiensis* (MPI 5a) and the upper subzone named *Gt. incisa* (MPI 5b). The

boundary between the two subzones is defined by the extinction level of *Gt. bononiensis* at 2.32 MA.

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PLATE 5

All Figs. are from the Monte S. Nicola section.

- Fig. 1, 2 - *Globigerinoides obliquus*. 1) Umbilical view; 2) spiral view. Level 11, sample 23, MPI 4 biozone; x 60.
- Fig. 3, 4 - *Globorotalia puncticulata*. 3) Umbilical view; 4) spiral view. Level 23, sample 47, MPI 4 biozone; x 60.
- Fig. 5 - *Globigerina quinqueloba*. Umbilical view. Level 140, sample 217, *G. cariacensis* biozone; x 240.
- Fig. 6, 7 - *Neogloboquadrina pachyderma* (right coiling). 6) Umbilical view; 7) spiral view. Level 140, sample 217, *G. cariacensis* biozone; x 120.
- Fig. 8 - *Neogloboquadrina pachyderma* (left coiling). spiral view. Level 140, sample 217, *G. cariacensis* biozone; x 240.
- Fig. 9, 10 - *Globigerinoides ruber*. Umbilical view. Level 80, sample 155, MPI 5 biozone; x 60.
- Fig. 11, 16 - *Globigerinoides elongatus*. Side view. Level 80, sample 155, MPI 5 biozone; x 60.
- Fig. 12 - *Globorotalia bononiensis*. Side view. Level 46, sample 93, MPI 5 biozone; x 100.
- Fig. 13, 14 - *Globigerinoides sacculifer*. Umbilical view. Level 11, sample 23, MPI 4 biozone; x 60.
- Fig. 15 - *Globigerinoides quadrilobatus*. Umbilical view. Level 11, sample 23, MPI 4 biozone; x 60.
- Fig. 17 - *Globorotalia margaritae*. Spiral view. Level 3, sample 7, MPI 3 biozone; x 60.
- Fig. 18 - *Globorotalia truncatulinoides*. Spiral view. Level 106, sample 183, MPI 6 biozone; x 60.
- Fig. 19-21 - *Globorotalia crassaformis*. 19, 20) Spiral view; 21) umbilical view. Level 54, sample 109, MPI 5 biozone; x 60.
- Fig. 22, 23, 25 - *Neogloboquadrina atlantica*. Umbilical view. Level 52.50, sample 106, MPI 5 biozone; x 60.
- Fig. 24 - *Globorotalia bononiensis*. Umbilical view. Level 46, sample 93, MPI 5 biozone; x 120.
- Fig. 26-28 - *Globorotalia inflata*. 26) Spiral view; 27) umbilical view; 28) side view. Level 103, sample 180, MPI 6 biozone; x 60.
- Fig. 29 - *Globigerinita glutinata*. Umbilical view. Level 46, sample 93, MPI 5 biozone; x 240.

