

12. INTEGRATED CALCAREOUS PLANKTON BIOSTRATIGRAPHY AND CYCLOSTRATIGRAPHY AT SITE 964¹

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ABSTRACT

Twenty-one calcareous plankton biostratigraphic events have been identified in Ocean Drilling Program Site 964, between the upper part of the Piacenzian and the Holocene and correlated to the relative abundance fluctuations of *Globigerinoides* spp. and the oxygen isotope stages. Our study essentially supports previous investigations on coeval Mediterranean sequences with one (minor) difference: the last occurrence of *Discoaster brouweri* is correlated with oxygen isotopic stage/relative abundance fluctuation 71 instead of 73. Correlation of the sequence of Site 964 with other Pliocene and Pleistocene sequences studied in the Mediterranean basin in the last years proves that the reported biostratigraphic events are essentially synchronous. Only minor discrepancies exist between the proposed ages in this paper and the ages reported by other authors. The chronostratigraphic subdivision of the studied interval is reported according to the accepted definition of the chronostratigraphic boundaries.

INTRODUCTION

The recently defined late Pliocene Gelasian stage (Rio et al., 1994) has its global boundary stratigraphic section and point (GSSP) in the Monte San Nicola section, outcropping in southern Sicily, near the Gela village (Fig. 1). Integrated calcareous plankton biostratigraphy, magnetostratigraphy, and relative abundance fluctuations of *Globigerinoides* spp. were published by Channell et al. (1992) and discussed by Sprovieri (1993). To correlate this land section to the deep-sea record, we studied the nearest Ocean Drilling Program (ODP) Leg 160 Site in the Eastern Mediterranean that encompasses the Gelasian, Site 964. At this site, oxygen and carbon isotopic records are also available (Howell et al., Chap. 13, this volume); the detailed correlation between the two sections provides a more complete stratigraphic record of the interval covered by the Gelasian stage.

Cyclostratigraphic interpretation of the studied interval was obtained by the relative abundance fluctuations of *Globigerinoides* spp. These fluctuations were compared and correlated with the oxygen isotopic stages.

MATERIAL

ODP Leg 160 Site 964 is located at the foot of the Calabrian Ridge in a water depth of 3650 m (36°15.62'N, 17°45.025'E; Fig. 1), about 350 km southeast of the Monte San Nicola section. Five holes were cored at this site. The studied sequence is represented by a composite of different segments of the five holes. The revised meter corrected depth scale (rmcd) was formulated postcruise by Sakamoto et al. (Chap. 4, this volume).

The lithologic sequence is represented essentially by a nannofossil ooze, but turbidites are present at some intervals. In particular, the thick turbiditic interval between 70.42 and 72.92 rmcd provides an

apparent increase in the thickness of an isotopic stage. Between 42.80 and 54.10 rmcd, repeated turbiditic intervals made it impossible to recover samples usable for a detailed analysis. Below 105.16 rmcd, several turbidites are also present. As a consequence, detailed biostratigraphy and cyclostratigraphy are hampered by the possibility of reworking. Therefore, this part of the borehole was discarded from our analysis. In the studied sequence, 59 sapropels were identified (Sakamoto et al., Chap. 4, this volume), 58 of which are included in the studied interval. Their stratigraphic position is reported in the lithology column of Figure 2. Sampling for the study was performed at an interval of 20 cm.

METHODOLOGY

Samples for foraminifer analysis were washed on a 63- μ m sieve. Only half of the residue of each sample was used for the study of the foraminifer assemblage. The other part of the residue was used for isotopic analysis. Generally, the same samples used to obtain the isotopic data were studied for the foraminifer analysis, but sporadic samples too small for this work were analyzed for isotopes only. Conversely, samples in which specimens of *Globigerina bulloides* were rare were studied only paleontologically.

Only the greater than 125- μ m residue was used, and all residue of the samples was analyzed to identify biostratigraphic markers. For quantitative analyses of the split residues, at least 300 planktonic foraminifer specimens were identified and counted, with reference to the taxonomic units reported in Table 1. The faunal curve used for cyclostratigraphic interpretation was obtained by plotting the sum of the percent values of all the *Globigerinoides* species present in each sample. Figures 2 through 6 display the relative abundance fluctuations of the most common taxonomic units. Benthic foraminifers were not studied, because they are rare or absent. Benthic foraminifers, including some shallow-water species, were common only in the turbiditic intervals.

Preparation of the smear slides for light microscope analysis of calcareous nannofossils followed standard techniques. The distribution pattern of selected calcareous nannofossil markers was determined by light microscope (transmitted light and crossed nicols) at about 1000 \times magnification. Only the first occurrence (FO) of *Emiliania huxleyi* was identified by scanning electron microscope analysis. The same unprocessed material used to prepare the smear slides was smeared on a stab. No removal of the biogenic material was performed to maintain the natural status of the nannofossil associations.

¹Robertson, A.H.F., Emeis, K.-C., Richter, C., and Camerlenghi, A. (Eds.), 1998. *Proc. ODP, Sci. Results*, 160; College Station, TX (Ocean Drilling Program).

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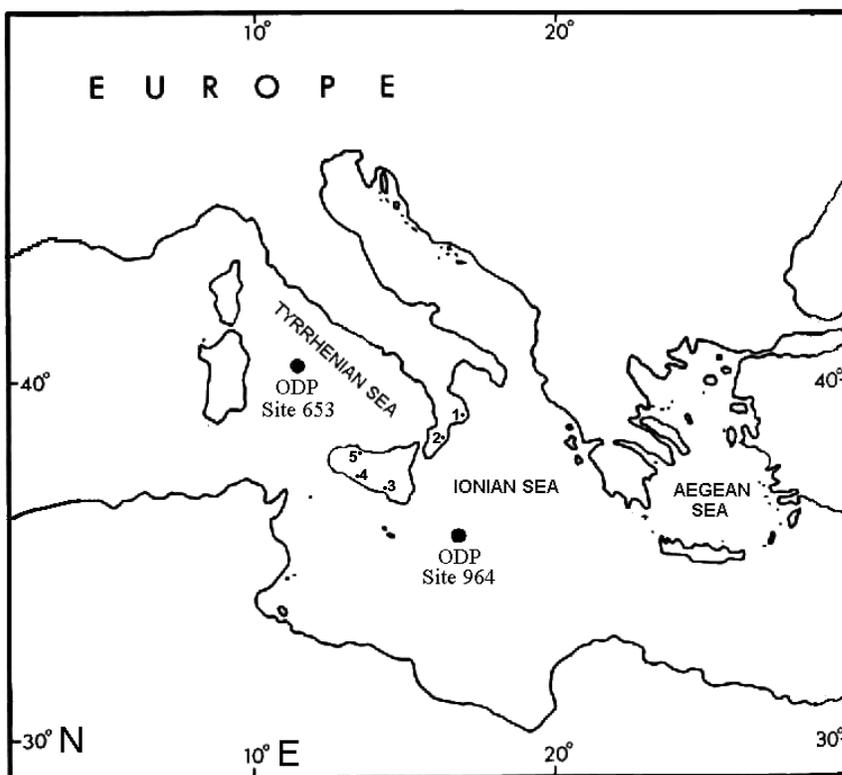


Figure 1. Index map. 1 = Ficarazzi; 2 = Capo Rossello; 3 = Monte San Nicola; 4 = Vrica; and 5 = Singa.

Abundance data were collected using the methodology described by Rio et al. (1990) to facilitate correlation to data collected from other Mediterranean sequences (e.g., ODP Site 653, Tyrrhenian Sea; land sections of southern Sicily, Monte San Nicola and Capo Rossello). The following counting methods were used:

- 1 = Index species vs. the total assemblages to detect the *E. huxleyi* FO and *Pseudoemiliana lacunosa* last occurrence (LO). Counts were restricted to the first 300 and to the first 500 nanofossils, respectively.
- 2 = Index species vs. a fixed number of taxonomically related forms. This was used to detect the abundance patterns of *Discoaster* markers (100 asteroliths), *Calcidiscus macintyreii* (100 *Calcidiscus*), *Helicosphaera sellii* (50 helicoliths), medium-sized *Gephyrocapsa* (300 placoliths >3 µm), Large *Gephyrocapsa* (100 *Gephyrocapsa* sp. >4 µm), and *Gephyrocapsa* sp. 3 (100 medium-sized *Gephyrocapsa*).
- 3 = Number of specimens of a taxon in a prefixed area of the slide (4.52 mm²). This was utilized to obtain the total accumulation of the genus *Discoaster* along the record.

Specimens of the planktonic foraminifer *Globigerina bulloides* were analyzed for δ¹⁸O. Samples from the >250-µm residue fraction were picked and treated sonically in methanol for ~2 min. Samples were analyzed at the University of South Carolina Stable Isotope Laboratory using a VG OPTIMA stable isotope ratio mass spectrometer equipped with an automated Isocarb preparation system. All stable isotope values are reported relative to the Peedee Belemnite standard in per million (‰) units using the δ notation.

BIOSTRATIGRAPHY

Planktonic Foraminifers

The Mediterranean zonation of Cita (1973, 1975), amended by Sprovieri (1992), was used. The planktonic foraminifer assemblage is rich and well diversified, with well-represented marker species. In

the Pleistocene segment, the FO of *Globorotalia truncatulinoides excelsa* could not be detected, as the integrated calcareous plankton biostratigraphy indicates its FO is well above the FO recognized in other Mediterranean sections. Therefore, the entire Quaternary stratigraphic interval was assigned to a nonsubdivided *Globigerina cariacoen-sis-Globorotalia truncatulinoides excelsa* Zone.

The basal interval of the studied section, up to 82.61 rmcd, falls within the MPI5a biozone, as indicated by the presence of *Globorotalia bononiensis* (Fig. 2). This species is never abundant and occurs discontinuously within the analyzed samples. It disappears in Sample 160-964C-8H-4, 10–12 cm (82.61 rmcd), where the MPI5a/MPI5b boundary was recognized. In the MPI5a biozone, specimens of *Globorotalia crassaformis* s.l. (*G. crassaformis*, *G. aemiliana*, *G. crotonensis*, *G. crassacrotonensis*, and *G. viola*) are present and are predominantly left coiling. Dominance of right-coiling *G. crassaformis* s.l. specimens was found at 102.24, 102.09, 100.86, 98.82, and 97.44 rmcd (Fig. 4). The repeated, high-frequency coiling shifts of this species in the lower part of the MPI5a biozone are a useful, second-order biostratigraphic tool for enhancing the biostratigraphic resolution in this part of the upper Piacenzian stratigraphic sequence. In the lower part of this biozone, the Pliocene FO of essentially left-coiling specimens of *Neogloboquadrina atlantica* occurs (Sample 160-964E-6H-2, 89–91 cm, 98.82 rmcd). In this sample the species is abundant, with well-developed, encrusted specimens. As in other Mediterranean sections, *Globigerinoides quadrilobatus* and *Globigerinoides obliquus* s.l. are more continuously present in the lower part of this biozone (Fig. 3; see also Sprovieri, 1992).

The segment between 82.61 and 66.86 rmcd represents the MPI5b biozone, defined at the top by the FO of *Globorotalia inflata*. This biostratigraphic interval is characterized by the absence of the *G. inflata* group taxa. The uppermost level with common specimens of *N. atlantica* (Sample 160-964E-4H-3, 100–102 cm, 76.52 rmcd) is recorded in the lower part of this biozone.

The MPI6 biozone, defined at the top by the first common occurrence (FCO) of *Neogloboquadrina pachyderma* left coiling, covers the stratigraphic interval between 66.86 and 58.12 rmcd. Left-coiling specimens of *N. pachyderma* are rare throughout the Pliocene–Pleis-

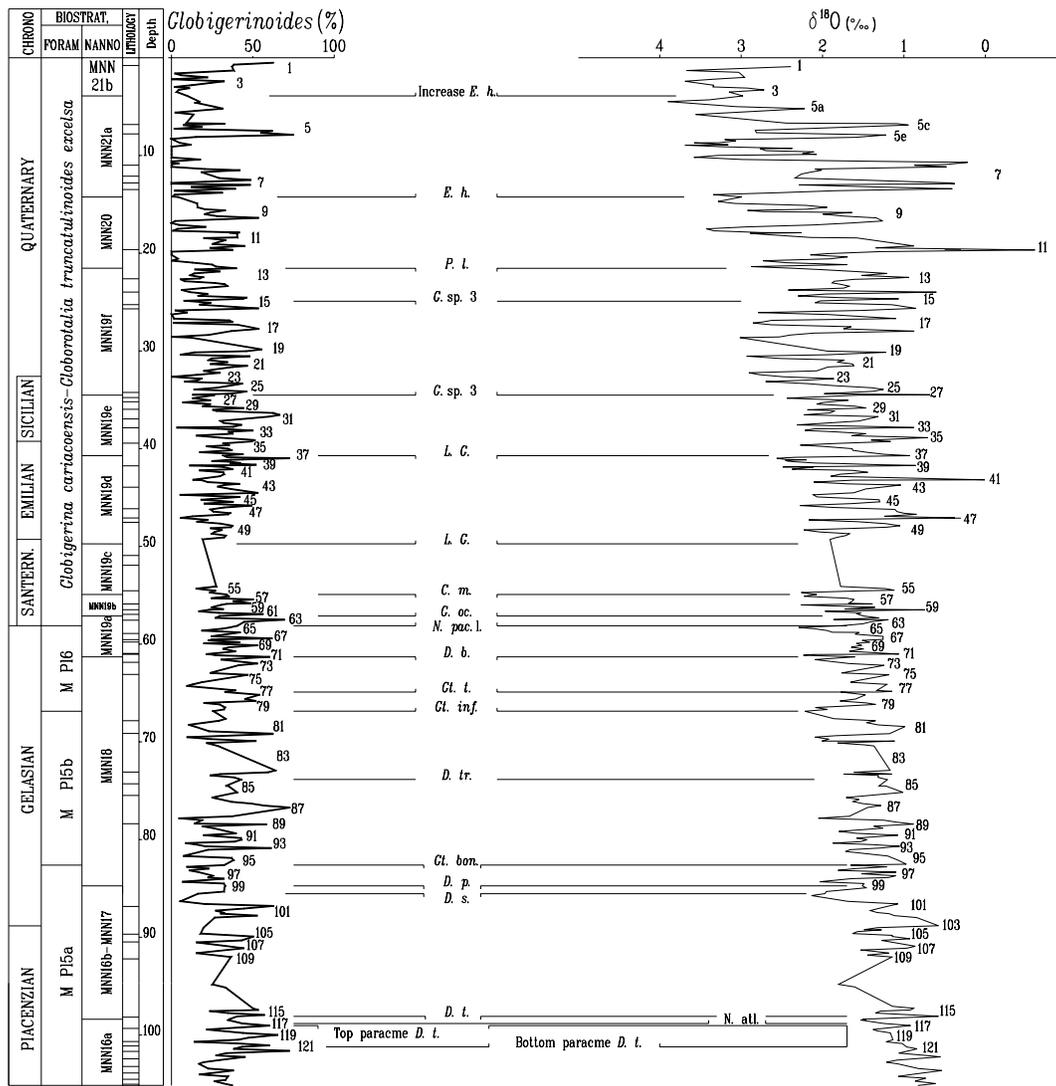


Figure 2. Calcareous plankton biostratigraphy, relative abundance fluctuations of *Globigerinoides* spp., and oxygen isotope stages in the studied sequence at Site 964. “Warm” fluctuations are labeled with odd numbers. *E. h.* = *Emiliania huxleyi*; *P. l.* = *Pseudoemiliania lacunosa*; *G. sp. 3* = *Gephyrocapsa* sp. 3; *L. G.* = Large *Gephyrocapsa*; *C. m.* = *Calcidiscus macintyreii*; *G. oc.* = medium-sized *Gephyrocapsa*; *N. pac. l.* = *Neogloboquadrina pachyderma* left coiling; *D. b.* = *Discoaster brouweri*; *Gt. t.* = *Globorotalia truncatulinoides*; *Gt. inf.* = *Globorotalia inflata*; *D. tr.* = *Discoaster triradiatus*; *Gt. bon.* = *Globorotalia bononiensis*; *D. p.* = *Discoaster pentaradiatus*; *D. s.* = *Discoaster surculus*; *D. t.* = *Discoaster tamalis*; *N. atl.* = *Neogloboquadrina atlantica*. Stratigraphic position of the sapropels is indicated by horizontal lines in the lithology column, on the left.

tocene stratigraphic sequence at Site 964 (Fig. 5). We identified the base of the *Globigerina cariacensis* Zone, defined by the FCO of *N. pachyderma* left coiling, in recognition of the level in which the first relative increase in abundance of the marker occurs, compared with the values recorded in the underlying strata. This is also the oldest level in which left-coiling *N. pachyderma* represents about 50% of the total *N. pachyderma* population.

The planktonic foraminifer biostratigraphic resolution is poor in the Mediterranean Pleistocene (Sprovieri, 1992). For this microfossil group, the distinctive faunal trend at Site 964 (as in other coeval sequences), is the general upsection increase of the “cold” species (*N. pachyderma*, *Turborotalia quinqueloba*, and *Globorotalia scitula*; Figs. 5, 6).

Calcareous Nannofossils

The zonal scheme of Rio et al. (1990), extensively used in the Pliocene–Pleistocene Mediterranean record (Channell et al., 1992; Di

Stefano et al., 1993; Castradori, 1993) and during the Leg 160 cruise, was adopted here. The only change is the recognition of the upper boundary of Biozone MNN16a according to the definition of Sprovieri et al. (1994) and Di Stefano (Chap. 8, this volume). The calcareous nannofossil biostratigraphy of the Site 964 sequence is shown in Figure 7.

Calcareous nannofossils are abundant to common in the smear slides. Preservation is generally good, but overgrowths and broken specimens consistently occur in samples where silt and volcanic ash are present. These intervals, interpreted as turbidites, also include reworked nannofossils from the Cretaceous and younger sediments.

The basal interval of the studied sequence, up to 98.38 rmc, includes nannofossils indicative of the uppermost part of MNN16a biozone. Assemblages are characterized by the occurrence of *Discoaster tamalis* and *Discoaster pentaradiatus*, whereas *R. pseudumbilicus* and *Sphenolithus* spp. are absent. According to the original definition of Rio et al. (1990), the upper boundary of this biozone coincides with the LO of *D. tamalis*. Low abundances of *D. tamalis* above

Table 1. Planktonic foraminifer taxonomic units used for quantitative analyses.

<i>Globigerina bulloides</i>
<i>Globigerinoides obliquus</i> s.l.
<i>Globigerinoides quadrilobatus</i> s.l.
<i>Globigerinoides ruber</i>
<i>Globorotalia bononiensis</i>
<i>Globorotalia crassaformis</i> sx
<i>Globorotalia crassaformis</i> dx
<i>Globorotalia inflata</i>
<i>Globorotalia planispira</i>
<i>Globorotalia scitula</i> sx
<i>Globorotalia scitula</i> dx
<i>Globorotalia truncatulinoides</i>
<i>Neogloboquadrina atlantica</i>
<i>Neogloboquadrina dutertrei</i>
<i>Neogloboquadrina pachyderma</i> sx
<i>Neogloboquadrina pachyderma</i> dx
<i>Orbulina</i> spp.
<i>Sphaeroidinella dehiscens</i>
<i>Turborotalita quinqueloba</i>
<i>Hastigerina siphonifera</i>

98.38 rmcd may be caused by reworking. Following Sprovieri et al. (1994), we recognize this boundary in coincidence of the last strong decrease in abundance (LCO) of *D. tamalis*, after the paracme interval that occurs in the highest part of its range (Fig. 7).

Between 98.38 and 85.54 rmcd, *D. pentaradiatus* and *D. surculus* co-occur up until the level in which discoasters abruptly decrease in abundance. In the two overlying samples, in which few discoasters occur, *D. pentaradiatus* is still present with relative high abundance values. In the two samples above this level, discoasters are rare and poorly preserved. Rare specimens of *D. pentaradiatus* and *D. surculus* are considered reworked because they co-occur with specimens of *D. tamalis* and *Discoaster* spp. that are surely reworked. Following Rio et al. (1990), we recognize the MNN16a-17/MNN18 boundary at 84.74 rmcd.

The MNN18 zone, defined at the top by the LO of *Discoaster brouweri* and *Discoaster triradiatus*, covers the interval between 84.74 and 61.30 rmcd. Along this biostratigraphic interval, these two taxa are the only indigenous discoasters. They are discontinuously present, with fluctuating relative abundance values. At 73.86 rmcd, the first abundance peak of *D. triradiatus* occurs. Above this level, high (40%) relative abundance values of *D. triradiatus* vs. *D. brouweri* is discontinuously present up to 61.30 rmcd, the level at which *D. triradiatus* and *D. brouweri* disappear (Fig. 7). In the interval between 61.30 and 59 rmcd, badly preserved assemblages with reworked mid-Pliocene *Discoasters* occur. In the sample at 60.32 rmcd, two broken and one broken specimen of *D. brouweri* and *D. triradiatus*, respectively, are present but are considered reworked.

At 57.12 rmcd, medium-sized *Gephyrocapsa* first occur, and the base of the MNN19b Zone was identified. They co-occur with *Calcidiscus macintyreii* up to 54.92 rmcd, where the LO of *C. macintyreii* is recognized, because its abundance values decrease below the threshold of 1% (Rio et al., 1990). Poorly preserved specimens of *C. macintyreii* are present with low abundance values in the two overlying samples, but they are considered reworked, because in this same samples nannofossil assemblages are badly preserved, in coincidence of turbiditic sediments.

Just above this turbiditic interval, at 49.72 rmcd, the first specimens of large *Gephyrocapsa* appear. Therefore, the MNN19c/MNN19d boundary was recognized. They progressively increase in abundance up to 40.71 rmcd, where the LO of large *Gephyrocapsa* was detected (Fig. 7). The upper boundary of MNN19d was identified by this bioevent. The LO of *Helicosphaera sellii*, the alternative event for the definition of this boundary (Rio et al., 1990), occurs in the same sample.

The interval between 40.71 and 34.52 rmcd is ascribed to the MNN19e zone, defined at the top by the FO of *Gephyrocapsa* sp. 3

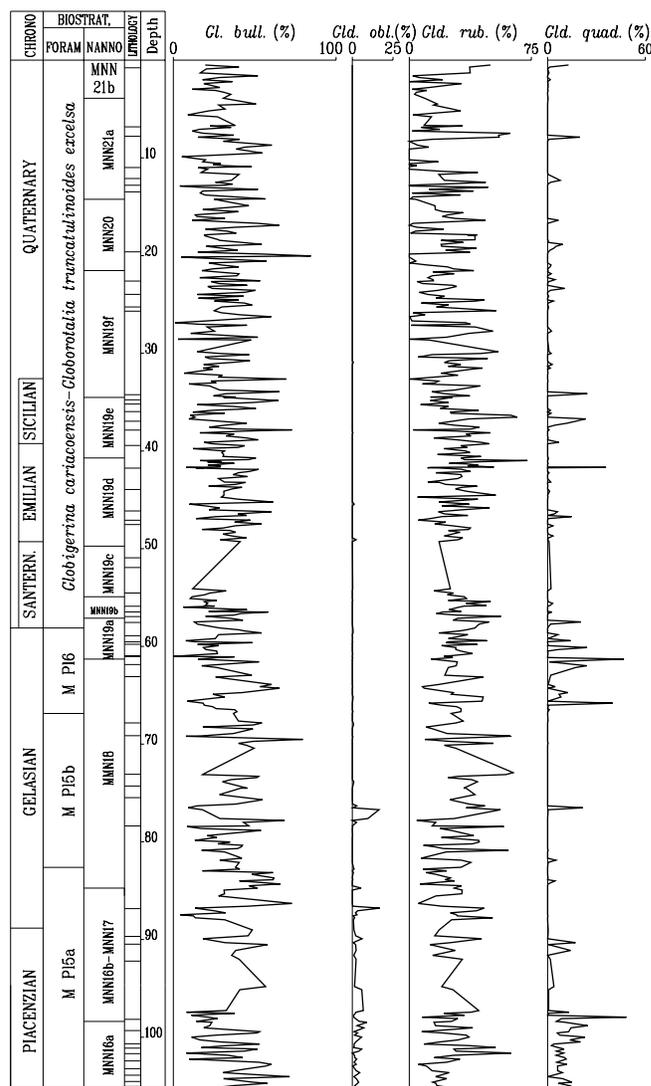


Figure 3. Relative abundance of planktonic foraminifer taxonomic units. *Gl. bull.* = *Globigerina bulloides*; *Gld. obl.* = *Globigerinoides obliquus*; *Gld. rub.* = *Globigerinoides ruber*; *Gld. quad.* = *Globigerinoides quadrilobatus*.

and by the reappearance of the other medium-sized *Gephyrocapsa*. Within this interval, some broken and overgrown specimens of medium-sized and large *Gephyrocapsa* have been found with taxa reworked from older sediments.

The MNN19f zone, defined at its top by the LO of *Pseudoemiliana lacunosa*, covers the stratigraphic interval between 34.52 and 21.54 rmcd. Within this biozone, *Gephyrocapsa* sp. 3 is present, up to 24.86 rmcd, with large abundance fluctuations separated by short intervals in which it is absent.

The stratigraphic interval between 21.54 and 14.24 rmcd is the MNN20 biozone, defined at its top by the FO of *Emiliana huxleyi*. This is the only bioevent that we identified, following Thierstein et al. (1977), by scanning electron microscope.

Above this level, *E. huxleyi* has low abundance values and is discontinuously present up to 3.9 rmcd, where it sharply increases in abundance, with percent values greater than 40%. Consequently, the interval between 14.24 and 3.9 rmcd belongs to Biozone MNN21a, and the following interval up to the top of the sequence is referred to the *Emiliana huxleyi* Acme Zone, MNN21b.

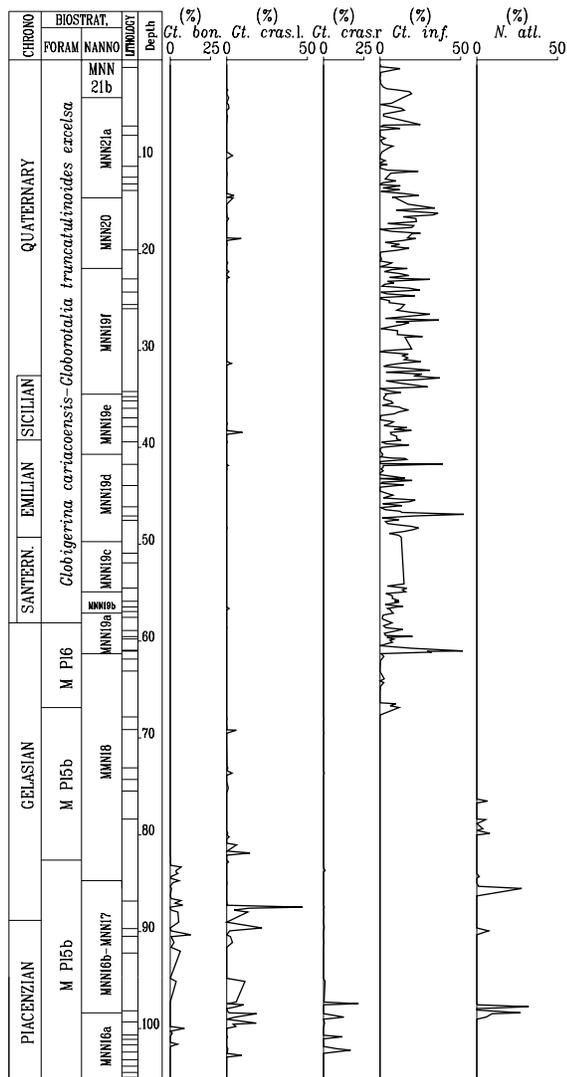


Figure 4. Relative abundance of planktonic foraminifer taxonomic units. *Gt. bon.* = *Globorotalia bononiensis*; *Gt. cras. l.* = *Globorotalia crassaformis* left coiling; *Gt. cras. r.* = *Globorotalia crassaformis* right coiling; *Gt. inf.* = *Globorotalia inflata*; *N. atl.* = *Neogloboquadrina atlantica*.

ISOTOPIC STRATIGRAPHY

The $\delta^{18}\text{O}$ of *Globigerina bulloides* is characterized by low-amplitude fluctuations in the lower portion of the record, moving towards more enriched values of $\delta^{18}\text{O}$ and higher amplitude shifts with decreasing age. Significant enrichments occur after 3.2 Ma, before 2.53 Ma, after 0.99 Ma and after 0.46 Ma and have previously been attributed to decreasing surface-water temperatures and increases in global ice volume (Thunell and Williams, 1983; Thunell et al., 1990). Increases in the amplitude of the $\delta^{18}\text{O}$ signal are observed after 2.82, 1.51, 0.99, and 0.46 Ma. The highest amplitude shifts are generally associated with sapropel events, with the largest shifts occurring after 0.46 Ma. Many workers have attributed these shifts to the reduction in surface-water salinity during the formation of sapropels in the Mediterranean (e.g. Williams et al., 1978; Rossignol-Strick et al., 1982; Vergnaud-Grazzini et al., 1986; Howell et al., 1990; Thunell et al., 1990), which may have triggered bottom-water anoxia through inhibiting the formation of the Mediterranean Deep Water. It should

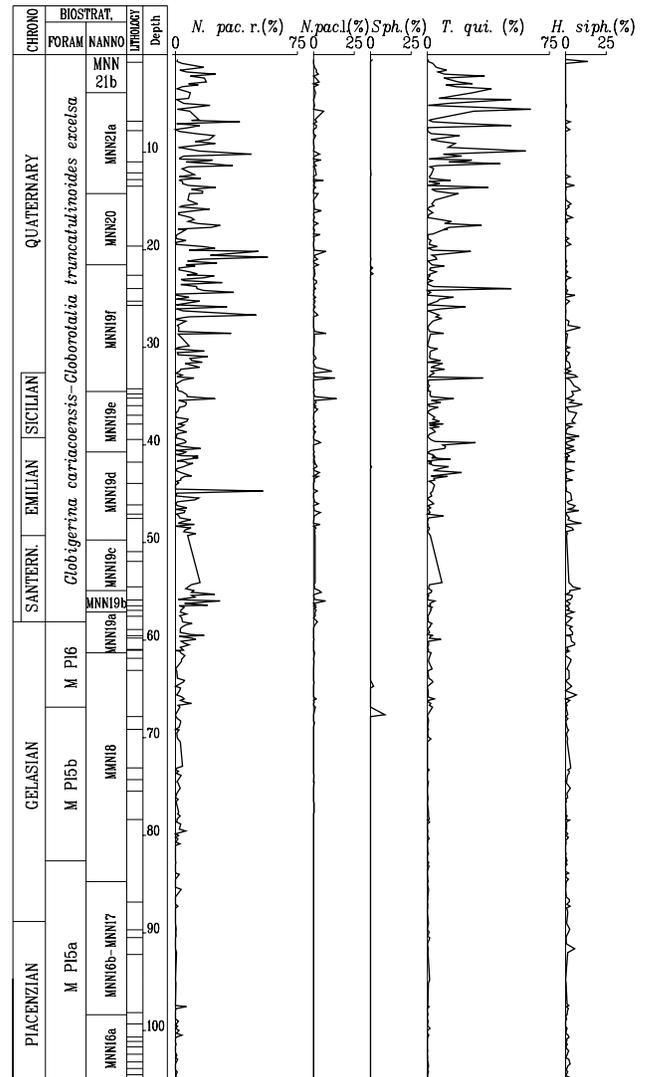


Figure 5. Relative abundance of planktonic foraminifer taxonomic units. *N. pac. r.* = *Neogloboquadrina pachyderma* right coiling; *N. pac. l.* = *Neogloboquadrina pachyderma* left coiling; *Sph.* = *Sphaeroidinella dehiscentis*; *T. qui.* = *Turborotalita quinqueloba*; *H. siph.* = *Hastigerina siphonifera*.

be noted that Jenkins (1980) and Thunell et al. (1987) attribute these amplitude shifts to anomalously high Mediterranean surface-water salinities during glacial periods, as opposed to the formation of very low or "brackish" surface waters during the transition to interglacial conditions. A more detailed discussion and interpretation of all the isotopic results is provided in Howell et al. (Chap. 12, this volume).

CYCLOSTRATIGRAPHY

Apart from the 59 sapropel levels identified, 58 of which were included in the studied interval, no clear evidence of lithologic cyclicity was identified in the composite sequence. However, the relative abundance of the *Globigerinoides* spp. population regularly fluctuates, and these abundance fluctuations are forced by precession astronomical cycles in the Zanclean and main part of the Piacenzian and by obliquity astronomical cycles during the uppermost part of the Piacenzian, Gelasian, and lower Pleistocene (Sprovieri, 1992, 1993).

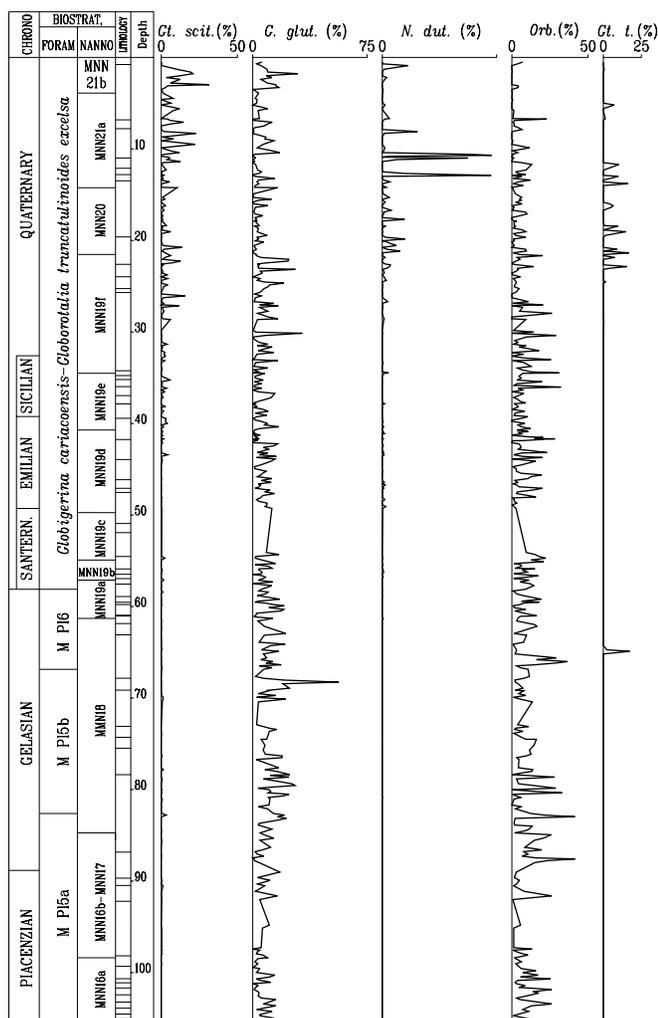


Figure 6. Relative abundance of planktonic foraminifer taxonomic units. *Gt. scit.* = *Globorotalia scitula*; *G. glut.* = *Globigerinita glutinata*; *N. dut.* = *Neogloboquadrina dutertrei*; *Orb.* = *Orbulina* spp.; *Gt. t.* = *Globorotalia truncatulinoides*.

Sprovieri (1993) numbered the relative abundance fluctuations correlated to the obliquity cycles, from younger to older stratigraphic levels, from fluctuation 22 (correlated to oxygen isotopic Stage 22) to fluctuation 64 at the Pliocene/Pleistocene boundary (approximated by the base of the *G. cariacensis* Zone) to fluctuation 121 in the lower part of Biozone MPI5a. Even numbers were used to label decreased abundances, and odd numbers were used to label increased abundances. The most important calcareous plankton biostratigraphic events were correlated to the *Globigerinoides* spp. relative abundance fluctuations. Based on this correlation, the age of the relative abundance fluctuation/isotopic stage was proposed for every bioevent (Sprovieri, 1993).

Relative abundance of *Globigerinoides* spp. for Site 964 are reported in Figure 2, in which the abundance fluctuations are numbered and compared with the oxygen isotopic stages reported for Site 964 by Howell et al. (Chap. 13, this volume). The stratigraphic level (rmcd) of the abundance fluctuation and oxygen isotopic stages up to the base of the mid-Pleistocene are listed in Table 2. A good cycle-by-cycle correlation exists between the two curves, with high relative abundance of *Globigerinoides* spp. occurring with the lighter oxygen isotopic values. Each abundance fluctuation was identified utilizing the well-established correlation of key biostratigraphic

events with these *Globigerinoides* spp. relative abundance fluctuations (Sprovieri, 1993) and isotopic stages. The following correlations with the oxygen isotope stages are generally accepted: the LO of *Pseudoemiliania lacunosa* with isotopic Stage 12 (Thierstein et al., 1977; Vergnaud-Grazzini et al., 1990), the top of the large *Gephyrocapsa* Zone (Biozone MNN19d) with isotopic Stage 37 (Raffi et al., 1993), the FCO of *N. pachyderma* left coiling with isotopic Stage 64 (Raymo et al., 1989; Lourens et al., 1992), the LO of *Discoaster brouweri* with isotopic Stage 71 (Raffi et al., 1993), the LO of *Gt. bononiensis* with isotopic Stage 96 (Lourens et al., 1992), and the sharp decrease of *Discoaster* population with isotopic Stage 100 (Rio et al., 1990; Thiedemann et al., 1994). In Figure 2, the first- and second-order calcareous plankton biostratigraphic events are reported for Site 964. Apart from the LO of *D. brouweri*, previously correlated by Sprovieri (1993) to abundance fluctuation 73 and now recognized in cycle 71, the correlations between the biostratigraphic event and the relative abundance fluctuation are consistent with those proposed by Sprovieri (1993). With reference to the estimates by Shackleton et al. (1990) for selected oxygen isotopic stages and magnetic reversal boundaries, Table 3 provides the age of each biostratigraphic event within the approximated time interval of the correlative obliquity astronomical cycle. The ages proposed by Sprovieri (1993) and Lourens et al. (1996) are included for comparison in Table 3. The smaller differences between the ages proposed by Lourens et al. (1996) and this paper may be a consequence of the different references used for age evaluation (precession and obliquity astronomical cycles, respectively). The more consistent differences greater than ~40 k.y. are possibly due to different interpretations of the oxygen isotopic stratigraphy (*Gt. inflata* FO, *Gt. truncatulinoides* FO, *Gephyrocapsa* >4 μm FO, *Gephyrocapsa* >5.5 μm FO, and *Gephyrocapsa* sp. 3 FO) or to a different taxonomic concept of some species (according to our taxonomic concept of the species, the *N. atlantica* FO is recorded in the Mediterranean sections below, not above the *D. tamalis* LCO).

A cyclostratigraphic interpretation of the Pliocene–lower Pleistocene stratigraphic interval was previously made for several Sicilian outcrops and for ODP Leg 107, Site 653 (Sprovieri, 1993). Results are reported in Figure 8, in which relative abundance fluctuations in the planktonic foraminifer assemblages of these sections are compared with the cyclostratigraphic results at Site 964.

The ages of the mid- and upper Pleistocene calcareous nannofossil bioevents were not calibrated by Sprovieri (1993). At Site 964, the LO of *Gephyrocapsa* sp. 3 is for the first time correlated to the oxygen isotopic Stage 15; the LO of *P. lacunosa* is correlated with isotopic Stage 12; the FO of *E. huxleyi* with isotopic Stage 8; and the initial increase of *E. huxleyi* with the transition between isotopic Stages 3 and 4 (Fig. 2). These results are comparable with those reported by Rio et al. (1990) in the Tyrrhenian basin and by Sanvoisin et al. (1993) for the 37.04 m long piston core KC01B, raised from the Calabrian Ridge near the location of Site 964. Quantitative investigations on planktonic foraminifers, calcareous nannofossils, calcium carbonate, and grain-size distribution were carried out on 337 samples taken along this core, in which magnetostratigraphy was also obtained down to the base of the Jaramillo subchron.

The only Pliocene–lower Pleistocene land section from which oxygen isotope stratigraphy (based on the planktonic foraminifer *Globigerinoides ruber*) biostratigraphy, and magnetostratigraphy were published in the Mediterranean basin is the Singa section (Lourens et al., 1992, 1996). In Figure 9, results from the Singa section and Site 964, and their proposed correlation, are plotted. Numbers in roman style indicate our interpretation, whereas numbers in italics and in parentheses indicate the original interpretation of Lourens et al. (1992). According to our interpretation, the two peaks of heavier isotopic values at about 105.45 and 102.95 m above the base of the section, assigned by Lourens et al. (1992) to one isotopic stage (74), are assigned to two different stages (74 and 76; Sprovieri, 1993). Conversely, the interval between 45 and 50 m, assigned by Lourens et al.

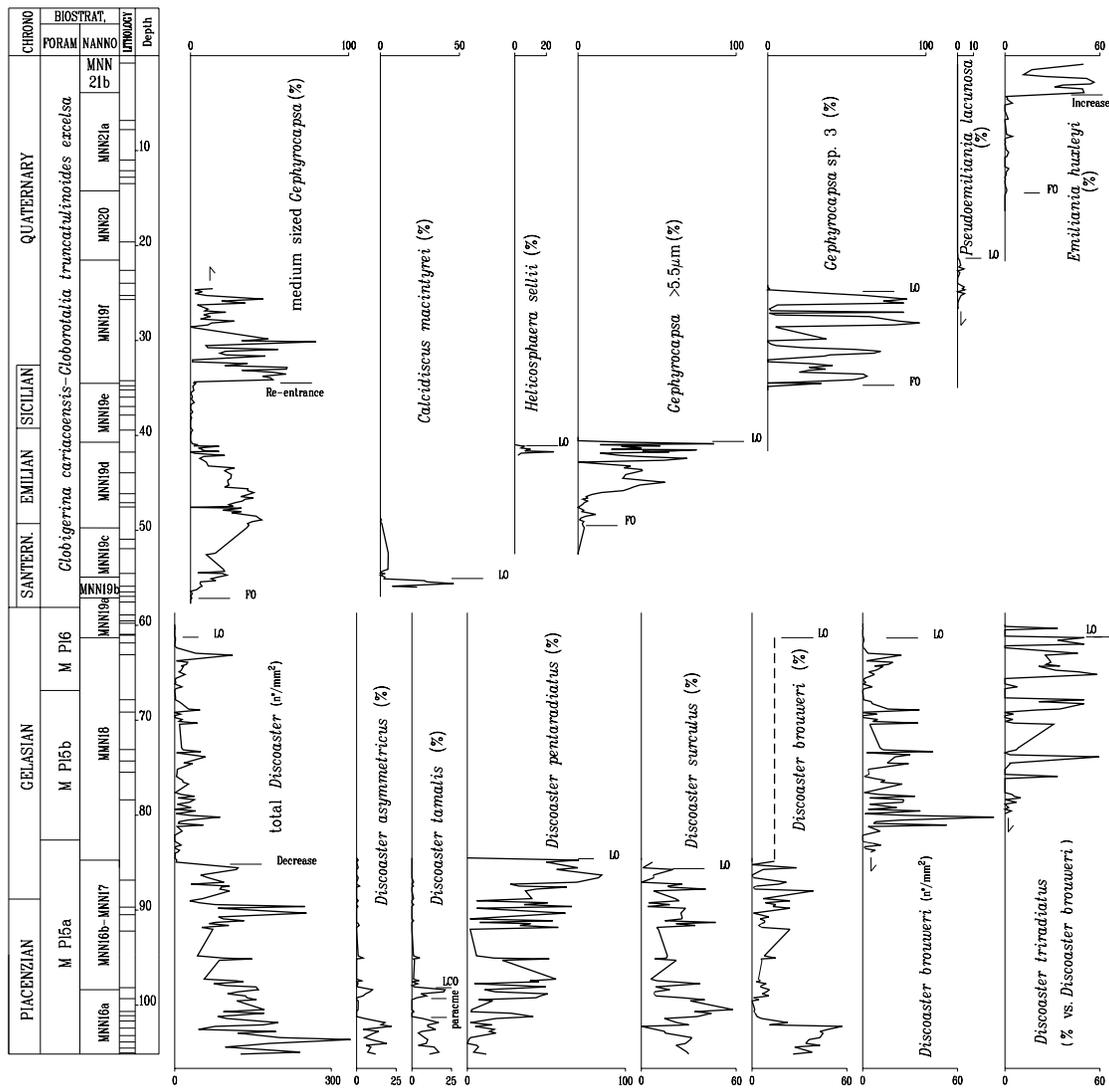


Figure 7. Relative abundance of calcareous nannofossil taxonomic units. Quantitative data for *D. brouweri* are given as percent values in the interval below the total *Discoaster* decrease (dashed line) and in number/mm² in the interval above the total *Discoaster* decrease.

(1992) to isotopic Stage 94, where no clear evidence of a shift to heavier values is present, is assigned entirely to isotopic Stage 95. In the lower Pleistocene interval, the isotopic stages were labeled only tentatively by Lourens et al. (1992). Our interpretation at Site 964 permits identification of these isotopic fluctuations, designating isotopic Stage 45 at the top of the sequence. This proposed correlation implies changes in the thickness of sediments in coincidence with some isotopic stages in the Singa section. The Singa section is an upper slope, terrigenous sequence where changes in the sediment accumulation rate can frequently occur. Anomalous, more or less long intervals with increased sediment accumulation rates are also present, and some coincide with relative abundance fluctuations of *Globigerinoides* spp., in the Monte San Nicola and Capo Rossello sections (Fig. 8).

CHRONOSTRATIGRAPHY

With reference to the recently accepted definition of the GSSP of the new Gelasian stage, which covers the upper part of the Pliocene (Rio et al., 1994), to the GSSP of the Neogene/Quaternary boundary

at Vrica (Aguirre and Pasini, 1985), and to the proposed definition of the base of the Piacenzian (Cita et al., in press) and of the base of the Emilian substage (Pasini and Colalongo, 1994), we propose in this chapter the chronostratigraphic subdivision of the stratigraphic interval studied at Site 964.

The GSSP of the Piacenzian is defined using the small-scale lithologic cycle 77 of Hilgen (1991), identified at the base of the Punta Piccola section in southern Sicily. At the top of this lithologic cycle, the magnetostratigraphic boundary between the Gilbert and Gauss Chrons was identified. At the base of lithologic cycle 79, the LO of *G. punctulata* occurs (Hilgen, 1991). The GSSP of the base of the Gelasian stage is defined in the Monte San Nicola section, near Gela (southern Sicily; Rio et al., 1994), in coincidence with a reddish laminated level correlated with oxygen isotopic Stage 103 and Mediterranean Precession Related Sapropel (MPRS) 250, and practically coincident with the Gauss/Matuyama boundary.

Several sapropels have been identified in the Pliocene–Pleistocene sequence at Site 964 (Sakamoto et al., Chap. 4, this volume). Most of them are also present in the Sicilian and Calabrian land sections, but a few of them are not present. Conversely, a small number of sapropels reported from these land sections are not present, or not

Table 2. Depth of the relative abundance positive fluctuations of *Globigerinoides* spp. and the oxygen isotopic stages.

<i>Globigerinoides</i> spp. abundance fluctuations	Depth (rmcd)	Isotopic stage	Depth (rmcd)
19	30.02-29.84	19	30.14
21	31.52	21	31.52
23	32.84	23	32.84
25	33.34-34.14	25	33.94
27	34.52-35.04	27	34.52-35.04
29	35.84	29	35.84
31	36.34-36.72	31	36.72
33	38.14	33	37.84
35	39.12	35	38.86
37	40.56-40.98	37	40.71
39	41.46-41.64	39	41.68-41.72
41	42.10-42.82	41	43.18
43	43.60-44.52	43	43.72
45	45.46-45.82	45	45.44
47	46.72	47	47.08
49	47.88	49	47.88
GAP			
55	54.54	55	54.48
57	55.42-55.82	57	55.88
59	56.42	59	56.58
61	56.92-57.12	61	57.32
63	57.50-57.72	63	57.50
65	58.80	65	58.80
67	59.42	67	59.52
69	59.80-60.32	69	60.48
71	61.30	71	61.02-61.30
73	61.98-62.16	73	62.16
75	63.14	75	63.14
77	65.18	77	65.18
79	65.81-66.68	79	66.17
81	67.84-69.20	81	68.44
83	69.92-73.12	83	69.92-72.92
85	73.86-75.17	85	75.17-73.86
87	76.52-76.72	87	76.52
89	78.41	89	78.41
91	79.85	91	79.55
93	80.87	93	80.69
95	82.11-82.61	95	82.52
97	83.70-84.00	97	83.33-83.70
99	84.50-84.94	99	84.50-84.94
101	86.79-87.78	101	87.88
103		103	88.82
105	89.92-90.32	105	90.15
107	91.12	107	90.92-91.12
109	92.02	109	91.62-92.02
GAP			
115	97.95-98.09	115	98.09
117	99.04	117	99.04
119	100	119	100.48
121	100.86-101.42	121	100.86-101.42

preserved, in the sequence at Site 964. Among these, MPRS 250, correlated with oxygen isotopic Stage 103, is not present (Fig. 2). Magnetostratigraphy is also not available at Site 964. Therefore, the base of the Gelasian was recognized in this deep-sea sequence by the identification of oxygen isotopic Stage 103 at 88.82 rmcd (Table 2; Fig. 2). No biostratigraphic event occurs in coincidence with the base of the Gelasian. It can be identified with approximation by the LO of the calcareous nannofossils *D. pentaradiatus* and *D. surculus*, which occur in coincidence with oxygen isotopic stages 99 and 100, respectively, ~80 k.y. above the base of the Gelasian. It can also be identified by the LO of *G. bononiensis* (*G. puncticulata* of some authors), which occurs in oxygen isotopic Stage 96, ~140 k.y. above the base of this chronostratigraphic unit. The segment at Site 964 between 105.16 and 88.82 rmcd is ascribed to the Piacenzian (upper part).

The top of the Gelasian is defined by the base of the Pleistocene coincident with oxygen isotopic Stage 65. The base of the Pleistocene is generally recognized by the FCO of *N. pachyderma* left coiling, which occurs in oxygen isotope Stage 64 (Sprovieri, 1993; Lourens et al., 1992; Fig. 2), some 20 k.y. above the GSSP of the base of the Pleistocene. On the basis of the calcareous nannofossil assemblage, this chronostratigraphic boundary is approximated by the FO of medium-sized *Gephyrocapsa*. Therefore, the interval between 88.82 and 58.12 rmcd at Site 964 is ascribed to the Gelasian.

Three substages, the Santerian, Emilian, and Sicilian, are generally used for the early Pleistocene by some stratigraphers in the Mediterranean basin. The Santerian was originally proposed by Ruggieri and Sprovieri (1977), the Emilian was redefined by Ruggieri et al. (1975), and the Sicilian was redefined by Ruggieri and Sprovieri (1975). Ruggieri et al. (1984) revised the chronostratigraphic classification of the lower Pleistocene, essentially with reference to the nannofossil biostratigraphy. On the basis of these papers, more recently Pasini and Colalongo (1994) proposed the GSSP of the base of the Emilian in coincidence with the lithologic level at which, in the Vrica section, *Hyalinea baltica* first appears (just below Sapropel p, in terms of Selli et al. [1977] nomenclature), practically coincident with the base of the large *Gephyrocapsa* (MNN19d) biozone (Pasini and Colalongo, 1982; Glaçon et al., 1990; Di Stefano et al., 1993). The base of the Sicilian is still waiting for a formal proposal of definition, and therefore this chronostratigraphic boundary is still recognized by the FO of *Globorotalia truncatulinoides excelsa*, as reported by Ruggieri et al. (1984). In some Sicilian sections and at ODP Leg 107, Site 653, the FO of *G. truncatulinoides excelsa* occurs in coin-

Table 3. Depth and proposed age of the identified bioevents.

Bioevent	Depth	Isotopic stage	Age (Ma)	Source	Lourens et al. (1996) (Ma)	This paper (Ma)
Increase <i>E. huxleyi</i> (N)	3.9	3-4		Sanvoisin et al. (1993)		0.057
FO <i>E. huxleyi</i> (N)	14.24	8	0.26	Rio et al. (1990)		0.26
LO <i>P. lacunosa</i> (N)	21.54	12	0.46	Rio et al. (1990)		0.46
LO <i>Gephyrocapsa</i> sp. 3 (N)	24.86	15	0.584	Castradori (1993)		0.58
FO <i>Gephyrocapsa</i> sp. 3 (N)	34.52	27	0.99	Sprovieri (1993)		0.99
LO <i>Gephyrocapsa</i> spp. >5.5 µm (N)	40.71	37	1.25	Sprovieri (1993)	1.24	1.25
LO <i>H. sellii</i> (N)	41.14	37	1.25		1.25	1.25
FO <i>Gephyrocapsa</i> spp. >5.5 µm(N)	49.72	49 (51?)	1.50	Sprovieri (1993)	1.61	1.50 (1.54?)
LO <i>C. macintyreii</i> (N)	54.92	56	1.62	Sprovieri (1993)	1.67	1.63
FO medium-size <i>Gephyrocapsa</i> (N)	57.12	61	1.75	Sprovieri (1993)	1.71	1.73
FCO <i>N. pachyderma</i> left (F)	58.12	64	1.81	Sprovieri (1993)	1.80	1.79
LO <i>D. brouweri</i> (N)	61.3	71	1.99	Sprovieri (1993)	1.95	1.95
LO <i>D. triradiatus</i> (N)	61.3	71	1.95		1.95	1.95
FO <i>Gt. truncatulinoides</i> (F)	64.9	77	2.07	Sprovieri (1993)	2.00	2.07
FO <i>Gt. inflata</i> (F)	66.86	80	2.13	Sprovieri (1993)	2.09	2.13
First abundance peak <i>D. triradiatus</i> (N)	73.86	85				2.22
LO <i>Gt. bononiensis</i> (F)	82.61	96	2.45	Sprovieri (1993)	2.41	2.45
LO <i>D. pentaradiatus</i> (N)	84.74	99	2.51	Sprovieri (1993)	2.51	2.51
<i>Discoaster</i> decrease (N)	85.54	100	2.53			2.53
LO <i>D. surculus</i> (N)	85.54	100	2.55		2.53	2.53
LCO <i>D. tamalis</i> (N)	98.38	115	2.82	Sprovieri (1993)	2.83	2.82
FO <i>N. atlantica</i> (F)	98.82	116	2.83	Sprovieri (1993)	2.72	2.83

Note: (F) = planktonic foraminifer; (N) = calcareous nannofossil.

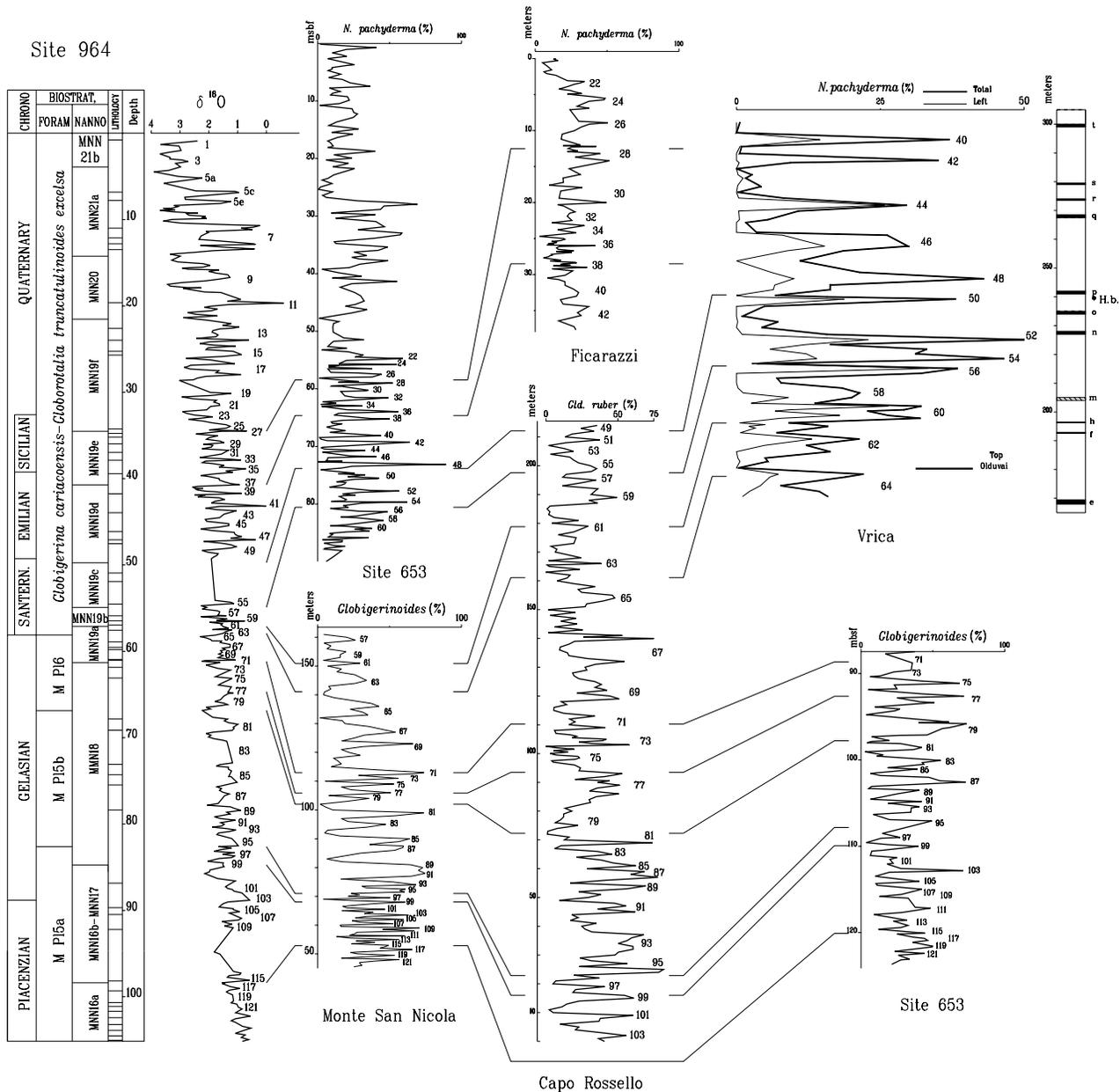


Figure 8. Correlation of the sequence at Site 964 to different Mediterranean sequences (amended from Sprovieri [1993]). *H. b.* = *Hyalinea baltica*.

cidence with oxygen isotopic Stage 35 (Sprovieri, 1993; Vergnaud-Grazzini et al., 1994). Because this taxon is usually rare or missing at this stratigraphic level (as at Site 964), this chronostratigraphic boundary may be well approximated by the base of the small *Gephyrocapsa* (MNN19e) biozone (Sprovieri, 1993), which occurs in oxygen isotopic Stage 37. Finally, the top of the Sicilian, coincident with the biocalcarentic level that is rich in *Arctica islandica* and outcrops at Ficarazzi (type locality of the Sicilian), near Palermo (Sicily), is correlated with oxygen isotopic Stage 22 (Ruggieri et al., 1984; Vergnaud-Grazzini et al., 1994).

We therefore ascribe the interval between 58.12 and 49.72 rmcd to the Santernian, the interval between 49.72 and 40.71 rmcd to the Emilian, and the interval between 40.71 and 32.24 rmcd to the Sicilian. The sequence above this level is ascribed to the undistinguished Quaternary, with the segment between ~8 and 5 rmcd correlatable to oxygen isotopic Stages 5a–5e and ascribed to the Tyrrhenian Stage.

CONCLUSIONS

In the composite sequence of ODP Site 964, integrated calcareous plankton biostratigraphy and cyclostratigraphy, based on relative abundance fluctuations of *Globigerinoides* spp. and oxygen isotope stages, provided an accurate resolution of the stratigraphic interval between slightly below the LCO of *D. tamalis* and the Holocene. All biozones already recognized in coeval Italian land sections and in the Tyrrhenian basin were identified. Their boundaries are isochronous, at least within the approximation of the time interval defined by the abundance fluctuations and oxygen isotopic stages, which in the Pliocene and lower part of the Pleistocene are correlated to the obliquity astronomical cycles. Each bioevent coincides with the same fluctuation already identified in those sequences. Compared with the correlation proposed by Sprovieri (1993), the LO of *D. brouweri*, previously correlated to isotopic stage/fluctuation 73, is now recognized in

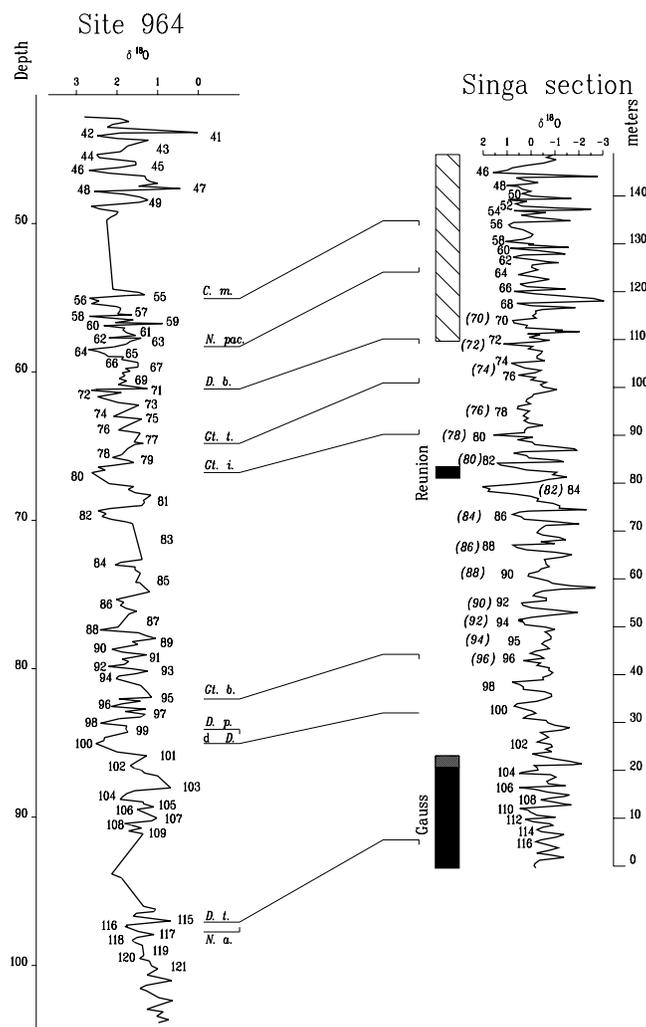


Figure 9. Proposed correlation between the sequence at Site 964 and the Singa section. Oxygen isotopic stages according to our interpretation are reported in roman type. Interpretation of Lourens et al. (1992) is reported in italics and parentheses. *C. m.* = *Calcidiscus macintyreii*; *N. pac. s.* = *Neogloboquadrina pachyderma* left coiling; *D. b.* = *Discoaster brouweri*; *Gt. t.* = *Globorotalia truncatulinoides*; *Gt. i.* = *Globorotalia inflata*; *Gt. b.* = *Globorotalia bononiensis*; *D. p.* = *Discoaster pentaradiatus*; *d. D.* = *Discoaster decrease*; *D. t.* = *Discoaster tamalis*; *N. a.* = *Neogloboquadrina atlantica*.

coincidence with relative abundance fluctuation/oxygen isotopic Stage 71.

All the chronostratigraphic units between the upper part of the Piacenzian and the Holocene were identified. The base of the Gelasian, recognized in coincidence with the oxygen isotope Stage 103, is not characterized at Site 654 by a sapropel level, which identifies the GSSP of the base of the Gelasian in the Monte San Nicola stratotype section.

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