

PALEOCEANOGRAPHIC CONDITIONS AT THE BASE OF THE PLIOCENE IN THE SOUTHERN MEDITERRANEAN BASIN

FRANCA SGARRELLA*, RODOLFO SPROVIERI**,
ENRICO DI STEFANO** & ANTONIO CARUSO**

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Riassunto. Una dettagliata analisi quantitativa dell'associazione a foraminiferi bentonici alla base (Zona M Pl 1) delle successioni plioceniche affioranti ad Eraclea Minoa e nell'area di Capo Rossello (Sicilia meridionale) hanno evidenziato condizioni paleoecologiche ampiamente fluttuanti, indicative di condizioni disaerobiche al fondo del bacino. In particolare, è stato possibile evidenziare un intervallo, riferibile alla parte alta della Zona M Pl 1, caratterizzato da una successione di picchi di abbondanza di *Uvigerina pygmaea-peregrina*. Tale intervallo è stato identificato come *U. pygmaea-peregrina* Event. Sulla base della biostratigrafia integrata a plancton calcareo e della ciclostratigrafia basata sulle fluttuazioni di abbondanza relativa nelle associazioni a foraminiferi planctonici, la base dell'*U. pygmaea-peregrina* Event coincide con il ciclo 6a e la sua sommità con il ciclo 10. Nel bacino tirrenico la durata di questo Evento è abbastanza ben comparabile con quella riconosciuta nelle sezioni della Sicilia meridionale. Al contrario esso interessò un più lungo intervallo di tempo nel bacino ionico dove è riconoscibile dal ciclo 4 al ciclo 12.

L'Evento ad *U. pygmaea-peregrina* con 10 picchi di abbondanza relativa nella sezione composta di Roccella Ionica - Capo Spartivento è correlabile con l'intervallo del Pliocene basale nel quale è stata individuata una sequenza di 10 livelli di sapropels nell'ODP Leg 160 Site 969. Tale correlazione implica un meccanismo di formazione di tali sapropels differente da quello proposto per i "sapropels" della base della Formazione di Monte Narbone, che sono legati ai massimi di eccentricità astronomica (Hilgen, 1991). Infatti l'intervallo nel quale sono riconoscibili i 10 picchi di abbondanza relativa di *U. pygmaea-peregrina* nella sezione composta di Roccella Ionica - Capo Spartivento copre un intervallo di minimo di eccentricità nella curva astronomica. Nei livelli stratigrafici più recenti la formazione dei sapropels coincide sempre con intervalli di massimo di eccentricità astronomica. E' ipotizzabile che le peculiari e ristrette condizioni al fondo del bacino, in coincidenza della base del Pliocene, abbiano avuto una influenza maggiore rispetto al segnale astronomico, che invece domina la formazione dei sapropels negli intervalli stratigrafici più recenti quando condizioni paleoceanografiche più "normali" si erano ristabilite al fondo del bacino mediterraneo.

Abstract. Detailed quantitative analyses of the benthic foraminiferal assemblage from the base of the Pliocene sections (M Pl 1 biozone) at Eraclea Minoa and the Capo Rossello area (southern Sicily) documented fluctuating paleoecological conditions indicative of a

dysaerobic bottom water environment. In particular, we identify the *Uvigerina pygmaea-peregrina* Event, which in the area studied covers the upper part of the M Pl 1 biozone. According to the integrated calcareous plankton biostratigraphy and to cyclostratigraphy based on fluctuations in the relative abundance of fauna in the planktonic foraminiferal assemblage, the base of the *Uvigerina pygmaea-peregrina* Event coincides with cycle 6a and its top coincides with cycle 10 in the Sicilian sections. A similar temporal correlation is seen in the Tyrrhenian basin (ODP Site 652). On the contrary, the *Uvigerina pygmaea-peregrina* Event covers a longer time interval in the Ionian basin, where it is recognizable from cycle 4 to cycle 12. The *Uvigerina pygmaea-peregrina* Event is time equivalent with an interval characterized by cyclically repeated sapropels in the eastern Mediterranean basin. As a matter of fact, 10 sapropels are present in the deep-sea sediments (ODP Site 969) and 10 *Uvigerina pygmaea-peregrina* peaks are present in the Roccella Ionica - Capo Spartivento composite section in the M Pl 1- lowest M Pl 2 biozones. The diachronous termination of the *Uvigerina pygmaea-peregrina* Event may indicate that well-oxygenated bottom conditions were established earlier in the western than in the eastern Mediterranean basin. Both the sapropels interval in the eastern Mediterranean and low-oxygen bottom conditions in the Ionian basin occurred during a time interval which straddles a minimum of eccentricity in the astronomical record.

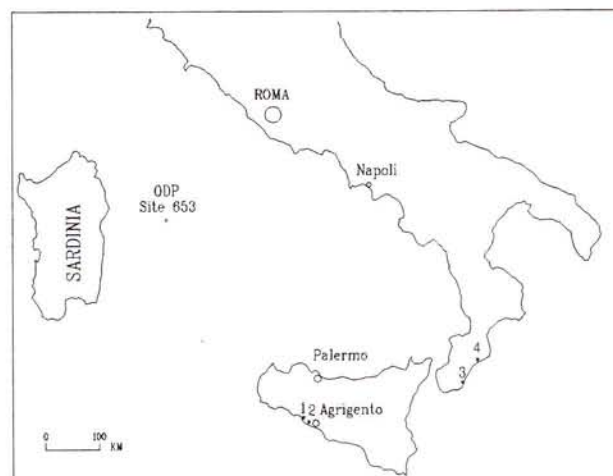


Fig. 1 - Index map of the sections studied. 1) Eraclea Minoa; 2) Capo Rossello; 3) Capo Spartivento; 4) Roccella Ionica.

*Department of Paleontology, Largo S. Marcellino, 10, 80138, Napoli, Italy.

** Department of Geology and Geodesy, C. Tukory, 131, Palermo, Italy.

Introduction.

The Miocene/Pliocene stratotype boundary was informally proposed by Cita (1975a) at Capo Rossello, to coincide with the lithological boundary between the base of the lower (Zanclean) Trubi marls and the top of the non-marine sediments of the uppermost Messinian Arenazzolo Formation. Hilgen & Langereis (1988, 1993) recognized, based essentially on a cyclostratigraphic study of small-scale sedimentary cycles, that the base of the Zanclean at Capo Rossello and at the Eraclea Minoa sections is synchronous. Since the contact between Trubi and Arenazzolo is more clearly exposed at Eraclea Minoa, and since magnetostratigraphic results were obtained from the base of the Eraclea Minoa section, but not from the base of the Capo Rossello section, they propose the Eraclea Minoa section as a candidate for the Miocene/Pliocene boundary stratotype.

We therefore selected these 2 sections (Fig. 1) to investigate in detail how the foraminiferal assemblages re-colonized the Mediterranean basin after the "post-Messinian flood". Bio- and chemostratigraphic analyses on sediments from the Tyrrhenian basin provided accurate information on the earliest Pliocene paleoceanographic conditions in the Mediterranean basin (McKenzie & Sprovieri, 1990; McKenzie et al., 1990), and a scenario was proposed for the main events that occurred during approximately the first 0.3 MA after the end of the Messinian salinity crisis. The presence of characteristic benthic foraminifera indicates an essentially dysaerobic bottom environment at the very base of the Pliocene and abnormally low-oxygen bottom content in the time interval between the end of the *Sphaeroidinellops* acme and the FCO (First Common Occurrence) of *Globorotalia margaritae*, which coincides with the M Pl 1 - M Pl 2 boundary. This interval is characterized by increased abundance of *Uvigerina pygmaea*. Its top coincides with the entrance of deep water, atlantic benthic foraminifera, indicating the beginning of well-oxygenated bottom conditions. At Capo Rossello, Brolsma (1978) reported an interval of about 7 meters with abundant *Uvigerina peregrina* beginning at the end of the *Sphaeroidinellops* acme. At Capo Spartivento (Jonian side of Calabria, southern Italy), Thunell et al. (1991) found an increase in abundance of *Uvigerina* spp. (*U. pygmaea* and *U. rutila*) coincident with the top of M Pl 1 biozone. From the Roccella Ionica-Capo Spartivento composite section, Di Stefano et al. (1996) reported a stratigraphic interval from just below the *Sphaeroidinellops* acme to slightly above the *Globorotalia margaritae* FCO with abnormal, highly fluctuating relative abundance of *Uvigerina peregrina*, that was always more abundant in the marly beds of each lithological cycle. A high abundance of *U. peregrina* is therefore well established in several

Mediterranean regions in the stratigraphic interval at the top of the M Pl 1 - base of M Pl 2 biozones.

The present work was undertaken to 1) verify the presence of this event at the base of the Eraclea Minoa section; 2) perform a detailed investigation of the benthic foraminiferal assemblage in the >125 μm and in the 63-125 μm fractions in the Capo Rossello area and in the Eraclea Minoa section. In the Tyrrhenian sediments (ODP Site 652), the number of benthic foraminifera in the 63-150 μm fraction is greater in the M Pl 1 biozone than in the M Pl 2 biozone, indicating a stressed environment in the former (Thunell et al., 1990). Schroeder et al. (1987) outlined the importance of studying the 63-125 μm fraction. Indeed artificial "barren zones" may result if only small-sized species are present, which can be totally missing in the >125 μm fraction.

Material.

Eraclea Minoa section.

Forty-two samples, each sample being about 5 cm thick, were collected in the first 10 lithological cycles, corresponding to a thickness of about 10 meters. The lowermost sample comes from the end of the road of the camping site, where the "Trubi"-Arenazzolo transition (transitional zone, according to Brolsma, 1978) is well exposed. The other samples were collected at Capo Bianco, about 200 meters to the west. In the first 7 lithological cycles samples are closely spaced, but only 2 samples were collected in cycles 8, 9 and 10.

Capo Rossello.

A borehole with continuous recovery was drilled in 1991 in the Sciabbarra locality, east of Punta di Maiata (Capo Rossello area). The borehole began in the basal part of the M. Narbone Formation and cut through the entire extent of the "Trubi", down to the top of the Arenazzolo, which was encountered 154.2 meters below the surface (mbs). A complete description of the borehole, drilling operations and core handling is in preparation. Here we report our analysis of the 7.45 m-thick interval between the base of the "Trubi" and the level at 146.75 mbs (M Pl 1 biozone). Samples were collected approximately every 25 cm.

Methodology.

The samples studied are listed in Tab. 1. Each sample was washed through a 63 and 125 μm sieve. Each fraction was microsplit to yield a sub-sample containing more than 300 specimens. Benthic foraminifera were picked, identified and counted separately from the 2 fractions. The quantitative raw data from these fractions were combined to obtain relative abundance values of the total assemblage >63 μm . Taxa abundance was expressed also as a percentage of the total assemblage >125 μm . The Benthic Number (BN) was estimated separately as the total number of specimens per gram of dry sediment in the 2 fractions and reported as BN >63 μm and BN >125 μm , respectively.

Quantitative data of planktonic foraminifera were obtained only from the >125 μm fraction. From the split residue at least 300 specimens were identified and counted. Relative abundance data of *Globigerinoides* spp. (essentially *Gld. obliquus* s.l. + *Gld. quadrilobatus* s.l.) were used for cyclostratigraphic analysis. Calcareous nannofossils were studied on smear slides at about 1000X magnification. Smear slides were prepared according to standard methods.

ERACLEA MINOA		BORE-HOLE
Samples	m	Samples (mbs)
40	9.6	146.75-146.80
39	9.25	147.10-147.15
38	8.85	147.55-147.60
37	8.5	147.85-147.90
36	8.05	148.20-148.25
35	7.7	148.47-148.52
34	7.5	148.76-148.81
33	7.2	149.01-149.06
32	7	149.27-149.32
31	6.9	149.52-149.57
30	6.75	149.84-149.89
29	6.6	150.17-150.22
28	6.45	150.47-150.52
27	6.3	150.77-150.82
26	6.15	151.08-151.13
25	5.95	151.40-151.45
24 bis	5.75	151.70-151.75
24	5.65	152.00-152.025
23	5.5	152.25-152.275
22	5.2	152.50-152.525
21	5.05	152.80-152.825
20	4.85	153.05-153.075
19	4.6	153.30-153.325
18	4.3	153.55-153.575
17	3.95	153.79-153.815
16	3.7	153.99-154.04
15	3.35	154.09-154.14
14	3.2	154.14-154.17
13	3	154.17-154.18
12	2.85	154.18-154.20
11	2.45	
10	2.05	
9	1.65	
8	1.55	
7	1.4	
6	1.2	
5	0.9	
4	0.8	
3	0.7	
2	0.45	
EM 94-1	0.2	
Gb 90-6	"Trubi" base	

Tab. 1 - List of samples from the two sections.

Results

Biostratigraphy.

Planktonic foraminifera.

Biostratigraphic subdivision of the sections was based on the biostratigraphic scheme of Cita (1973, 1975b) as emended by Sprovieri (1992). The drilled section from the of Capo Rossello area is referable to the

M Pl 1 - M Pl 5 (pars) biozones. In this paper we report results only from the basal part of the sequence referable to the M Pl 1 biozone. In this interval, the bio-events studied in great detail in the composite section sampled from Roccella Ionica and Capo Spartivento (Jonian side of Calabria, southern Italy) by Di Stefano et al. (1996) were also considered (Fig. 1) to obtain a more detailed biostratigraphic resolution. In particular, the base and top of the *Sphaeroidinellopsis* acme, the 2 discrete levels with left coiling of *Neoglobobquadrina acostaensis*, and a sharp increase in relative abundance of *Globigerinoides* spp. were used for a more detailed biostratigraphic correlation. Results are reported in Fig. 2 and 3. In the drilled section, the presence of a relatively high abundance of *Sphaeroidinellopsis* spp. from the basal samples and the presence of left coiling specimens of *N. acostaensis* at 153.99-154.04 m, only 16 cm above the local base of the Trubi, indicate that the lowermost part of the Zanclean was not represented. The time interval of the missing part will be discussed below, based on a cyclostratigraphic interpretation.

The entire segment from Eraclea Minoa belongs to the M Pl 1, with the top sample interpreted as occurring just below the FCO of *Gt. margaritae*. According to our detailed biostratigraphic analysis the segment we sampled included the basal Pliocene (Fig. 3).

The calcareous bio - events are reported in Tab. 2.

Calcareous nannofossils.

The entire interval sampled in the Eraclea Minoa section is referable to the lower part of the MNN 12 zone. The borehole sequence is referable to the MNN 12 - MNN 15a zones of Rio et al. (1990). A paracme interval of *Reticulofenestra pseudoumbilicus* (Rio et al., 1990; Di Stefano et al., 1996) was present between 152.02 and 143.67 mbs in the borehole. In the Roccella Ionica - Capo Spartivento composite section the base of this paracme interval was recognized between cycles 6a and 6b and its top was in cycle 13 (Di Stefano et al., 1996). The base of the paracme interval was identified in the Eraclea Minoa section between cycles 6a and 6b (Tab. 2), whereas the top occurred higher in the section.

Benthic foraminifera.

A detailed quantitative analysis of the benthic foraminiferal assemblage pointed out several events in the M Pl 1 biozone. Two bio-events were easily recognizable from a qualitative analysis. In the borehole, *Cibicidoides bradyi-robertsonianus* and *Cibicidoides italicus* appeared at 149.03 and 148.22 mbs, respectively, in cycle 9 (see below). At Eraclea Minoa the first occurrence of these two species was recorded at 8.50 and 8.55 m respecti-

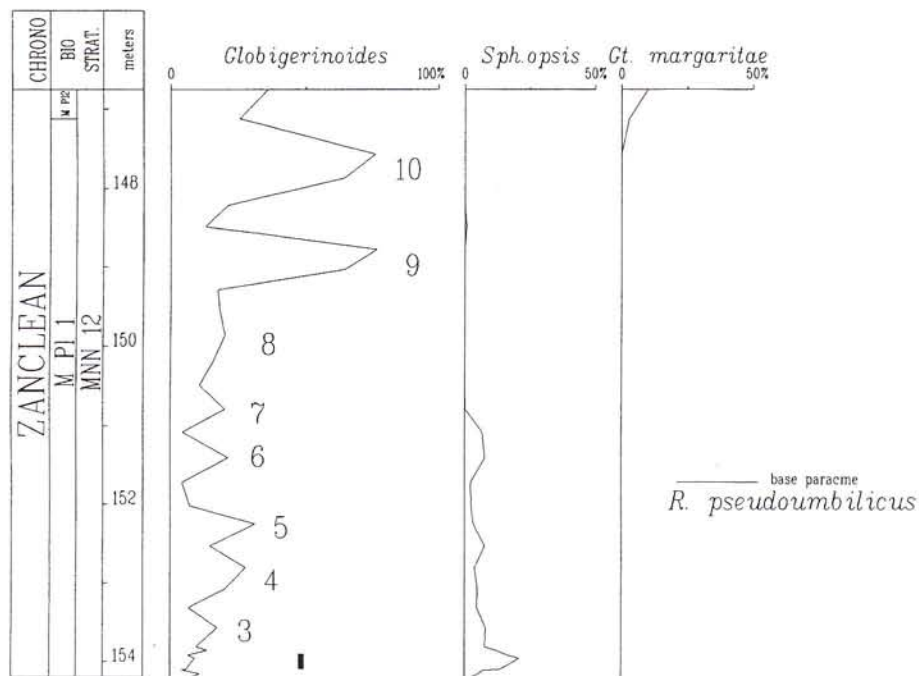


Fig. 2 - Quantitative distribution of the main planktonic foraminifera biostratigraphic markers in the Capo Rossello borehole. On the left, *Globigerinoides* spp. relative abundance fluctuations are reported and labeled for comparison. Vertical black bars indicate the presence of dominant left coiling *N. acostaensis*. Base paracme of *R. pseudoumbilicus* is also indicated.

vely, and was correlated to the same cycle. These 2 bio-events had the same stratigraphic position in the Roccella Ionica - Capo Spartivento composite section (Di Stefano et al., 1996) (Fig. 4). At ODP Leg 107 Sites 652, 653 and 654, *C. italicus* and *C. brady-robertsonianus* appear

red just below the FCO of *Gt. margaritae* (Sprovieri & Hasegawa, 1990). These 2 bio-events appeared to be synchronous in the early Zanclean Mediterranean sections and may be used to improve the biostratigraphic resolution provided by planktonic assemblages.

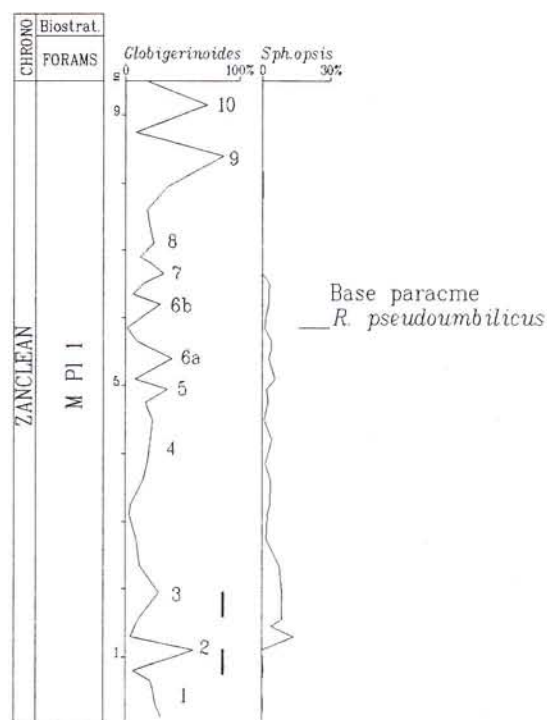


Fig. 3 - Quantitative distribution of *Sphaeroidinellopsis* spp. in the Eraclea Minoa segment. Relative abundance fluctuations of *Globigerinoides* spp. are reported and labeled on the left. Vertical black bars indicate the presence of dominant left coiling *N. acostaensis*. Base paracme of *R. pseudoumbilicus* is also indicated.

ERACLEA MINOIA	BIO - EVENTS	BORE-HOLE
—	top paracme <i>R. pseudoumbilicus</i>	143.97 mbs
—	FCO <i>Gt. margaritae</i>	147.10 mbs
9.15 m	increase relative abundance <i>Globigerinoides</i> spp.	149.01 mbs
6.5 m	top acme <i>Sphaeroidinellopsis</i>	151.03 mbs
5.85 m	base paracme <i>R. pseudoumbilicus</i>	151.70 mbs
1.65 m	second shift <i>N. acostaensis</i> sx	153.99 mbs
1.55 m	base acme <i>Sphaeroidinellopsis</i>	—
0.55 m	first shift <i>N. acostaensis</i> sx	—

Tab. 2 - Bio - events and stratigraphic levels of the main calcareous plankton recorded in the M Pl 1 interval of the 2 sections considered.

Cyclostratigraphy.

Lithological cycles could not be clearly identified, or at least not unambiguously detected in the cores of the borehole and along the segment sampled at Eraclea Minoa. Therefore, in order to attempt a cyclostratigraphic interpretation of the sections investigated, the procedure proposed by Sprovieri (1992, 1993) was followed. Consequently, cyclostratigraphic interpretations were based only on faunistic cycles. The relative abundance fluctuations in *Globigerinoides* spp. are plotted and labeled in Fig. 2 and 3. The sequence of abundance fluctuations was correlated with the biostratigraphic events. According to Sprovieri (1993) and Di Stefano et

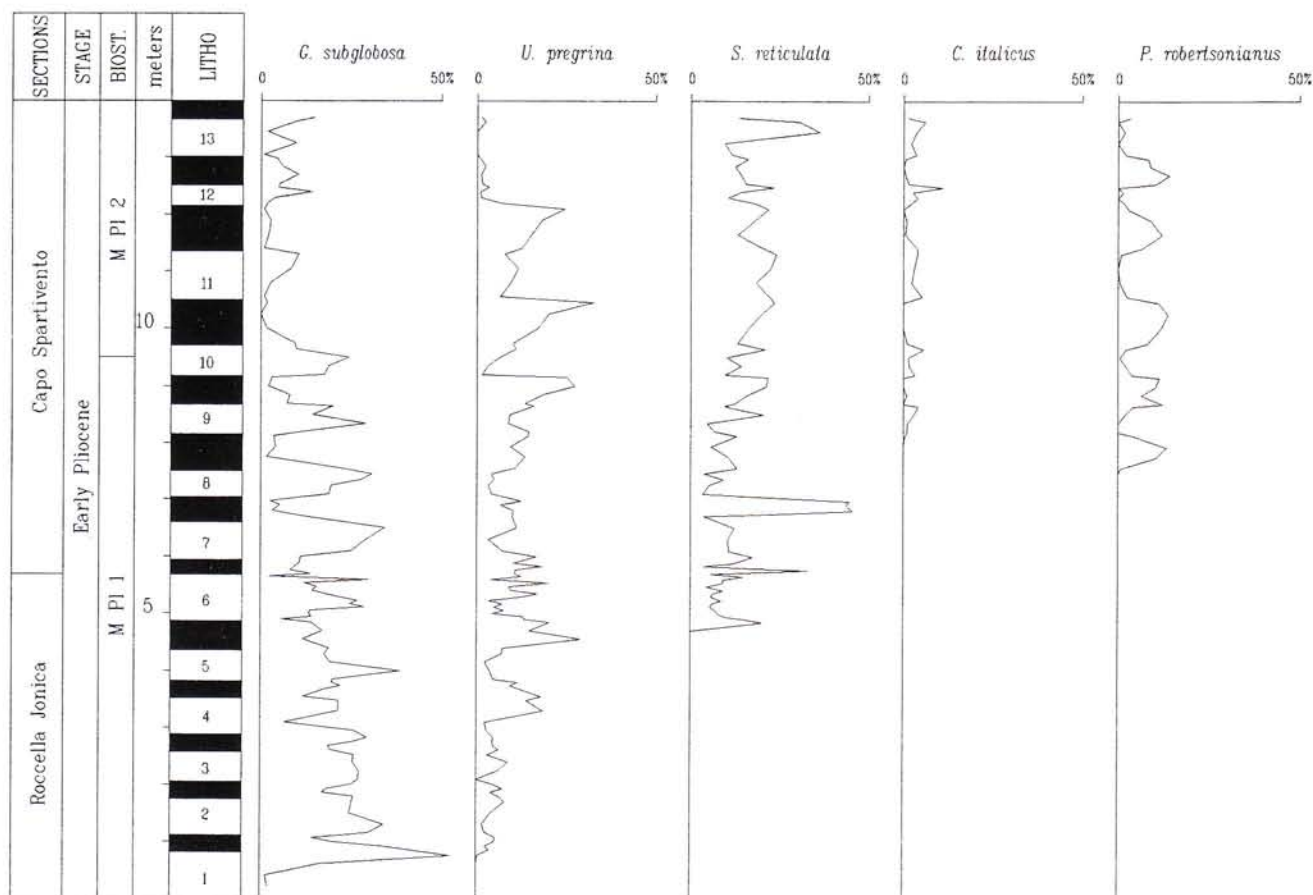


Fig. 4 - Quantitative distribution of benthic foraminifera species in the Roccella Jonica-Capo Spartivento composite section. Horizontal black bars indicate marly beds. Horizontal white bars indicate limestone beds. From Di Stefano et al. (1996).

al. (1996): a) the base of the *Sphaeroidinellopsis* acme falls in cycle 2; b) its top occurs at the top of cycle 6b; c) 2 discrete, short intervals with left coiling *Neoglobobulina acostaensis* occur at the boundary between cycle 1 and cycle 2, and between cycle 2 and cycle 3, respectively; d) a sharp increase in abundance of *Globigerinoides* spp. occurs in cycle 9; and e) the FCO of *G. margaritae* is recorded in the upper part of cycle 10. The same correlations were obtained in the sections studied here (see Fig. 2 and 3).

Cyclostratigraphic analyses indicated that the basal 2 cycles were missing in the borehole. Therefore a time interval of about 40 ky at the base of the Pliocene was not represented in this section. Two abundance fluctuations, labeled 6a and 6b, were recorded between 5.5 - 6.3 m in the Eraclea Minoa section. They corresponded to lithological cycle 6, which included 2 precessional cycles (Hilgen, 1991). Nevertheless, only cycle 6b was recorded in the borehole at 151.4 mbs; its identification resulted from the recognition of the base of the paracme of *R. pseudoumbilicus* at 151.7 mbs. The base of the paracme of *R. pseudoumbilicus* occurred at Eraclea Minoa and in the Capo Spartivento composite section between cycle 6a and 6b (Fig. 3).

Benthic Foraminifera: detailed analysis.

Eraclea Minoa.

Total assemblage (> 63 μ m).

Benthic foraminifera from the 63-125 μ m fraction always represented the greater part of the total assemblage, with relative abundance values between 69% and 97% (Fig. 5). The lowest values were found between 5.40 and 6.35 m and at 8.40 m above the base. *Eponides pusillus*, *Bolivina savanae*, *Epistominella rugosa convexa*, *Stainforthia complanata* and *Felsinella diaphana*, the dominant species, were not present in the > 125 μ m fraction. In the basal sample the 63-125 μ m fraction represented 96.8% of the total benthic assemblage, with *E. pusillus* (42%) and *E. exigua* (22%) dominant. *Epistominella exigua* (Fig. 6) was abundant only in this sample, while *E. pusillus* was abundant up to the top of cycle 1, ranging between 28% and 45% (Fig. 6). In this same interval, and up to the basal part of cycle 3 (2 meters above the base), *Globocassidulina subglobosa* was abundant (Fig. 6). This species was present in both fractions, varying between 12% and 35% of the total. *B. savanae* was common from the base of cycle 2 and was generally present in high abundance up to the top of the segment studied (Fig. 6). The highest values were 52%-88% between 2.45 and 4.85 m, and 40%-92% from 6.50 m to the top.

S. complanata, *G. subglobosa*, *Gyroidina* spp., *Rotamorphina laevigata* and *E. rugosa convexa* total abundance data had an opposite trend to that of *B. savanae* (Fig. 6).

Assemblage > 125 μ m.

Relative abundance fluctuations characterized the quantitative data of all identified species. In the basal part, *Oridorsalis umbonatus* and *Gyroidina soldanii* were dominant (Fig. 7), with *E. exigua* frequen-

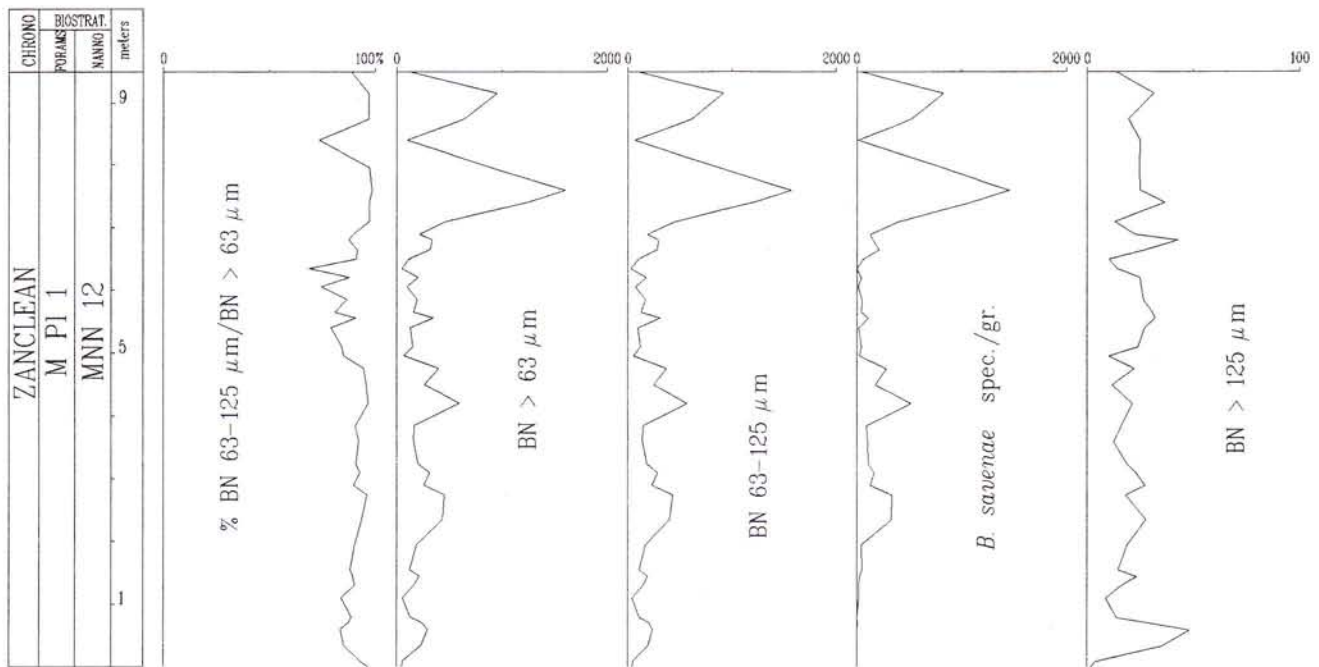


Fig. 5 - Distribution of benthic number values in the Eraclea Minoa segment.

tly found in the basal sample and *Karreriella bradyi* at 0.10 m. *O. umbonatus* was found at greater than 20% of the total only at the base of the section. Between 0.45 and 0.90 m *G. subglobosa* was strongly dominant (66%-86%). In the segment above, *Gyroidina* spp., *G. subglobosa*, *K. bradyi*, and *Oridorsalis stellatus* (Fig. 7) prevailed, with *O. stellatus* appearing at 1.20 m. Between 2.05 and 2.85 m, *Pullenia quinqueloba*, *Nonionellina labradorica*, *Sigmoilopsis schlumbergeri*, *Cibicidoides ungerianus*, *Sphaeroidina bulloides*, *Cibicidoides dutemplei* and *Anomalinoidea helicinus* appeared and were generally present in all the samples. Other, more scattered species which contributed to the dominant assemblage were *Bigenerina nodosaria* (more than 10% at 1.20 and 4.85 m), *Discorbinella berteloti* (abundant only between 3 and 3.35 m), *N. labradorica* (well represented between 2.45 and 5.05 m), *Rotamorphina laevigata* (frequent from the base of cycle 3), *Sphaeroidina bulloides* (frequent from the top of cycle 5), *Astrononion umbilicatum* (more frequent from the top of cycle 7), and *Anomalinoidea helicinus* (better represented from the top of cycle 8). *C. bradyi* (Fig. 7) and *C. italicus* were present from cycle 9. *U. pygmaea*, present from the base of cycle 4, had high percent values between the base of cycle 6 and the upper part of M Pl 1 (Fig. 7). *Siphonina reticulata* and *Pullenia bulloides*, present from 5.20 and 6.15 m respectively, were always very rare.

Benthic Number.

The trend of BN > 63 μm and BN > 63-125 μm are plotted in Fig. 5. BN > 63 μm (Fig. 5) was low at the base of the segment (about 50 specimens /g), but rapidly increased to values greater than 100-200 specimens/g at 0.45 m, with 2 marked peaks in the upper part. Fig. 5 clearly shows that this trend was strongly influenced by the total number/g of sediment of *B. savanae* (Fig. 5). BN > 125 μm (Fig. 5) had lower values (20-30 specimens/g), but with frequent fluctuations. Between the base and about 6 m the highest values coincided with maximum abundance of *G. subglobosa*. Above this interval, they coincided with the maximum abundance values of *U. pygmaea*. In this interval BN > 63 μm and BN > 125 μm were anti-covariant.

The borehole.

Total assemblage (> 63 μm).

Benthic foraminifera were the most abundant part of the total assemblage in the 63-125 μm fraction, with percent values ranging be-

tween 60% and 70% with maximum values up to 98% (Fig. 8). The lowest values (53%) were between 152 and 151.08 mbs. The same species reported in the Eraclea Minoa sequence were found in this fraction. *E. pusillus* dominated (20% and 31%) the lowermost 11 cm (Fig. 9), while *G. subglobosa* and *B. savanae* were frequent (Fig. 9). Together they represented 46-50% of the assemblage. From 153.79 mbs *B. savanae* was the dominant species, being most abundant between 153.60 and 152.25 mbs (45%-73%) and 150.77 and 148.20 mbs (43-84%). Again, the abundance of *G. subglobosa*, *Gyroidina* spp. and *E. rugosa convexa* had an opposite trend to that of *B. savanae* (Fig. 9).

Assemblage > 125 μm .

O. umbonatus, *Gyroidina* spp. (essentially *G. soldanii*), *G. subglobosa*, *K. bradyi* and *O. stellatus* dominated the interval between 154.20 and 153.79 mbs, ranging from 73% to 84% of the totals (Fig. 9). *O. umbonatus* was abundant only in this interval (26% at the base and 7% at the top). In this segment *P. quinqueloba*, *S. schlumbergeri*, *N. labradorica* and *C. ungerianus* appeared. Above this interval *C. dutemplei* and *A. helicinus* appeared at 153.60 mbs, *U. pygmaea* and *C. agri-gentinus* at 153.25 mbs, *S. reticulata* at 150.82 mbs, *Sphaeroidina bulloides* at 149.89 mbs, *Lagena gibbera* at 149.57 mbs, *C. bradyi* and *C. italicus* at 149.06 mbs, and *Uvigerina auberiana* at 147.90 mbs.

Between 153.79 and 147.85 mbs *G. subglobosa*, *U. pygmaea*, *Gyroidina* spp., *K. bradyi* and *O. stellatus* were dominant. Subordinate species included *B. nodosaria*, *A. helicinus*, *C. dutemplei*, *A. umbilicatum*, *N. labradorica*, *R. laevigata* and *Pleurostomella alternans*.

U. pygmaea (Fig. 9) was abundant within 2 discrete segments of this interval. The first was between 153.35 and 153.05 mbs and the second was between 151.45 and 147.85 mbs, where generally higher percent values (between 7% and 50% of the assemblage) were present. Above this interval *U. pygmaea* was not present in the samples referable to the M Pl 1 biozone. *A. umbilicatum* was frequent from 150.52 mbs, and *S. schlumbergeri* was rare when *U. pygmaea* was dominant. *C. bradyi* (Fig. 9) and *C. italicus* were abundant at the top of this segment. Above 147.85 mbs, the assemblage was dominated by *O. stellatus*, *G. subglobosa*, *S. reticulata*, *C. bradyi*, *K. bradyi* and *Gyroidina* spp.

Benthic Number.

BN > 63 μm was low in the first 2 samples above the base (Fig. 8), but rapidly increased to values greater than 100-200 speci-

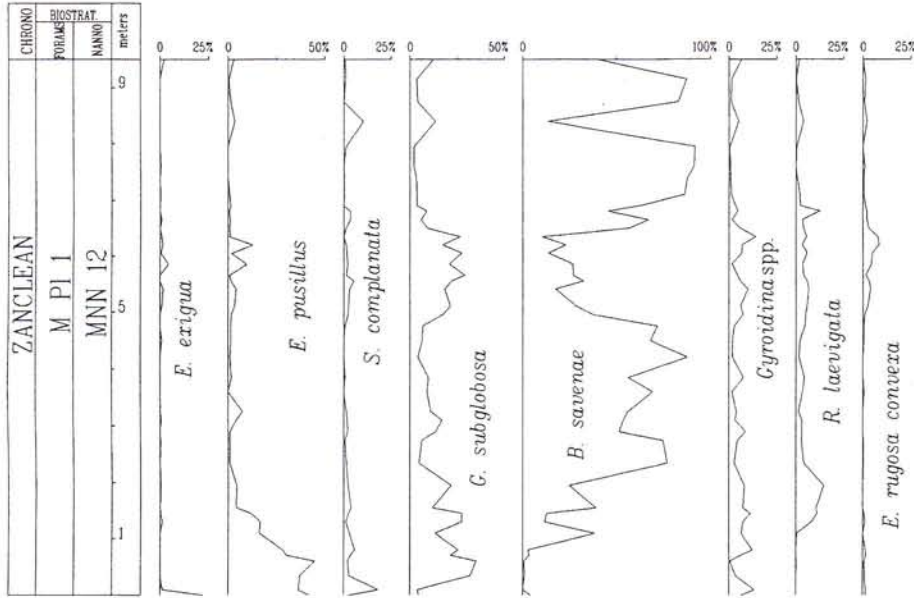


Fig. 6 - Relative abundance fluctuations of the most frequent taxa in the assemblage > 63 μm at Eraclea Minoa.

mens/g, with small decreases at 152 and 151.08 mbs. Two strong peaks were present in the upper part, between 149.52 and 149.27 mbs (1113 and 657 specimens/g, respectively) and 148.47 and 148.2 mbs (868 and 771 specimens/g, respectively). These peaks coincided with an increase in the number of specimens of *B. savanae* (Fig. 8), as in the Eraclea Minoa section. BN >125 μm was low, between 20 and 30 specimens/g (Fig. 8), with several fluctuations. Maximum values now coincided with the highest abundance of *U. pygmaea*. In the upper part, BN > 63 μm and BN > 125 μm had opposite trends, as in the Eraclea Minoa sequence.

Interpretation and discussion.

Most of the more abundant species in the earliest part of the M PI 1 biozone are typical of the bathyal environment. *E. pusillus* has an upper depth limit of 350 m, but is more abundant between 1,000-3,000 m (Sgarrella & Moncharmont Zei, 1993). The frequency of *O. stellatus*, which is recorded to a depth of 900 m in the

Recent of the Gulf of Mexico (Pflum & Frerichs, 1976), and of *B. nodosaria*, which is frequent in the Recent of the Mediterranean to a depth of 700-800 m (Sgarrella & Moncharmont Zei, 1993) suggest a depth of about 600-800 m.

The several bio-events identified in the M PI 1 biozone of the 2 sections provide evidence for the rapid re-colonization and/or sharp changes in the dominance of some species. Dominance of a few species, which gives an oligotypic character to the assemblage, is recognizable in the total (> 63 μm) and in the > 125 μm assemblages. The 15 main benthic foraminifera bio-events and their stratigraphic levels are reported in Tab. 3. Bio-events 6 to 14 are present in both sections, but the last bio-event was detected only in the borehole, since the segment studied at Eraclea Minoa includes only the first 9 cycles and the very base of cycle 10. The first 5 bio-

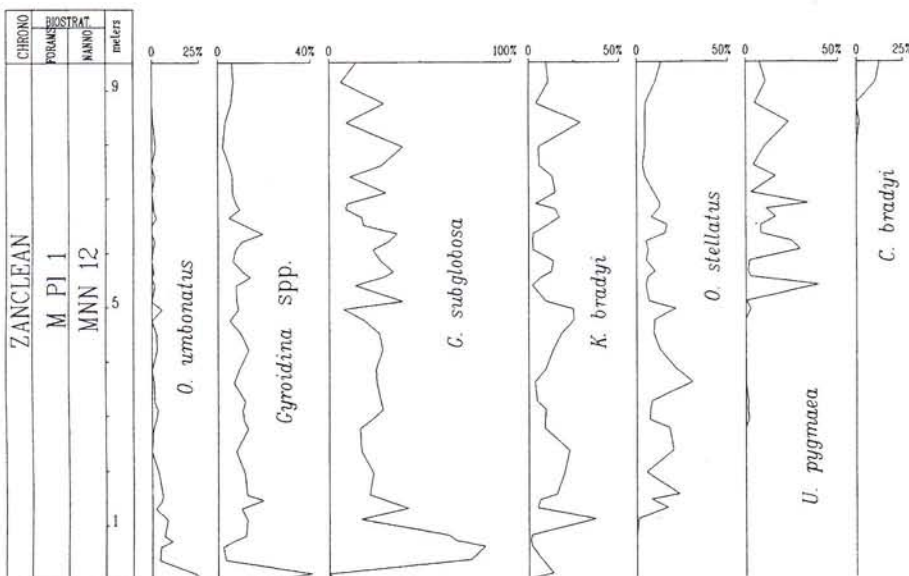


Fig. 7 - Relative abundance fluctuations of the most frequent taxa in the assemblage > 125 μm at Eraclea Minoa.

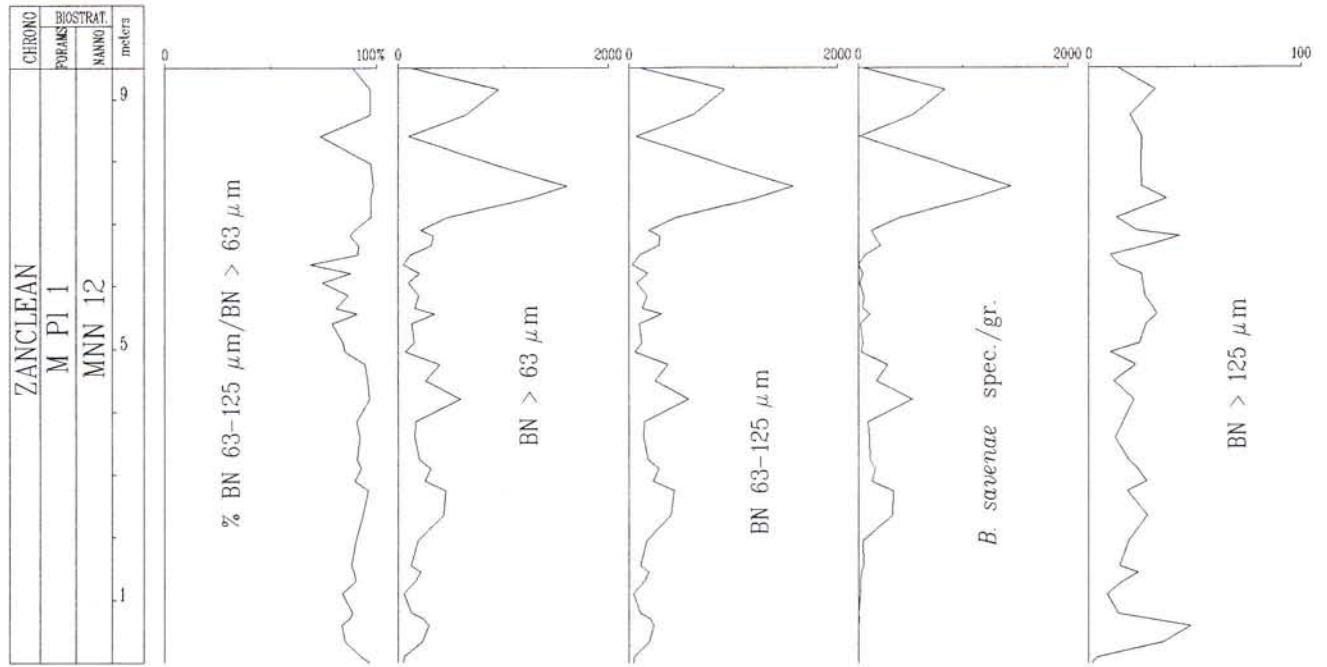


Fig. 8 - Distribution of benthic number values in the segment studied from the Capo Rossello borehole.

events are well represented in Eraclea Minoa, while in the borehole only bio-events 2 and 3 are present. This suggests that the base of "Trubi" is missing in the drilled section. On the contrary, the first benthic bio-event is well represented in the classical Lido Rossello section (see Broelsma, 1978; p. 49, fig. 17).

Benthic bio-events 1 to 4 (cycle 1).

In the basal part of the "Trubi", just above the top of the Arenazzolo and referable to cycle 1 of Hilgen (1991), *E. exigua* and *E. pusillus* dominate in the total assemblage. In the same interval *G. soldanii* and *O. um-*

bonatus are the best represented species in the assemblage $> 125 \mu\text{m}$. *E. exigua* is present only in the level just above the Arenazzolo. *E. pusillus* is dominant up to the top of cycle 1. *G. subglobosa* is abundant in the total assemblage in the first 2 meters above the base and dominant in the assemblage $> 125 \mu\text{m}$ in the top of cycle 1. These re-colonizing species prevail in deep water environments (see summaries in Murray, 1991) with *E. exigua*, *G. subglobosa* and *O. umbonatus*, cosmopolitan species that have been associated with different water masses (Streeter, 1973; Schnitker, 1974, 1979, 1980, 1994; Weston & Murray, 1984; Denne & Sen Gupta, 1991). In recent papers (Gooday, 1988, 1993; Smart et al., 1994)

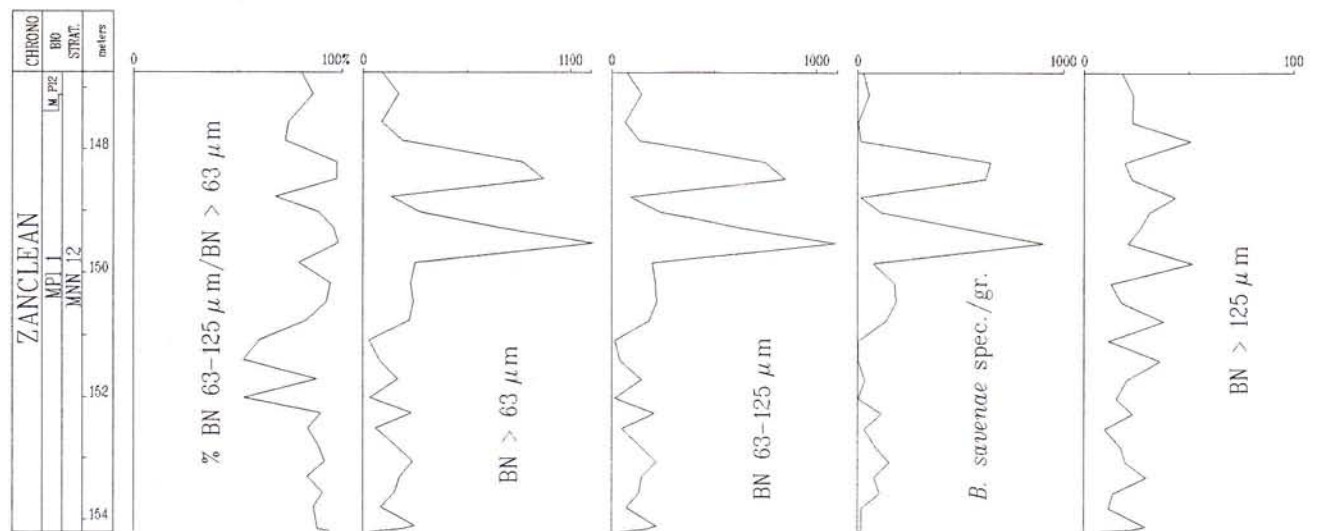


Fig. 9 - Relative abundance fluctuations of benthic foraminifera in the assemblage $> 63 \mu\text{m}$ (A - E) and in the assemblage $> 125 \mu\text{m}$ (F - N) in the segment studied from the Capo Rossello borehole.

E. exigua, *E. pusillus* and *G. subglobosa* have been reported to be included in phytodetritus aggregates from the northeastern Atlantic and considered as opportunistic species. According to these authors, they are adapted to seasonal fluctuations of food supply in a food-limited environment with *E. exigua* more abundant at abyssal depths and *E. pusillus* at bathyal depths. *G. subglobosa* prevails at abyssal depths, but with low percent values (Gooday, 1988). Smart et al. (1994) propose *E. exigua* in the fossil record as a proxy of pulsed organic matter inputs. The dominance of *E. exigua* and *E. pusillus* just above the Arenazzolo-"Trubi" boundary confirms the opportunistic character of these species, which rapidly colonized the unfavorable bottom environment of the basin just after the end of the Messinian salinity crisis. On the other hand, they could also be indicative of strong organic matter input (or phytodetritus) to the bottom, subsequent to strong mixing at the beginning of the flooding event (Cita, 1975a). Above the very base of cycle 1, and throughout this cycle, only *E. pusillus* is dominant. This species (reported as *E. tumidulus*) is recorded as dominant by Vismara Schilling (1986) in pre- and post-sapropelitic Pleistocene levels in the eastern Mediterranean. Consequently, it is considered tolerant to low-oxygen environments. Therefore, dominance of *E. pusillus* is considered indicative of a change to dysaerobic bottom conditions during the upper part of cycle 1. Concomitant with the *E. pusillus* event in the assemblage >125 μm BN strongly increases (up to 48 specimens/g) and *G. subglobosa* is dominant. Since no evidence for a change of sediment accumulation rate is present in this interval (see also Hilgen, 1991) we correlate this abundance of benthic foraminifera to an increase in productivity (Berger & Diester-Haass, 1988; Herguera & Berger, 1991; Herguera, 1992). In conclusion, this event may be correlated with an increase in productivity and/or preservation of organic matter and sluggish bottom circulation, which resulted in partial bottom under-oxygenation.

Benthic bio-events 5 through 15 (cycles 2-10).

From the second cycle new species gradually appear, essentially in the assemblage >125 μm . The total assemblage changes again to oligotypic, dominated by *B. savanae* from the base of cycle 3, slightly above the base of the *Sphaeroidinellopsis* acme interval. *B. savanae* is dominant in 2 intervals: the first ends at the top of cycle 5, while the second is present between the base of cycle 7 (just above the top of the *Sphaeroidinellopsis* acme interval) and the base of cycle 10. In the second interval, *B. savanae* has high percent values, with 2 very high peaks of absolute abundance. The first peak occurs at the top of cycle 8 and the second at the top of cycle 9 (Fig. 5

and Fig. 8). In cycle 6a, below the top of the *Sphaeroidinellopsis* acme interval, dominance of *Uvigerina pygmaea* in the assemblage >125 μm begins (Fig. 7). It ends in cycle 10, just below the first common occurrence of *Gt. margaritae*. The abundance of *Bolivina* and *Uvigerina* species is often correlated with low-oxygen bottom conditions (Boltovskoy & Wright, 1976). The morphology of *Bolivina*, with flattened elongate, highly perforate, thin tests and a high surface/volume ratio, is considered indicative of a species found in a generally low-oxygen environment and adapted to low oxygen content (Colliss & Fois, 1991), and is common in anoxic deposits (Bernhard, 1986). Faunistic assemblages from Oxygen Minimum Zones are characterized by low diversity, with dominance of a few species among which *Bolivina* species are frequent (Phleger & Soutar, 1973; Ingle et al., 1980; Perez-Cruz & Machain-Castillo, 1990; Hermelin & Shimmield, 1990; Sen Gupta & Machain-Castillo, 1993) among others. *U. pygmaea* belongs to the hispid/costate *Uvigerina peregrina* group. The present-day distribution of this group is often correlated with a high organic bottom content (Van der Zwaan et al., 1986). *U. peregrina* is correlated with a high organic bottom content (Miller & Lohman, 1982; Lutze & Colbourn, 1984; Lutze, 1986; Van Leeuwen, 1986; Miao & Thunell, 1993), which in turn is inversely related to oxygen bottom content; abundance of this species is correlated to low oxygen levels (Pflum & Frerichs, 1976; Lohmann, 1978; Streeter & Shackleton, 1979; Schnitker, 1979, 1980, 1994). Quale & Van Weering (1985) found that in the Norwegian Channel *U. peregrina* is associated with a low-energy environment, with low organic content and low oxygen values. Abundance of this species is therefore indicative of low oxygen content, with a possible relationship to high organic carbon content. Abundance of *B. savanae* and *U. pygmaea* infers dysaerobic ("oxygen restricted" sensu Wignall & Myers, 1988) environment, with low-energy bottom conditions and stratified water masses during most part of the M Pl 1 biozone, as already proposed for the Tyrrhenian basin (McKenzie et al., 1990).

Above the *Sphaeroidinellopsis* acme interval, BN >125 μm increases, coinciding with the relative abundance peaks of *U. pygmaea* in cycles 7 to 10. Since an increased abundance of benthic foraminifera is correlated with increased productivity, this event may suggest an increase in food supply and/or preservation of organic matter. Two strong peaks of BN >63 μm coincide with abundance peaks of *B. savanae* and are anti-covariant with BN >125 μm in the upper part of the M Pl 1 biozone. These peaks occur during the second abundance event of *B. savanae*, when percent values of this species are generally high, and therefore may have originated due to a different environmental factor in an alrea-

dy stressed environment. Jorissen et al. (1992), who studied benthic foraminifera in the assemblage $>63 \mu\text{m}$ in the Adriatic sea, suggested that oxygen content in particular, but also food availability have a strong influence on the standing stock of benthic foraminifera.

Above a critical level of oxygen content, food availability becomes the limiting factor. Phleger & Soutar (1973) found a high standing stock of benthic foraminifera with small-sized specimens, low diversity and dominance of only a few taxa in low-oxygen and high-nutrient environments. They emphasized that small-sized specimens can be correlated with very fast reproductive rates when the food supply is abundant. Similar conditions were recognized in transitional environments, just pre- and post-dating the Pleistocene Sapropel S-6 in the eastern Mediterranean (Vismara Schilling, 1986). Since small-sized specimens require only small amounts of oxygen for metabolism (Bradshaw, 1961), it is possible that the peaks of BN $>63 \mu\text{m}$, essentially due to the high abundance of *B. savanae*, indicate low-oxygen bottom conditions and increased productivity. Moreover, since chemical analyses show high values of sulphur and iron that coincide with *U. pygmaea* peaks (unpublished data) and high sulphur values are reported from all the sapropels of the ODP Leg 160 Site 969 (Emeis et al., 1996), *U. pygmaea* seems more indicative than *B. savanae* of dysaerobic conditions and closely correlated with the M Pl 1-base of the M Pl 2 sapropels of the eastern Mediterranean, as detailed below. The dysaerobic conditions may have been induced by sluggish bottom circulation, increased productivity and/or preservation of organic matter.

The *Uvigerina pygmaea-peregrina* Event.

The cyclostratigraphic approach allows a very detailed timing and sequencing of events. At the base of the Pliocene, small scale sedimentary cycles and relative abundance fluctuations of *Globigerinoides* spp., are forced by the periodicity of the astronomical precession cycles (Hilgen, 1991; Sprovieri, 1993). Therefore, isochrony of the events correlated to these cycles can be estimated to within approximately one precessional semi-cycle, about 1 ky long. In this section we compare the intervals during which the *Uvigerina peregrina-pygmaea* Event was detected in the Capo Rossello and Eraclea Minoa areas (southern Sicily, western Mediterranean) and in the Roccella Ionica-Capo Spartivento composite section (Jonian Calabria, eastern Mediterranean), using the cyclostratigraphic data as reference time scale.

In the southern Sicily sections, *U. pygmaea* appears at the base of cycle 4. It increases in abundance from cycle 6a and definitely ends at the base of cycle 10.

During this interval the relative abundance of the species has several strong fluctuations, with the highest values coinciding with the positive abundance fluctuations of *Globigerinoides* spp. In the Roccella Ionica-Capo Spartivento composite section, *U. peregrina* is present from cycle 1, is abundant in cycle 4 and from cycle 6a the percent values increase, with the highest values always coinciding with the marly bed of each cycle. *U. peregrina* is still well represented at the base of cycle 12, but vanishes from the base of cycle 13 (Fig. 4). Therefore, the *U. pygmaea-peregrina* Event in the Jonian composite section begins 2 cycles before and ends 2 cycles after then in the Capo Rossello area. Furthermore, the species is present from the base of cycle 2. In terms of planktonic bio-events, the species appears just below the base of the *Sphaeroidinellopsis* acme interval in the Roccella Ionica-Capo Spartivento composite section. At ODP Leg 107 Sites 652, 653 and 654 in the Tyrrhenian basin, cyclostratigraphic data are not available, but the base of this Event is just below the base of the *Sphaeroidinellopsis* acme interval, and therefore correlates well with its distribution in the Capo Rossello area, even if frequent specimens of *U. pygmaea-peregrina* are still present in samples a few centimeters above the FCO of *Gt. margaritae* (Sprovieri & Hasegawa, 1990; McKenzie & Sprovieri, 1990).

In all of the western Mediterranean lowermost Pliocene sequences (including ODP Leg 107 Sites) no sapropel levels have been identified. Also, sapropels are not present in the Roccella Ionica-Capo Spartivento composite section. Conversely, at some Sites of the recent ODP Leg 160 (for instance, at Site 969) 10 sapropel levels have been identified in the M Pl 1 - base of M Pl 2 biozones (Emeis et al., 1996). In the DSDP Leg 42A Site 374 (Messina abyssal Plain) and 376 (Florence Rise) rare, scattered sapropel levels (the "mystery sapropel") were encountered in sediments referable to the M Pl 1 biozone (Cita et al., 1978). In these levels "giant tests" of *Orbulina universa* are present (Cita et al., 1978) and benthic foraminifera are either rare or not present at all in the $>125 \mu\text{m}$ fraction (Katz & Thunell, 1984), possibly indicating that the sediments were deposited in an anaerobic environment. In the Roccella Ionica-Capo Spartivento composite section and in the Capo Rossello area benthic foraminifera are common, suggesting that the sediments were deposited above this anaerobic environment. These paleoenvironmental and paleobathymetric differences between the eastern Mediterranean Roccella Ionica-Capo Spartivento composite section and the Site 969 sequence suggest that the cyclical abundance of *U. peregrina* in the marly beds of each cycle in the Roccella Ionica-Capo Spartivento composite section may be a response of the benthic faunal assemblage in a shallower environment, time equivalent with intervals

ERACLEA MINOA	CYCLES	BIO - EVENTS NUMBER	BIO - EVENTS	BORE - HOLE
—	base 10	15	end of <i>U. pygmaea</i> Event	147.85 mbs
8.85 - 9.25 m	top 9	14	2° BN >63 peak (<i>B. savaenae</i>)	148.47 - 148.2 mbs
8.50 - 8.85 m	9	13	appearance of <i>C. bradyi</i> and <i>C. italicus</i>	149.06 mbs
7.50 - 7.70 m	top 8	12	1° BN >63 peak (<i>B. savaenae</i>)	149.52 mbs
from 6.9 m	base 7	11	frequency of <i>A. umbilicatum</i>	from 150.47 mbs
6.6 - 9.6 m	above top 6	10	2° <i>B. savaenae</i> peak	150.77 - 148.2 mbs
5.5 m	base 6	9	beginning dominance of <i>U. pygmaea</i>	151.40 mbs
3 m	base 4	8	appearance of <i>U. pygmaea</i>	153.3 mbs
2.45 - 4.85 m	top 3 - top 5	7	1° <i>B. savaenae</i> peak	153.55 - 152.25 mbs
2.05 - 2.85 m	top 3	6	appearance of <i>P. quinqueloba</i> , <i>S. schlumbergeri</i> , <i>N. labradorica</i> , <i>C. ungerianus</i> , <i>C. dutemplei</i> , <i>A. helicinus</i>	153.79 - 153.55 mbs
1.20 m	2	5	appearance of <i>O. stellatus</i>	base
0.45 - 0.90 m	1	4	<i>G. subglobosa</i> (>125) peak	—
base - 0.90 m	1	3	<i>E. pusillus</i> peak	base - 154.09 mbs
base - 0.20 m	1	2	<i>O. umbonatus</i> and <i>Gyroidina</i> spp. (>125)	base - 154.14 mbs
base	1	1	<i>E. exigua</i>	—

Tab. 3 - Bio - events, stratigraphic levels and cycle correlation of the main benthic foraminifera recorded in the M Pl 1 interval of the 2 sections considered.

of severe anoxic conditions in deeper waters where sapropels were forming. Cyclostratigraphic data based on relative faunistic abundance data are not available from Site 969, but the 10 identified sapropels in the M Pl 1 - base of M Pl 2 interval closely match the 10 positive relative abundance fluctuations of *U. peregrina* in the Calabrian sequence.

In the Capo Rossello area (and in the Tyrrhenian basin) the *Uvigerina pygmaea-peregrina* Event is identified during a shorter interval of time. It began after, and ended before, the event recorded in the Calabrian section. We conclude that the beginning and end of the cyclically repeated intervals characterized by a decrease in oxygen bottom content began later and ended earlier in the western basin of the Mediterranean compared to the eastern basin, due to a more open and rapid exchange of bottom water masses entering the Mediterranean from the Atlantic. The eastern Mediterranean, possibly separated from the western Mediterranean by the Malta escarpment sill (Casero et al., 1984), underwent a longer crisis of bottom under-oxygenation. Faunistic evidence shows that this crisis in the eastern Mediterranean began just above the base of the Pliocene and ended slightly above the top of M Pl 1 biozone.

Conclusion.

The evolution of paleoecological bottom conditions during the lower part of the Zanclean interval was evaluated by a quantitative analysis of the benthic foraminifera assemblage from closely-spaced samples of a borehole drilled at Capo Rossello and from a short segment sampled at the base of the Eraclea Minoa section.

The detailed timing and sequencing of the identified events was calibrated using the sequence of astronomical precessional cycles recorded as relative abundance fluctuations of *Globigerinoides* spp. The reliability of this sequence of fluctuations is supported by the correlation with the calcareous plankton biostratigraphic events which show the same relative abundance fluctuation already recognized in several other Mediterranean coeval sequences.

Fifteen highly correlated paleoecological events have been identified in the benthic foraminifera assemblages, separately analyzed in the >63 μm and >125 μm fractions, in the M Pl 1 stratigraphic interval of the southern Sicilian sections (Tab. 3). They provide evidence for several different, short-lived paleoecological bottom conditions during this approximately 0.23 MA time interval. Some of these benthic foraminifera events (FOs of *C. bradyi*-*C. robertsonianus* and *C. italicus*) have the same stratigraphic position in the 2 sections and in a coeval sequence cropping out on the Jonian coast of Calabria, in the eastern Mediterranean. Furthermore, they are more or less isochronous when compared with the results from the ODP Leg 107 Sites in the Tyrrhenian basin. The *Uvigerina pygmaea-peregrina* Event, characterized by high relative abundance fluctuations of this taxonomic unit, when calibrated to the sequence of precessional cycles (or correlated with the calcareous plankton events) clearly occurs in a shorter time interval in the Capo Rossello and Tyrrhenian areas than in the Jonian basin, where it began 2 precessional cycles below, and ended 2 precessional cycles above, than the event recorded in the 2 other areas. This Event provides evidence for decreased oxygen fluctuating conditions at

the bottom, possibly correlated with the sapropel levels identified at the base of the Pliocene in the eastern Mediterranean basin by the recent ODP Leg 160. We conclude that these under-oxygenated bottom conditions at the base of the Pliocene occurred during a longer time interval in the eastern basin than in the western basin, possibly separated by a sill, tentatively identified as the Malta escarpment.

Compared with the astronomical record (Berger & Loutre, 1991), the time interval characterized by under-oxygenated bottom water conditions in the Roccella Ionica - Capo Spartivento composite sections, which correlates with sapropel levels recently identified at ODP Leg 160 Site 969, straddles an eccentricity minimum, whereas clusters of sapropels in younger Plio-Pleistocene stratigraphic intervals occur in coincidence of eccentricity maxima.

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Appendix.

Species List of More Common Benthic Foraminifera

- Anomalinoidea helicinus* (Costa) = *Nonionina helicina* Costa, 1857
Astrononion umbilicatum Uchio, 1952
Bigenerina nodosaria d'Orbigny, 1826
Bolivina savaenae (Conato) = *Spiroloxostoma savaenae* Conato, 1964

- Cibicoides agrigentinus* (Schwager) = *Discorbina agrigentina* Schwager, 1878
Cibicoides bradyi (Trauth) = *Truncatulina bradyi* Trauth, 1918
Cibicoides dutemplei (d'Orbigny) = *Rotalina dutemplei* d'Orbigny, 1846
Cibicoides italicus (di Napoli) = *Cibicides italicus* di Napoli, 1952
Cibicoides robertsonianus (Brady) = *Planorbulina (Truncatulina) robertsoniana* Brady, 1881
Cibicoides ungerianus (d'Orbigny) = *Rotalina ungeriana* d'Orbigny, 1846
Discorbina bertheloti (d'Orbigny) = *Rosalina bertheloti* d'Orbigny, 1839
Epistominella exigua (Brady) = *Pulvinulina exigua* Brady, 1884
Epistominella rugosa convexa Parker, 1958
Eponides pusillus Parr, 1950
Felsinella diaphana Conato, 1964
Globocassidulina subglobosa (Brady) = *Cassidulina subglobosa* Brady, 1881
Gyroidina soldanii (d'Orbigny) = *Rotalia soldanii* d'Orbigny, 1826
Karrerella bradyi (Cushman) = *Gaudryina bradyi* Cushman, 1911
Lagena gibbera Buchner, 1940
Nonionellina labradorica (Dawson) = *Nonionina labradorica* Dawson, 1860
Oridorsalis stellatus (Silvestri) = *Truncatulina tenera* Brady var. *stellata* Silvestri, 1898
Oridorsalis umbonatus (Reuss) = *Rotalina umbonata* Reuss, 1851
Pleurostomella alternans Schwager, 1866
Pullenia bulloides (d'Orbigny) = *Nonionina bulloides* d'Orbigny, 1846
Pullenia quinqueloba (Reuss) = *Nonionina quinqueloba* Reuss, 1851
Rotamorphina laevigata (Phleger & Parker) = *Valvulinera laevigata* Phleger & Parker, 1951
Sigmoilopsis schlumbergeri (Silvestri) = *Sigmoilina schlumbergeri* Silvestri, 1904
Siphonina reticulata (Czjzek) = *Rotalina reticulata* Czjzek, 1848
Sphaeroidina bulloides d'Orbigny, 1826
Stainforthia complanata (Egger) = *Virgulina schreibersiana* Czjzek var. *complanata* Egger, 1893
Uvigerina auberiana d'Orbigny, 1839
Uvigerina peregrina Cushman, 1923
Uvigerina pygmaea d'Orbigny, 1826
Uvigerina rutila Cushman & Todd, 1941

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