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The age of the Miocene–Pliocene boundary in the Capo Rossello area (Sicily)

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Detailed correlations of magnetostratigraphy, biostratigraphy and lithostratigraphy reveal that the basal Pliocene is equally complete in the Eraclea Minoa and Capo Rossello sections (Sicily) and the Singa section (Calabria), and that, in accordance with the model of the Pliocene flooding event in the Mediterranean, the deposition of the pelagic marls of the Trubi Formation started synchronously on Sicily and in adjacent Calabria. In addition, the data obtained from the Trubi in the Eraclea Minoa section allows the age of the Miocene–Pliocene boundary to be adjusted slightly from 4.83–4.84 [1] to 4.86 Ma because downward extrapolation of both sedimentation rate and average duration of small-scale sedimentary cycles in the Trubi yields this age for the boundary in this section. Linearly interpolated ages for the top of the *Sphaeroidinellopsis* acme and the first substantial increase in *Globorotalia margaritae* (the FOD of this species is non-existent in the Mediterranean Pliocene) at Eraclea Minoa arrive at 4.74 and 4.63 Ma respectively.

Because of the detailed magnetostratigraphy and the very accurate dating of the Miocene–Pliocene boundary, it is preferable to select the Eraclea Minoa section as the boundary stratotype rather than the Capo Rossello section.

Finally, this age of 4.86 Ma for the Miocene–Pliocene boundary suggests that the beginning of the Pliocene is connected with the termination of a series of latest Miocene glaciations and that the re-establishment of open marine conditions in the Mediterranean might be of glacio-eustatic origin.

1. Introduction

The Miocene–Pliocene (M-P) boundary was formally proposed by Cita [2] to be defined at the base of the pelagic marls of the Trubi Formation at Capo Rossello (Sicily). In the boundary stratotype, the Trubi marls abruptly overlie non-marine, silico-clastic sediments of the Upper Messinian Arenazzolo unit. This major break in sedimentary facies reflects the permanent restoration of the Atlantic–Mediterranean connection and the instantaneous return to open marine conditions in the Mediterranean after the Messinian "salinity crisis" [2,3].

Since the basal Pliocene at Capo Rossello [1,4] and in DSDP Site 132 [5] proved to be paleomagnetically unsuitable to establish a reliable magnetostratigraphy, Zijderveld et al. [1] resorted to adjacent southern Calabria and provided the first accurate age estimates for the M-P boundary on the basis of a detailed magnetostratigraphy of the basal part of the Trubi in the Singa and Roccella sections. In Calabria, the boundary was anchored slightly below the base of the Thvera subchron and has linearly extrapolated ages of 4.83 and 4.84 Ma. Outside the Mediterranean, the M-P boundary could be equated with the base of planktonic foraminiferal zone N19 and with carbonate spike GI 14 in the equatorial Pacific [1].

The base of Pliocene pelagic depositional sequences, however, is often diachronous in the Mediterranean [6,7]. This has been related to bottom currents [8], which resulted in periods of non-deposition or even submarine erosion, or to tectonically controlled processes of redeposition [7]. This is especially relevant considering the inferred incompleteness of the basal part of the Trubi Formation at Capo Rossello [7,9,10]. For this reason we decided to investigate in detail whether the basal Pliocene in the Rossello stratotype section is equally complete as in the Calabrian

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Singa section used by Zijderveld et al. [1]. Since magnetic properties in the Rossello stratotype proved unsuitable for establishing a reliable magnetostratigraphy, conclusive evidence was gathered from the nearby Eraclea Minoa section.

2. Miocene–Pliocene boundary sections

The Eraclea Minoa and Rossello sections are situated in a series of cliffs along the south coast of Sicily (Fig. 1) in which the marls of the Trubi are excellently exposed. At both localities, the M-P boundary is characterized by a sharp break between non-marine, finegrained silico-clastic sediments of the Upper Messinian Arenazzolo unit and full-marine Trubi marls of the Lower Zanclean [11]. The lower part of the Trubi at Eraclea Minoa, however, is less weathered and tectonically less disturbed than at Capo Rossello. The Eraclea Minoa section has been sampled at the far end of the camping-site where the steep cliffs are accessible to the top (Fig. 1).

The Singa section in Calabria is that of Zijderveld et al. [1] (Fig. 1). Here, the M-P boundary is materialized by a sharp change-over from Upper Messinian non-marine, coarse grained sediments to full-marine marls of the Lower Pliocene Trubi.

3. Lithostratigraphy and biostratigraphy

3.1. Lithostratigraphy

The most obvious lithological feature of the Trubi are the small-scale sedimentary cycles which are described in detail by Hilgen [12]. In Calabria, these small-scale cycles are usually bipartite and consist of an indurated, whitish-coloured, $CaCO_3$-rich and a grey-coloured, $CaCO_3$-poor marl-bed. On Sicily these small-scale cycles are generally quadripartite due to the intercalation of an additional, beige-coloured, $CaCO_3$-poor marl-bed in the white marls. The small-scale cycles were found to have an average duration of approximately 20 ka and have been interpreted in terms of climatic variations that are induced by the orbital cycle of precession [1,12,15].

High-resolution bed-to-bed correlations in the Trubi of Sicily and Calabria can be obtained on the basis of distinct variations in thickness of the small-scale cycles [12]. The disproportionately thick cycles 6 and 20–22, for example, are excellent marker-beds which have been used to correlate the Calabrian Singa section to the Eraclea Minoa section on Sicily ([12] Fig. 2). The first six cycles of the Trubi are recognizable both in the

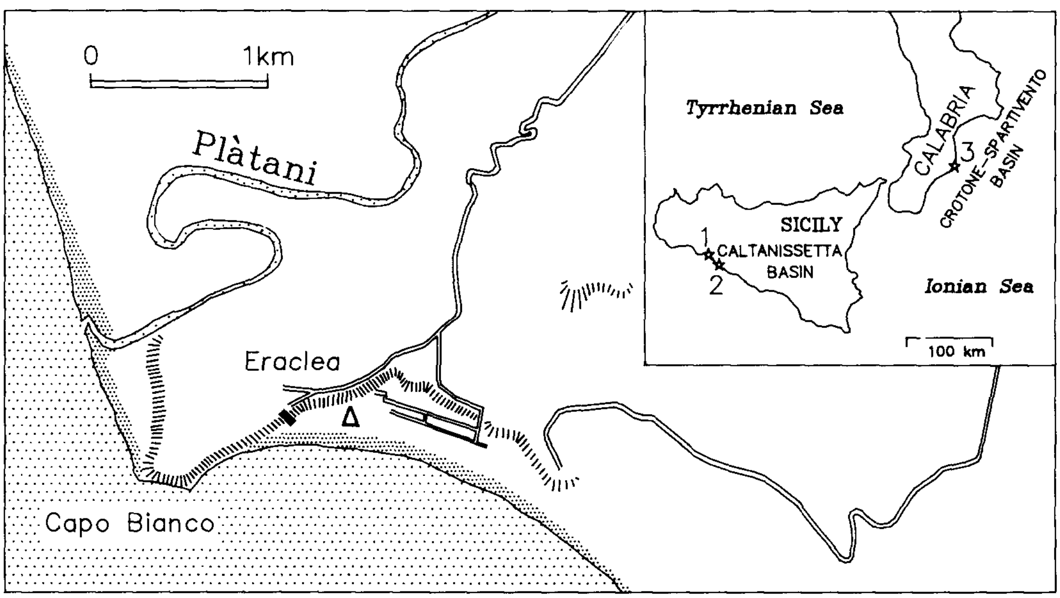

Fig. 1. Location map of the Eraclea Minoa (*1* + detailed map), Capo Rossello (*2*) and Monte Singa (*3*) sections. Triangle denotes the Eraclea Minoa camping-site.

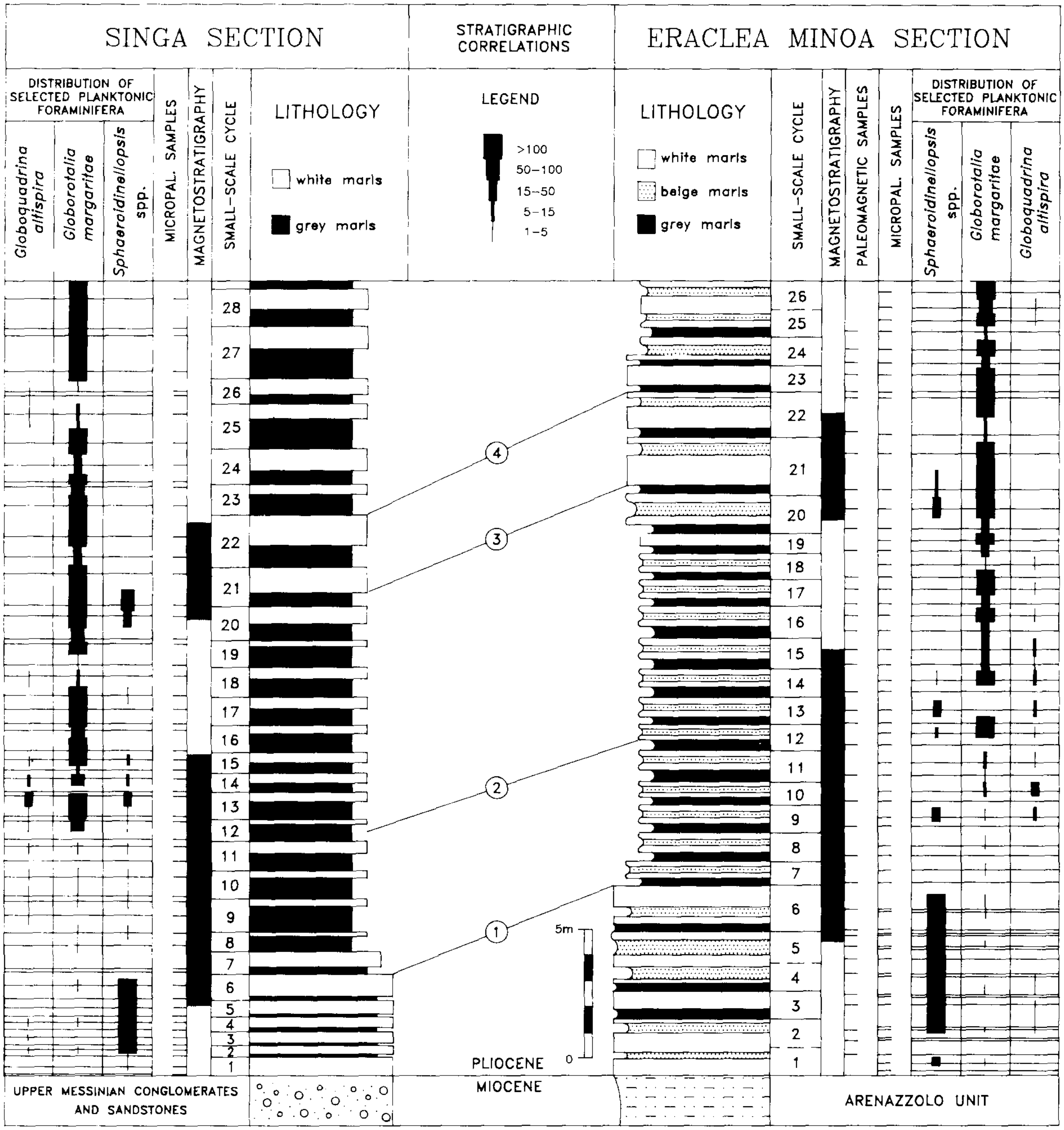

Fig. 2. Magnetostratigraphy, biostratigraphy and lithostratigraphy of the Eraclea Minoa and Singa sections. The magnetostratigraphy and lithostratigraphy of the Singa section is based on Zijderveld et al. [1], the magnetostratigraphy of Eraclea on the data presented in Fig. 5. The two normal polarity zones in the Singa section represent the Thvera and Sidufjall subchrons [1]. The subdivision in small-scale sedimentary cycles is after Hilgen [12]. Cycles 6, 21 are disproportionately thick and are considered to be a composite of 2 cycles. Semi-quantitative faunal data are based on surveying one picking tray of 10,000–15,000 specimens. Numbered stratigraphic correlations refer to (1) top small-scale cycle 6, (2) first substantial increase of *G. margaritae*; (3) cycle 21, and (4) top cycle 22. The top of the *Sphaeroidinellopsis* acme corresponds with top cycle 6.

Singa and Eraclea Minoa section (Fig. 2), but are difficult to distinguish at Capo Rossello (Fig. 3). Nevertheless, the disproportionately thick cycle 6 as well as the well-developed beige marl-beds of cycles 2, 4 and 6 are easily recognized and used to correlate the Eraclea Minoa and Capo Rossello

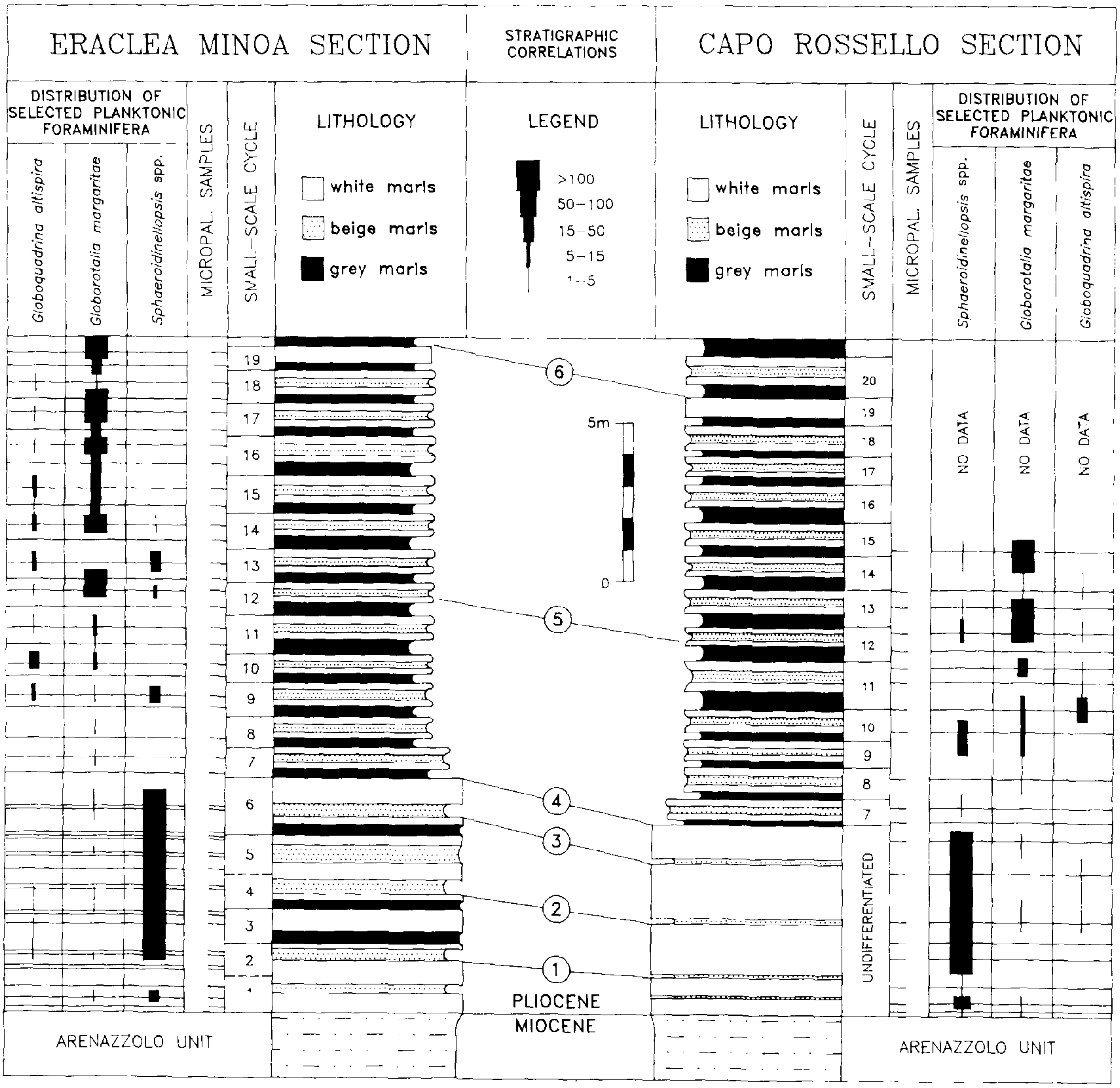

Fig. 3. Biostratigraphy and lithostratigraphy of the basal Trubi at Eraclea Minoa and Capo Rossello. Numbered stratigraphic correlations refer to (1) base beige marls of cycle 2, (2) base beige marls of cycle 4, (3) base beige marls of cycle 6, (4) top cycle 6, (5) first substantial increase of *G. margaritae*, and (6) top cycle 19. The top of the *Sphaeroidinellopsis* acme corresponds with top cycle 6.

sections (Fig. 3). Supportive evidence for this correlation is provided by the absence of the beige marl-bed within cycle 19 in both the Sicilian sections.

3.2. Biostratigraphy

Biostratigraphic correlations between all three M-P boundary sections are possible by using semi-quantitative data on the distribution of the planktonic foraminifers *Sphaeroidinellopsis* spp., *Globorotalia margaritae* and *Globoquadrina altispira* (Figs. 2, 3). The interval with relatively abundant specimens of *Sphaeroidinellopsis* in the basal part of the Trubi is recognizable in all sections and corresponds with the Mediterranean *Sphaeroidinellopsis* Acme-zone [16–18]. The top of this Acme-zone provides a useful biohorizon located between small-scale cycle 6 and 7, whereas the base falls within cycle 2 (Figs. 2, 3). From the base of the Trubi up to cycle 12, *G. margaritae* is rare and discontinuously present. In small-scale cycle 12, *G. margaritae* substantially increases for the first time in all sections providing another useful Early Pliocene biohorizon in the Mediterranean.

4. Magnetostratigraphy

Magnetic properties in the Rossello stratotype section unfortunately proved to be unsuitable for establishing a magnetostratigraphy [1,4]. The magnetostratigraphy of the Singa section has been dealt with in detail by Zijderveld et al. [1]. In this paper we present the paleomagnetic data for the Eraclea Minoa section.

The Eraclea Minoa section has been sampled at 38 levels with an average sampling interval of ca. 75 cm (Fig. 2). At each level we took two cores of 25 mm diameter with an electric drill and a generator as power supply. At most levels it was possible to remove the weathered surface and to drill into fresh (blue-coloured) sediment. Inter-level

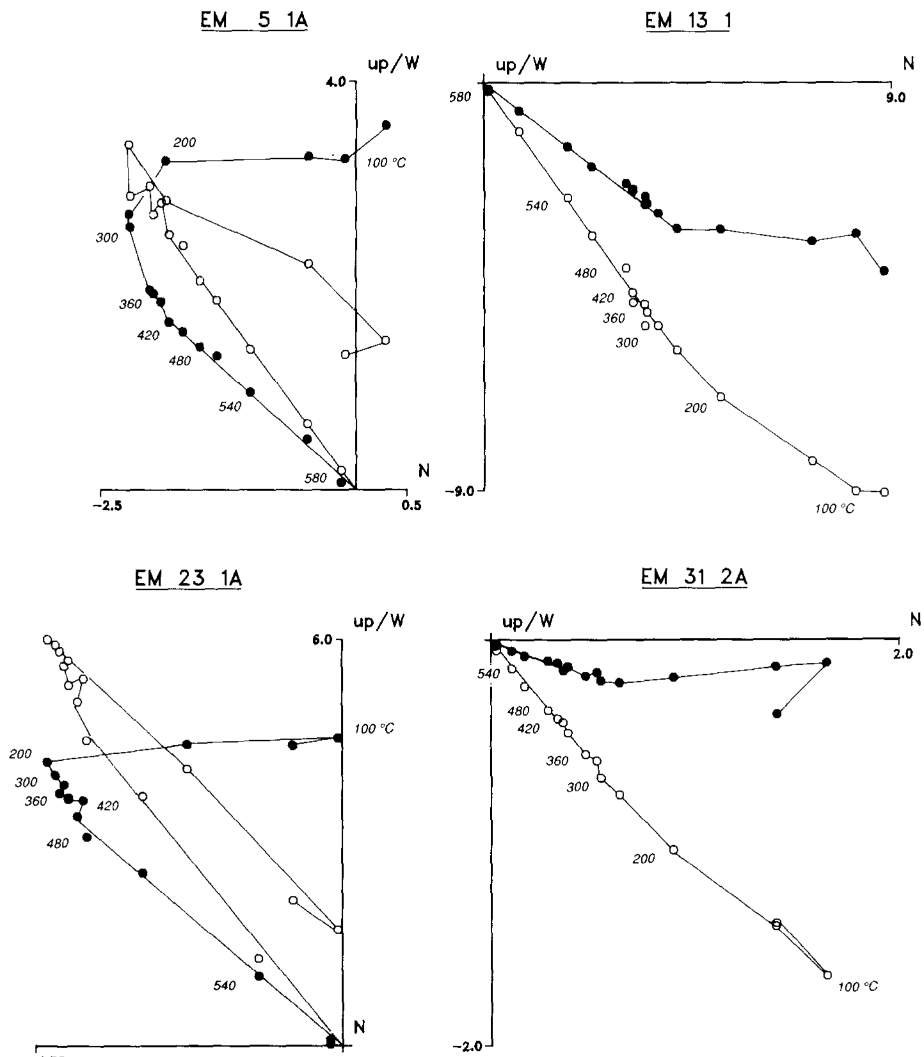

Fig. 4. Representative stepwise thermal demagnetization diagrams [24] of some selected specimens in the Eraclea Minoa section. Small temperature increments are used: 50 ° C increments between 100 and 300 ° C, 30 ° C increments between 300 and 540 ° C, and 20 ° C increments between 540 and 580 ° C. Solid (open) circles denote projection on the horizontal (vertical) plane; units along the axes are in mA/m.

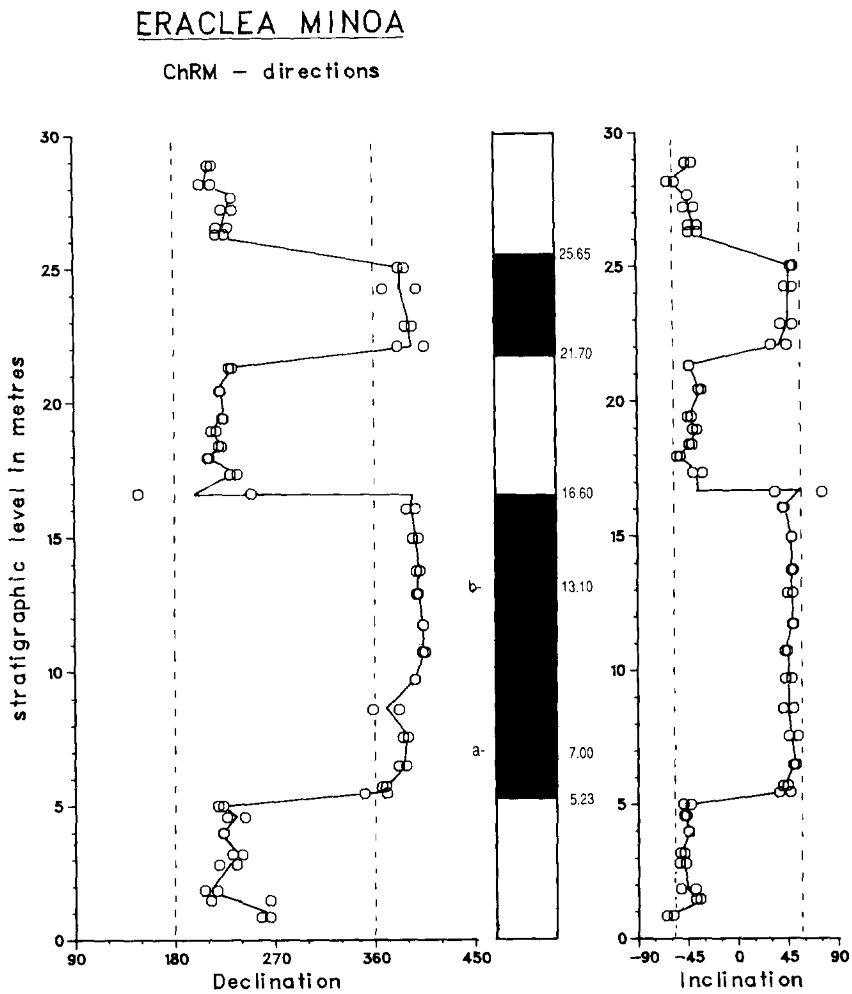

Fig. 5. Declination and inclination of ChRM in the Eraclea Minoa section. Black (white) denotes normal (reversed) polarity. Dashed lines indicate declination and inclination (57.5°) of the geocentric axial dipole field for the present latitude of the locality. Solid lines connect average declination and inclination per sampling level. Positions of polarity reversals and biostratigraphic datum planes (a = top of *Sphaeroidinellopsis* acme, b = first massive increase of *G. margaritae*) are indicated and are based on interpolation between sampling levels, except at the 16.60 m level where intermediate directions are found with a southerly and westerly declination and a positive inclination.

distances were calculated according to Langereis [19].

The natural remanent magnetization (NRM) was measured on a 2G Enterprises cryogenic magnetometer. Total NRM intensities of the Eraclea Minoa section are typically between 1.0 and 20.0 mA/m. Initial measurements revealed mainly normal polarities due to secondary overprint.

Generally two specimens per sampling level were demagnetized progressively by using stepwise thermal demagnetization over small temperature increments. The thermal demagnetizations produce excellent results. A small viscous and randomly directed component is generally removed at 100°C. Another component showing a (normal polarity) present day direction is almost or entirely removed between 100 and 200–250°C and is supposed to be of recent origin (Fig. 4). A characteristic remanent magnetization (ChRM) component consists generally of two phases: a low-temperature (LT) phase removed between 250 and 420°C and a high-temperature (HT) phase removed between 420 and 580°C. In normal polarity specimens the LT and the HT phase have no apparent different directions, but in reversed polarity specimens there is a clear directional difference (Fig. 4). Whether this difference is an artefact (e.g. spectral overlap of different components) or real is still being studied. The HT phase of the ChRM resides most probably in magnetite because of the maximum blocking temperature of 560–580 °C, which suggests that it is of primary origin. The direction of this (HT phase) ChRM component is used for magnetostratigraphic purposes, also because the HT phase clearly shows opposite directions for the two polarities (Fig. 4).

Inclinations of the ChRM (with an average of 46°) are consistently shallower than the inclinations of the geocentric axial dipole field for the locality (57.5°). This might indicate the presence of an inclination error due to sediment compaction and may be taken as additional evidence for the primary origin of the ChRM [20]. Normal and reversed polarity (HT phase) ChRM components in the Eraclea Minoa section are consistently grouped in three reversed and two normal polarity zones (Fig. 5).

Comparison of the results with those for the Singa section [1] (see also Fig. 2) shows that the two normal polarity zones in the Eraclea Minoa section represent the Thvera and Sidufjall subchrons of the Gilbert Chron. The average sedimentation rate per polarity zone is fairly constant (5.7, 5.1 and 5.6 cm/ka from Thvera to Sidufjall), as well as the average duration of the small-scale cycles (18.2, 21.4 and 19.1 ka, respectively, with an overall average of 19.1 ka). Linear downward extrapolation of the Thvera sedimentation rate yields an age of 4.86 ± 0.005 Ma for the M-P boundary (Fig. 6a).

5. Discussion and conclusions

The polarity reversals occur in the small-scale cycles 5, 15, 20 and 22, in both the Eraclea Minoa and Singa sections (Fig. 2), indicating that the basal Pliocene is equally complete in the Singa, Eraclea Minoa and Capo Rossello sections since the number of pre-Thvera cycles is identical (Figs. 2, 3). This conclusion is in line with the beginning of the *Sphaeroidinellopsis* acme slightly above the base of the Trubi in all sections. Consequently, the deposition of the Trubi started at the same time both on Sicily and in Calabria. The linearly extrapolated age of 4.86 Ma for the M-P boundary in the Eraclea Minoa section (Fig. 6A, option I)

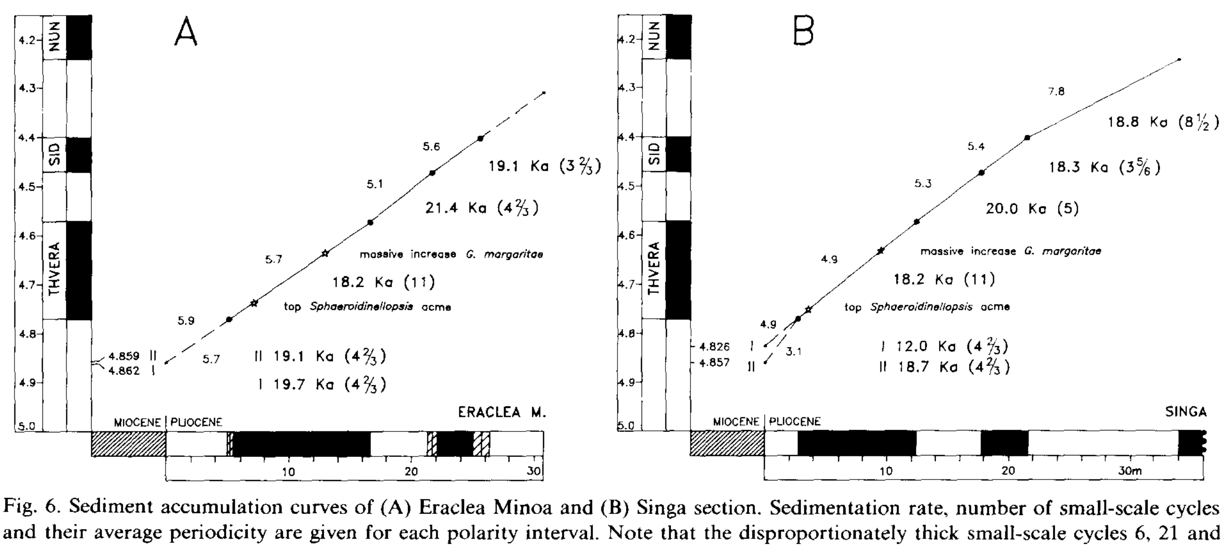

Fig. 6. Sediment accumulation curves of (A) Eraclea Minoa and (B) Singa section. Sedimentation rate, number of small-scale cycles and their average periodicity are given for each polarity interval. Note that the disproportionately thick small-scale cycles 6, 21 and 22 are considered composite cycles which contain an additional small-scale cycle. Various options to calculate the age of the M-P boundary are shown by roman numerals: (I) downward extrapolation of the Thvera sedimentation rate, and (II) downward extrapolation of the average periodicity of 19.1 and 18.7 ka for the small-scale cycles between the base of the Thvera and the top of the Sidufjall subchron in the Singa and Eraclea Minoa sections, respectively. The polarity time-scale used (shown in left columns) is that of Berggren et al. [25].

nevertheless differs slightly from the 4.83 ± 0.01 Ma age estimate for the boundary in the Singa section [1].

In the Singa section, the small-scale cycles in the pre-Thvera part are reduced in thickness compared to the cycles in the Thvera to Sidufjall polarity zones (Fig. 2). Downward extrapolation of the Thvera sedimentation rate, therefore, yields an age of 4.83 Ma for the M-P boundary and an average periodicity of 12.0 ka for the pre-Thvera cycles (Fig. 6B, option I). A periodicity of 12.0 ka, however, deviates strongly from the average periodicity of 18.7 ka for the small-scale cycles between the base of the Thvera and the top of the Sidufjall subchron in this section.

In the Eraclea Minoa section, on the other hand, small-scale cycles are equally thick throughout (Fig. 2), Downward extrapolation of the Thvera sedimentation rate yields an age of 4.86 Ma for the boundary and an average periodicity of 19.7 ka for the pre-Thvera cycles (Fig. 6, option I). A periodicity of 19.7 ka is in good agreement with the average periodicity of 19.1 ka for the small-scale cycles between the base of the Thvera and the top of the Sidufjall subchron in this section.

Downward extrapolation of the average periodicities of 18.7 and 19.1 ka for the small-scale cycles between the base of the Thvera and the top of the Sidufjall subchrons in the Eraclea Minoa and Singa sections (the small discrepancy in periodicity results from differences in sample density) yields an age of 4.86 Ma for the M-P boundary in both sections (Fig. 6A, B, option II). We therefore conclude that the age of 4.86 Ma for the M-P boundary is more accurate than the age of 4.83 Ma. The latter age probably results from a reduced sedimentation rate in the pre-Thvera part of the Singa section (Fig. 6). Indeed, field observations indicate that condensed pre-Thvera sequences are typical for the Trubi in Calabria.

Biostratigraphically, the top of the *Sphaeroidinellopsis* acme and the first substantial increase of *G. margaritae* provide the most reliable and accurate planktonic foraminiferal datum planes in the lowermost Pliocene. Both biohorizons are located within the Thvera subchron and have linearly interpolated ages of 4.74 and 4.63 Ma in the Eraclea Minoa and of 4.75 and 4.63 Ma in the Singa section. This increase of *G. margaritae* has earlier been taken as the migrational appearance of this species in the Meditteranean [1]. However, *G. margaritae* already sparsely occurs directly above the base of the Pliocene (Figs. 2, 3), which confirms earlier findings of Cita [17]. Consequently, the presence of *G. margaritae* at the base of the Trubi does not necessarily imply that the basal part of the Trubi is missing at Capo Rossello as has been suggested by Sprovieri [7,9] and Rio et al. [10]. On the contrary, the completeness of the Trubi in the boundary stratotype of Capo Rossello—as previously suggested by Cita and Gartner [11] and Cita [2]—is now definitively proved both biostratigraphically and lithostratigraphically. The high-quality magnetostratigraphy in the Eraclea Minoa section, however, makes the Eraclea Minoa section definitely more suitable as Miocene–Pliocene boundary stratotype than Capo Rossello (see [2]).

Finally, this age of 4.86 Ma for the M-P boundary supports recent views which link the Pliocene flooding of the Mediterranean to the end of a series of latest Miocene glaciations and the beginning of a long period of relatively warm climatic conditions at approximately 4.8 Ma [21–23]. The Pliocene flooding of the Mediterranean, therefore, could be of glacioeustatic origin. If so, the present age of 4.86 Ma for the M-P boundary provides a very accurate age estimate for this deglaciation event.

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