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The Rossello composite: a Mediterranean and global reference section for the Early to early Late Pliocene

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ABSTRACT

A high-resolution magnetostratigraphy (planktonic foraminiferal) biostratigraphy and cyclostratigraphy is presented for the Pliocene Trubi marls in the Punta di Maiata section on Sicily. The integrated stratigraphy of the Rossello composite section of Hilgen ([1], Newslett. Stratigr., 17, 1987) is thereby completed. This composite section provides an unprecedented high-quality reference section for the Early to early Late Pliocene, containing a continuous sequence ranging from below the Thvera Subchron into the Matuyama Chron (4.86–2.45 Ma).

The Punta di Maiata section extends from the Sidufjall Subchron of the Gilbert into the Gauss Chron (4.50–3.30 Ma). Linear interpolation between paleomagnetic datum planes in this section yields first-order age estimates of 3.72 ($\pm$0.01) and 3.59 ($\pm$0.01) Ma for the last common occurrence (LCO) and the actual last occurrence (LO) of *Globorotalia margaritae*.

In addition, this age of 3.59 Ma provides an accurate age for the Zanclean–Piacenzian (Z/P) boundary, provided the LO of *G. margaritae* is maintained as a criterion to define this boundary in the Mediterranean. Irrespective, however, of the criterion used, the Punta di Maiata and Punta Piccola subsections of the Rossello composite are at present the most suitable sections to be designated as stratotypes for the Z/P boundary. The global significance of the Rossello composite is further strongly enhanced by the establishment of an astronomically calibrated geomagnetic polarity time scale based on the correlation of the Trubi sedimentary cycles with the astronomical record.

1. Introduction

The Italian peninsula has played a prominent role in establishing a standard chronostratigraphic frame for the Pliocene because all stages of global significance have been defined there (see [2]). Age calibration of chronostratigraphic boundaries in Italian stratotype sections to the global time scale have long relied mainly on long-distance biostratigraphic correlations to extra-Mediterranean sequences [3]. Only quite recently have paleomagnetic studies provided reliable magnetostratigraphies for a number of Italian land sections, including the Pliocene–Pleistocene boundary stratotype section [4,5] and several Miocene–Pliocene boundary sections [6–8]. Magnetostratigraphic records have further been presented for the early Late Pliocene on Sicily [9,10] and for a number of deep-sea cores which together cover the complete Plio-Pleistocene in the Tyrrhenian Sea [11].

In this paper, we present new paleomagnetic data from the Punta di Maiata section on Sicily to complete the integrated stratigraphy of the Rossello composite section (that of [1]) and, at the same time, to provide an accurate, first-order age estimate of the last occurrence (LO) of *Globorotalia margaritae* in the Mediterranean. This planktonic foraminiferal datum plane is at present commonly used to delimit the base of the Piacenzian stage in the Mediterranean [3,12,13]. Due to serious stratigraphic problems encountered in the stratotype section of the Piacenzian (see [14]), it became necessary to obtain an accurate age estimate for this important biohorizon in a continuous sequence exposed elsewhere in the Mediterranean, preferably in the stratotype section of the preceding stage, the Zanclean.

2. Sections

Punta di Maiata is a small, but prominent cape in a series of cliffs along the south coast of Sicily

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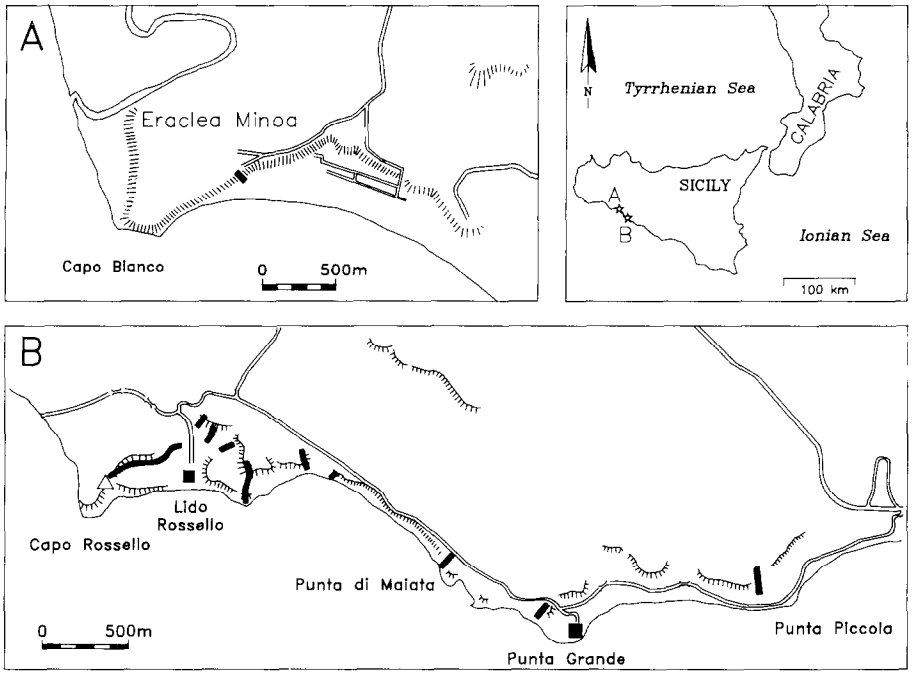


Fig. 1. Location of the Eraclea Minoa, Punta di Maiata, Punta Grande and Punta Piccola subsections of the Rossello composite section of Hilgen [1]. The location of the Miocene/Pliocene boundary annex Zanclean stratotype section of Capo Rossello [15,16] is also indicated.

(Fig. 1). It is located 1 km east of Capo Rossello where the succession of Trubi marls in the Capo Rossello section defines the neostratotype of the Zanclean [15]. In addition, Cita [16] formally proposed the Miocene–Pliocene boundary to be defined at the base of the Trubi in the same section, while there was also a proposal for a Rossellian superstage with the stratotype at Lido Rossello [17].

The Punta di Maiata section forms part of the Rossello composite section of Hilgen [1]. The rhythmically bedded marls of the Pliocene Trubi Formation are excellently exposed and the section contains a complete and relatively undisturbed succession of the Trubi. Problems such as stratigraphic hiatuses [3,15] and unnoticed slump levels [18] are thus avoided. The Rossello composite section is composed of the Eraclea Minoa section (lower part), Punta di Maiata (middle part) and the Punta Grande and Punta Piccola sections (upper part). The various subsections were correlated using characteristic thickness and colour patterns in the cyclic bedding of the Trubi [1]. The magnetostratigraphy, biostratigraphy and cyclostratigraphy of Eraclea Minoa—comprising the Thvera and Sidufjall Subchrons of the Gilbert Chron [7]—and of Punta Grande/Piccola—containing the entire Gauss Chron [9,10]—have already been reported on elsewhere.

Sampling of the Punta di Maiata section started on the beach directly west of the cape, and, after passing a minor but distinct fault, was soon continued on the regular, western side of Punta di Maiata up to the top of the cliffs where the marls of the Trubi are discordantly overlain by Pleistocene terrace deposits (Fig. 2). Three intervals of disturbed Trubi marls in the upper part of the section have been interpreted as sedimentary slumps (Figs. 2 and 3). Sampling was nevertheless continued to reach the Gilbert–Gauss (G/G) boundary in this section and hence to provide a magnetostratigraphic correlation to the Punta Piccola section. In addition, we extended the sampling at Punta Grande slightly upwards to include

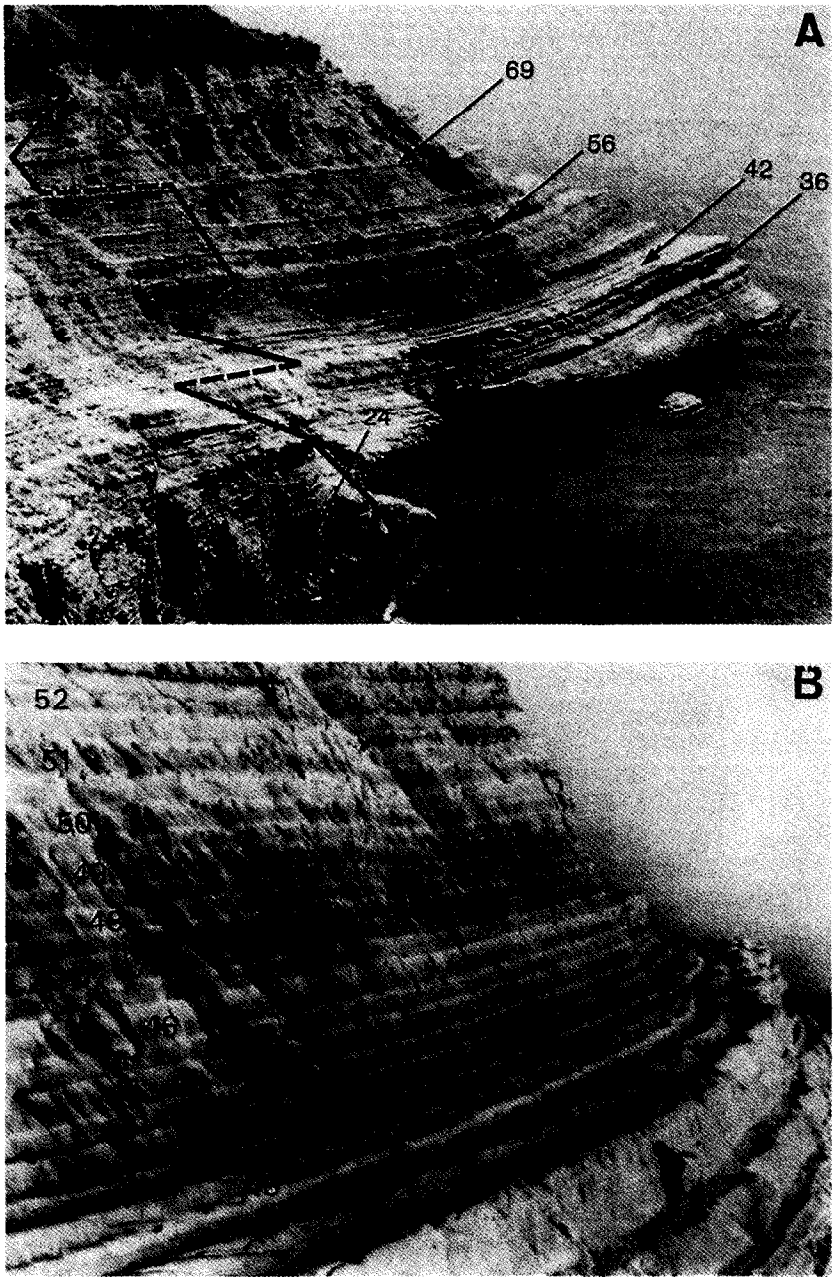
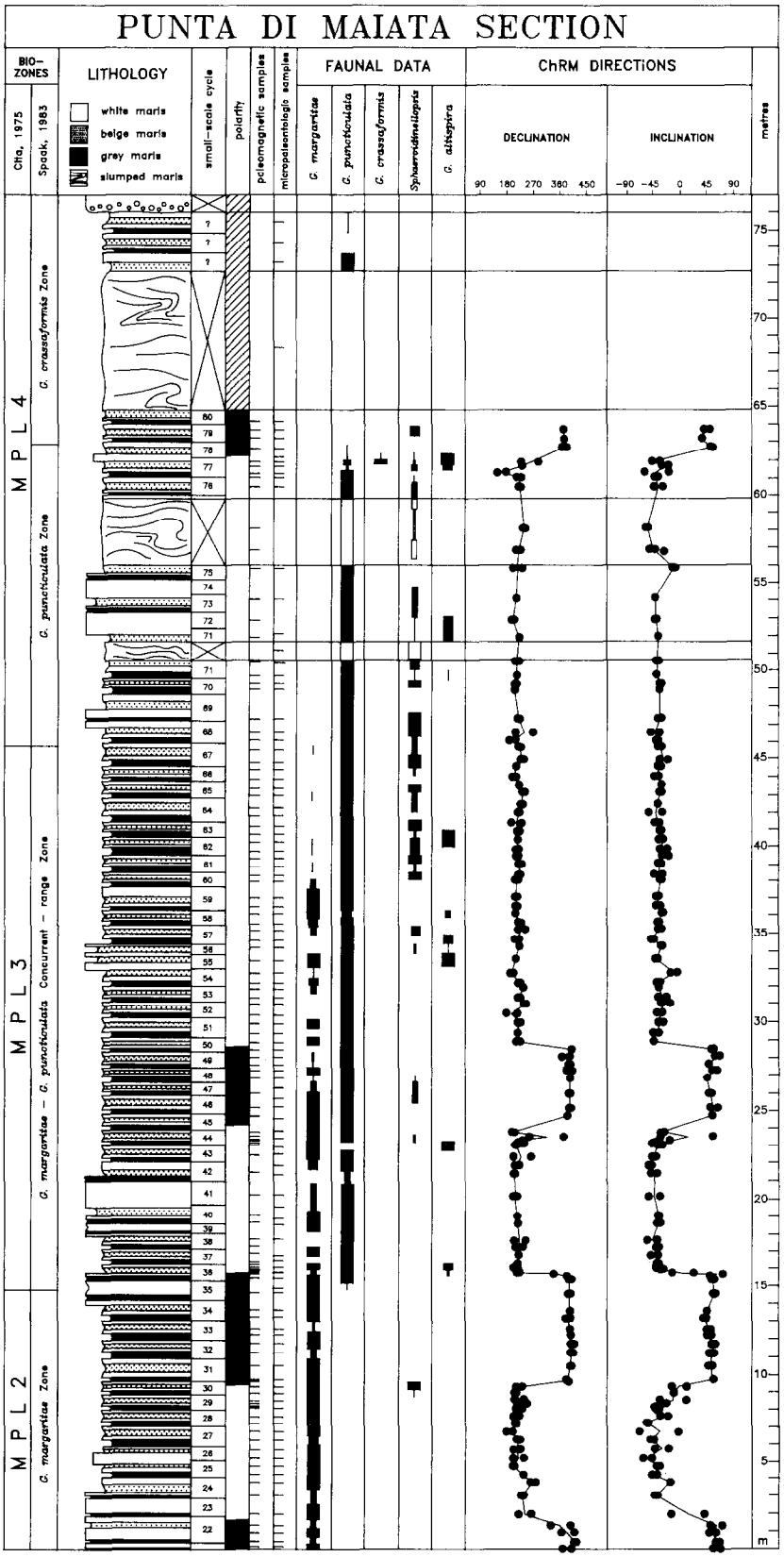


Fig. 2. (A) Western flank of Punta di Maiata. Solid line denotes sampling route. Several characteristic small-scale cycles are indicated. (B) The sedimentary cycles 42 to 52 in the middle part of the section.

the G/G boundary in this section as well. The sampling at Eraclea Minoa was extended to enlarge the overlap with the Punta di Maiata section.

Sampling was carried out following routine Utrecht procedures, i.e. using an electric water-cooled drill and a generator as power supply. Generally, two cores of 2.5 cm diameter were taken per sampling level, yielding two or three standard specimens (22 mm) each. Care was taken to remove the weathered surface, but in the Punta


PUNTA DI MAIATA SECTION
BIO-ZONES
Cita, 1975
Spaak, 1983
LITHOLOGY
white marls
beige marls
grey marls
slumped marls
small-scale cycle
polarity
paleomagnetic samples
micropaleontologic samples
FAUNAL DATA
G. margaritae
G. puncticulata
G. crassaformis
Sphaeroidinellopsis
G. altispira
ChRM DIRECTIONS
DECLINATION
90 180 270 360 450
INCLINATION
−90 −45 0 45 90
metres
MPL 4
MPL 3
MPL 2
G. crassaformis Zone
G. puncticulata Zone
G. margaritae – G. puncticulata Concurrent – range Zone
G. margaritae Zone

Maiata section this proved to be difficult: fresh (blue) sediment could not be sampled at several intervals.

3. Results

3.1. Punta di Maiata

At Punta di Maiata, the marls of the Trubi display the pronounced rhythmic bedding which is characteristic of this formation on Sicily. Small-scale sedimentary cycles—with an average thickness of approximately 1 m—are quadripartite and show a distinct grey–white–beige–white colour alternation in which the grey and beige marls represent the less indurated, $CaCO_3$-poor beds. Larger scale sedimentary cycles can be distinguished by the cyclical recurrence of relatively thick and/or indurated marly intervals in the succession (Figs. 2 and 3; see also [1]). A detailed report on how these $CaCO_3$ cycles in the Trubi are related to the astronomical cycles of the Earth's orbit has already been published: it was shown that the small-scale cycles are related to the precession cycle and thus represent an average duration of 21.7 ka [19].

In the Rossello composite section, the small-scale sedimentary cycles have been numbered from the base of the Trubi upwards [19]. The succession in the Punta di Maiata section up to the first slump level encompasses the small-scale cycles 22 to 71. Numbering of the sedimentary cycles could even be continued up to the third and last slump level based on the recognition of the characteristic pattern of these cycles in time-equivalent sections (Punta Grande, Punta Piccola, Lido Rossello and Capo Bianco; data in part unpublished).

The biostratigraphy of the Punta di Maiata section is based on the semi-quantitative distribution of selected planktonic foraminiferal species (Fig. 3). The following succession of events can be recognized:

(1) The first occurrence (FO) of *Globorotalia puncticulata* in small-scale cycle 35.

(2) The last common occurrence (LCO) of *Globorotalia margaritae* in small-scale cycle 60.

(3) The actual last occurrence (LO) of *G. margaritae* in small-scale cycle 67.

(4) The FO of *Globorotalia crassaformis* in the top part of small-scale cycle 77.

(5) The temporary disappearance of *G. puncticulata* in cycle 79. After its almost continuous presence in relatively large numbers from the FO of this species onward, *G. puncticulata* vanishes temporarily from the record shortly after the first occurrence (influx) of *G. crassaformis* (first absence interval of Spaak [18]).

Paleomagnetic samples were taken at 116 levels with an average spacing of 55 cm, corresponding to a resolution of approximately 10 ka. Grey and beige marls were preferentially sampled because they appeared to be less thoroughly weathered than the white marls in the small-scale sedimentary cycles. Per sampling level, two marl specimens were demagnetized by progressive thermal demagnetization using small (50 and 30°C) temperature steps, up to a maximum of 600°C.

The total natural remanent magnetization (NRM) shows low intensities of 0.1–0.5 mA/m in the lower part of the section (level 0–10 m), somewhat higher intensities of 1.5–2.0 mA/m in a subsequent interval (10–20 m) and moderately high intensities of 4.0–6.0 mA/m in most of the remaining part (20–60 m) with the exception of the uppermost part (60–65 m) where values are approximately 0.2 mA/m.

There are almost no weathered surfaces close to the shoreline. Demagnetization characteristics, however, are essentially different from those of the Trubi marls in the same interval elsewhere. The Trubi marls usually show a characteristic remanent magnetization (ChRM) consisting of both a low temperature (LT) component, possibly resid-

Fig. 3. Magnetostratigraphy, planktonic foraminiferal biostratigraphy and cyclostratigraphy of the Punta di Maiata subsection of the Rossello composite. Note the three slump levels intercalated in the upper part of the section. Numbering of small-scale sedimentary cycles pertains to the total number of cycles of the Trubi in the Rossello composite as numbered from the base of the Trubi upward [19]. Semi-quantitative faunal analysis is based on surveying one picking tray containing between 10,000 and 15,000 specimens. Declination and inclination are derived from the high-temperature (HT) component of the ChRM, except in the lower part where only the LT component is present (see also Fig. 4).

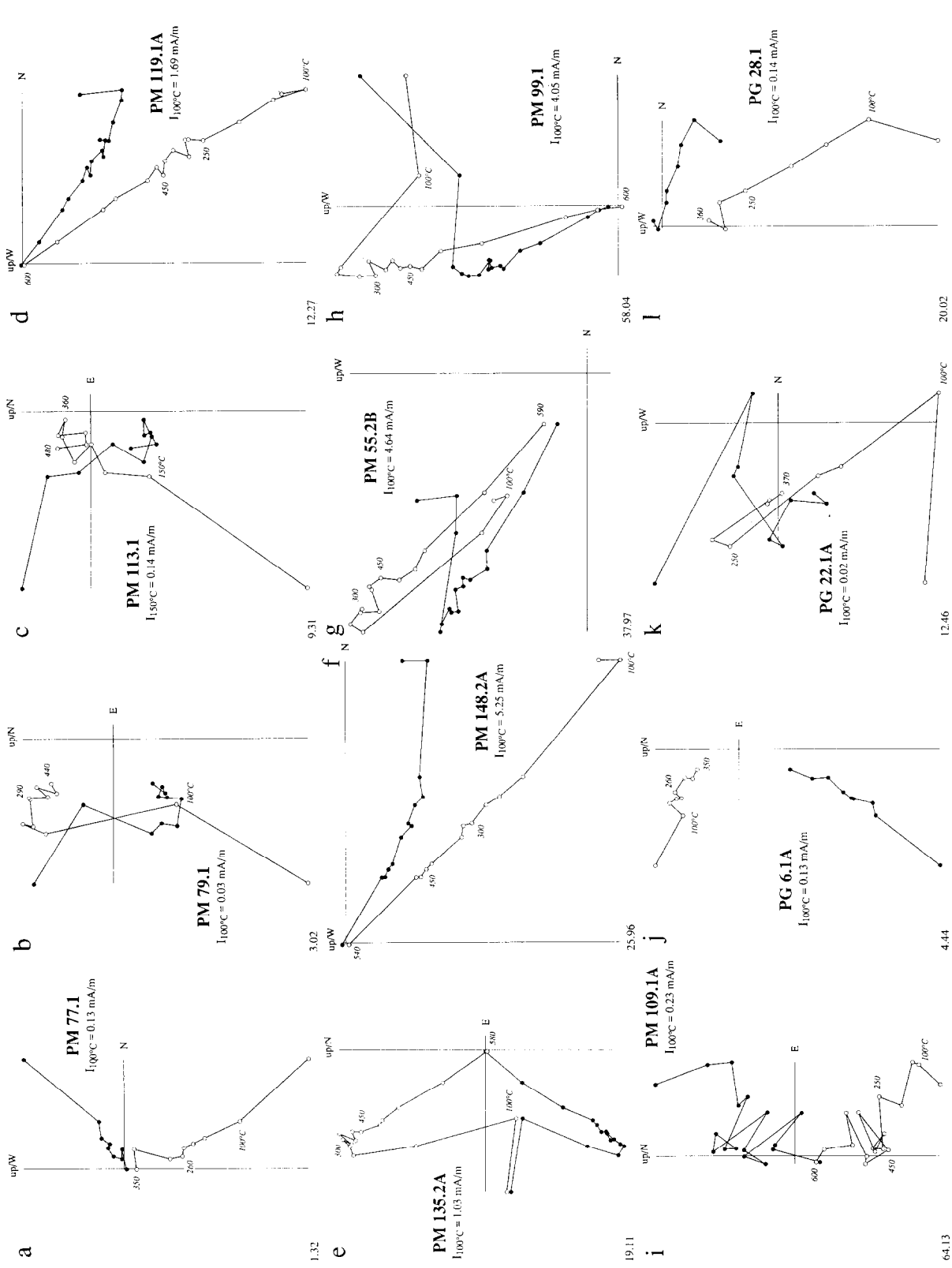


Fig. 4. Stepwise thermal demagnetization diagrams [40] of representative specimens from Punta di Maiata. Dots denote projection on the horizontal plane; circles denote projection on the vertical plane; values are temperatures (°C).

ing in pyrrhotite, as well as a high temperature (HT) component carried by single-domain magnetite [7,9,10,20]. In the lower part of the Punta Maiata section, however, the HT component is entirely or mostly absent, and only the LT component is removed, at temperatures of 350°C or somewhat higher (Fig. 4a and b). Demagnetization at higher temperatures either produces randomly directed (viscous) magnetization, or a cluster around the vector endpoints at 330–360°C (Fig. 4c). Despite the low intensities, the polarity—if not the direction—of the ChRM is easily determined.

Approximately from the 10 m level upwards, demagnetization diagrams show the familiar components usually seen in the Trubi (Fig. 4d–g): a small viscous and laboratory-induced component removed at 100°C, a relatively small present-day field secondary component removed at 200–250°C, and a characteristic (LT and HT) remanence usually removed at 580–600°C, or occasionally at a somewhat lower temperature (540°C, Fig. 4f). The discrimination between ChRM and secondary component is facilitated by the fact that the characteristic remanence shows a consistent clockwise rotation of approximately 35°.

Samples from the second slump level (56–60 m) —deliberately taken from vertically folded layers —not only show exactly the same (viscous, secondary, LT and HT) components, but also the same (reversed) polarity as those from below and above the slump, although the ChRM direction does show a rotation of 65° rather than 35°, and a steeper inclination than usual (Fig. 4h). This indicates that either (synsedimentary) "resetting" of the remanence occurred due to the probably high water content involved in slumping, or that there is a time-lag in recording the geomagnetic field. In either case it probably concerns a post-depositional remanence (see [21]); the mechanism by which geomagnetic field changes are recorded is one of the subjects of detailed polarity reversal studies [41].

The resulting polarity sequence is composed of four normal and three reversed polarity intervals. The successive reversal boundaries occur in the top part of cycle 22, the middle part of 30, the upper part of 35, the lower part of 45, the middle part of 50 and the lower part of 78 (Fig. 3).

3.2. *Eraclea Minoa*

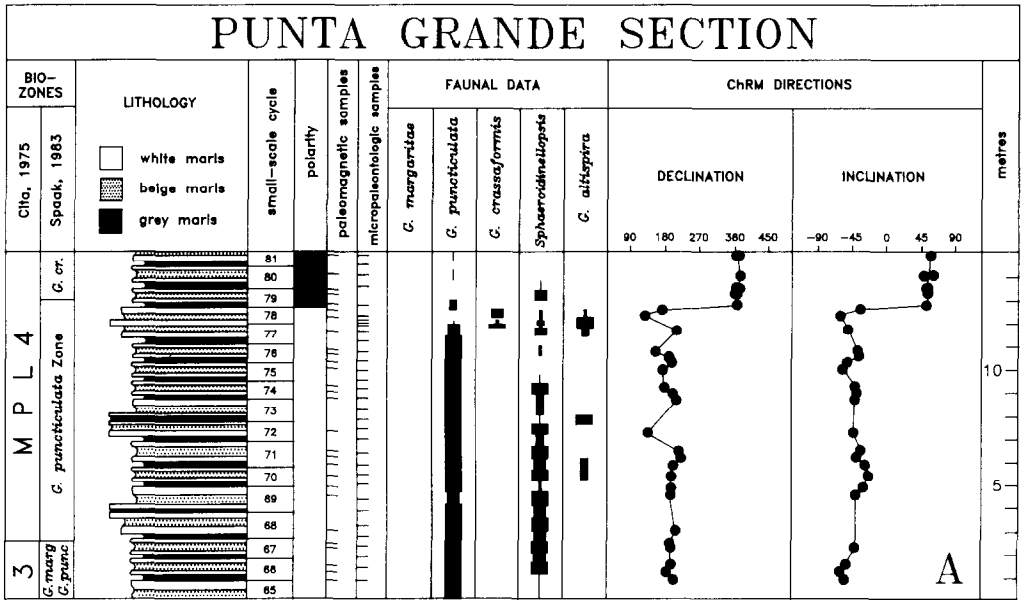
The Eraclea Minoa section has been extended with respect to the earlier sampling [7] in order to provide a more substantial overlap with Punta di Maiata. This extension encompasses cycles 26 to 33 (Fig. 5). Biostratigraphically, the FO of *G. puncticulata* was not reached and the extension thus belongs entirely to the *G. margaritae* Zone [18] or MPL 2 [22]. Thermal demagnetization shows the same characteristic remanence as observed in the previous study, where the polarity sequence revealed the presence of the Thvera and Sidufjall Subchrons. The next polarity reversal, the lower Nunivak, occurs in the middle of sedimentary cycle 30 (Fig. 5).

3.3. *Punta Grande*

The Punta Grande section has been extended upward with respect to the earlier sampling [9] to reach the Gilbert–Gauss (G/G) boundary. The weathering profile of the Trubi in this section is different and in addition the lithology does not show the same distinct grey–white–beige–white colour cycles: grey and beige layers are not easily distinguished, although the white, indurated layers are easily recognized. Nevertheless, lithological correlation with the other subsections of the Rossello composite is quite straightforward [1] and confirmed by the biostratigraphic data. In the gullies, the weathering surface is at most a few centimetres, and fresh, dark blue marl samples could be taken at all levels.

Despite the fresh, unweathered samples, NRM intensities are very low (0.05–0.30 mA/m). Thermal demagnetization shows that the magnetic properties of the (entire) Punta Grande section are very similar to the lowermost part of the Punta di Maiata section: only a LT characteristic component is removed at ca. 350°C (Fig. 4j–l); demagnetization at higher temperatures introduces only random viscous magnetizations. Time-equivalent intervals at Punta di Maiata and at Punta Piccola, in contrast, show the more familiar (LT and HT) and high-intensity components.

The different rock magnetic properties of both the lowermost part of Punta di Maiata (cycles 21–30) and the entire Punta Grande section (cycles 65–81) compared to the same cycles elsewhere may be due to local variations in the magnetic


PUNTA GRANDE SECTION
BIO-ZONES
Cita, 1975
Spaak, 1983
LITHOLOGY
white marls
beige marls
grey marls
small-scale cycle
polarity
paleomagnetic samples
micropaleontologic samples
FAUNAL DATA
G. margaritae
G. puncticulata
G. crassaformis
Sphaeroidinellopsis
G. altispira
ChRM DIRECTIONS
DECLINATION
INCLINATION
metres
MPL 4
G. cr.
G. puncticulata Zone
3
G. marg
G. punc
A

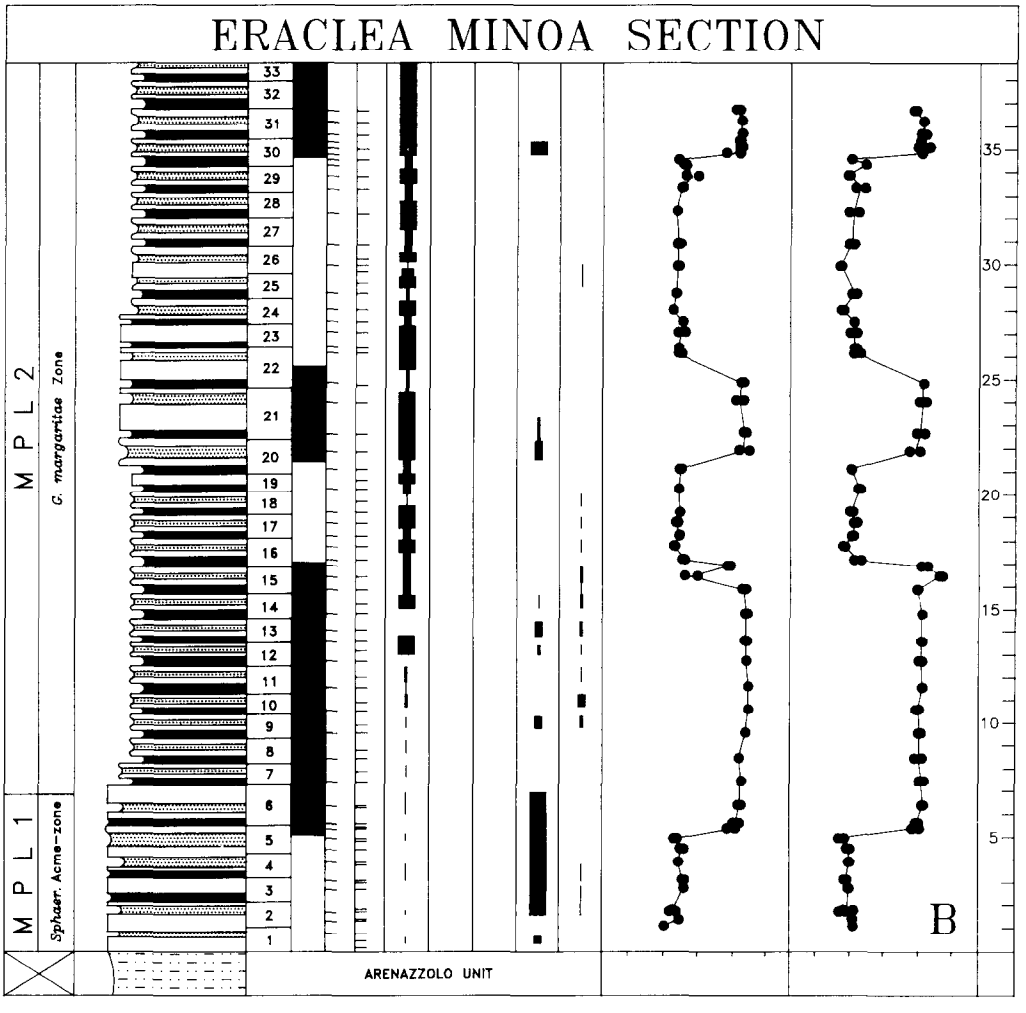

ERACLEA MINOA SECTION
MPL 2
G. margaritae Zone
MPL 1
Sphaer. Acme-zone
ARENAZZOLO UNIT
B

TABLE 1

Ranges and ages of datum levels in the Rossello composite section. Ages of datum planes are presented according to (1) the conventional time scale of Berggren et al. [23] and (2) the astronomical time scale of Hilgen [34]. Ages for bioevents have been calculated by linear interpolation or extrapolation between paleomagnetic reversal boundaries. The age of 2.55 Ma* is taken from Zachariasse et al. [10].

Magnetostratigraphic datum planes		Range	Age 1	Age 2
Gauss/Matuyama		129.94 - 132.79	2.47	2.59 - 2.62
Upper Kaena		103.92 - 104.61	2.92	3.02
Lower Kaena		100.76 - 101.70	2.99	3.09
Upper Mammoth		96.93 - 97.02	3.08	3.21
Lower Mammoth		91.83 - 92.87	3.18	3.33
Gilbert/Gauss		80.37 - 81.10	3.40	3.59
Upper Cochiti		53.39 - 53.84	3.88	4.23
Lower Cochiti		48.74 - 49.65	3.97	4.35
Upper Nunivak		40.72 - 40.80	4.10	4.53
Lower Nunivak		34.25 - 34.54	4.24	4.65
Upper Sidufjall		25.01 - 26.28	4.40	4.85
Lower Sidufjall		21.31 - 22.08	4.47	4.93
Upper Thvera		17.07 - 17.35	4.57	5.03
Lower Thvera		5.00 - 5.45	4.77	5.27
Biostratigraphic datum planes		**Range**	**Age 1**	**Age 2**
N. atlantica	FO	123.34 - 124.04	2.55*	2.67 - 2.70
G. crassaformis	D/S coiling change	109.26 - 110.38	2.78 ± 0.06	2.91 ± 0.01
G. crassaformis	S/D coiling change	106.03 - 106.58	2.84 - 2.89	2.98 ± 0.01
G. crassaformis	D/S coiling change	98.73 - 99.03	3.04 ± 0.01	3.15 - 3.16
G. altispira	LO	98.59 - 98.73	3.04 - 3.05	3.16
S. seminulina	LO	97.33 - 97.52	3.07	3.19 - 3.20
G. crassaformis	S/D coiling change	94.63 - 94.90	3.13 ± 0.01	3.26 - 3.27
G. puncticulata	reappearance	92.86 - 93.31	3.15 - 3.18	3.31 - 3.32
G. crassaformis	reappearance	91.33 - 91.58	3.20 ± 0.01	3.35
G. puncticulata	disappearance	81.62 - 81.79	3.38 ± 0.01	3.57
G. crassaformis	FO	80.36 - 80.63	3.40 ± 0.01	3.59 - 3.60
G. margaritae	LO	70.41 - 71.39	3.56 - 3.59	3.82 ± 0.01
G. margaritae	LCO	62.91 - 63.24	3.71 ± 0.01	4.00 - 4.01
G. puncticulata	FO	39.54 - 39.84	4.12 - 4.13	4.55
G. margaritae	FCO	12.88 - 13.30	4.64 ± 0.01	5.11 - 5.12
Sphaeroidinellopsis	top acme	6.48 - 7.54	4.74 ± 0.01	5.23 ± 0.01
Sphaeroidinellopsis	bottom acme	1.50 - 1.84	4.83 ± 0.01	5.33 - 5.34

carriers or to (presently unknown) secondary processes such as early and/or late diagenesis. The paleomagnetic data of the extended section shows that the G/G reversal boundary can be placed in the basal part of cycle 79 (Fig. 5).

4. The Rossello composite completed

The integrated magnetostratigraphy, biostratigraphy and cyclostratigraphy of the Rossello composite section of Hilgen [1] has been completed with the present study of the Punta di Maiata subsection (Fig. 6). The positions of the reversal boundaries are presented in Table 1. The resultant polarity sequence shows that the Rossello composite extends from below the Thvera Subchron into the Matuyama Chron (Fig. 5).

The results further reveal that the polarity sequence of the Punta di Maiata section ranges from below the upper Sidufjall into the Gauss Chron. The two complete intervals of normal polarity thus represent the Nunivak and Cochiti Sub-

Fig. 5. Magnetostratigraphy, planktonic foraminiferal biostratigraphy and cyclostratigraphy of the extended subsections of Eraclea Minoa and Punta Grande. ChRM directions are based on the HT component at Eraclea Minoa and on the LT component at Punta Grande. See further explanation in Fig. 3.

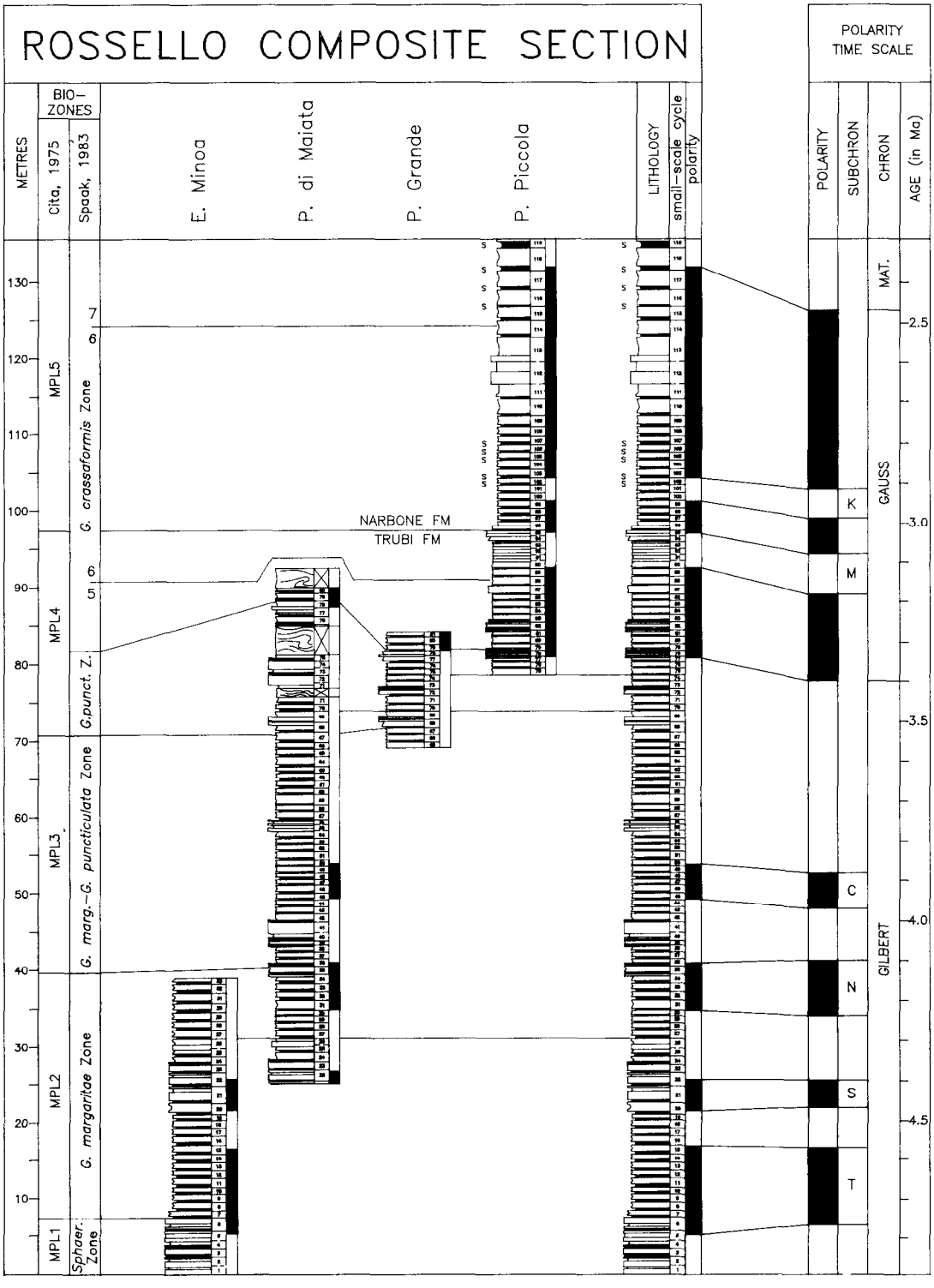


Fig. 6. Integrated stratigraphy of the Rossello composite section showing calibration of the total polarity sequence to the geomagnetic polarity time scale of Berggren et al. [23]. Horizontal lines indicate which part of which subsection has been used for the construction of the composite section. Grey levels marked with *s* in the Punta Piccola section contain brown, laminated ("sapropelic") sediments.

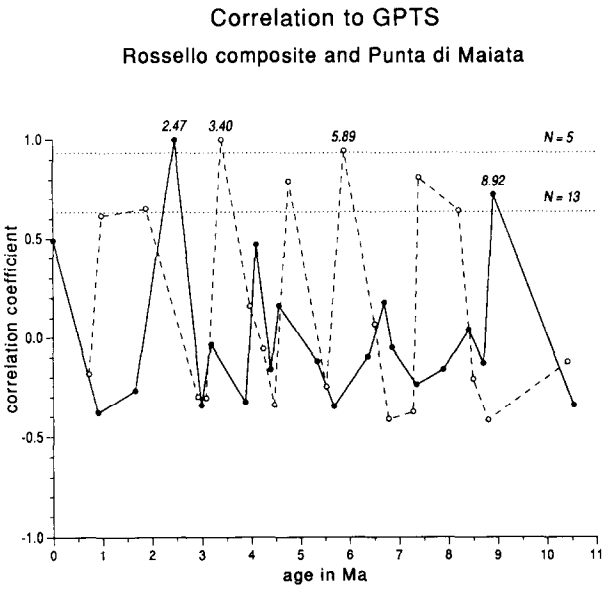


Fig. 7. Correlation coefficients between the lengths of polarity zones in the Punta di Maiata section and the Rossello composite and the durations of each succession of five and thirteen polarity zones from the polarity time scale of Berggren et al. [23] between the Recent and 11 Ma. Dashed line is based on Punta di Maiata (with the exclusion of the slumped intervals), solid line on the Rossello composite section. Values are ages of the youngest reversal in the sedimentary successions which have correlations exceeding the 99% significance level (dotted lines).

chrons. In addition, we have calculated the correlation coefficients between the stratigraphic thicknesses of the polarity zones and the durations of every possible sequence of five polarity zones from the Geomagnetic Polarity Time Scale [23]. This correlation method [24] shows that the highest correlation coefficient corresponds to an age of 3.40 Ma for the youngest reversal boundary in the Punta di Maiata section (Fig. 7) and confirms that this reversal boundary indeed represents the G/G boundary. The same method applied to all thirteen polarity zones in the Rossello composite shows an almost one to one correlation with the polarity time scale if the youngest reversal boundary represents the Gauss/Matuyama boundary with an age of 2.47 (Fig. 7).

The cyclostratigraphic (and biostratigraphic) correlations between the various subsections on which the Rossello composite section was originally based [1] are essentially confirmed by the new paleomagnetic data from Punta di Maiata, Eraclea Minoa and Punta Grande. There is one exception: the exact position of the Gilbert/Gauss reversal boundary at Punta Grande is located in cycle 79, whereas this boundary has been found in cycle 78 at both Punta di Maiata and Punta Piccola (Figs. 3 and 5). This discrepancy could be due to an error in the logging and numbering of the sedimentary cycles, but the (high-resolution) biostratigraphy and the cyclostratigraphy have been thoroughly rechecked and the results exclude this possibility. The low intensities of the Punta Grande section, which are even lower during a polarity reversal, the low intensities in the topmost part of Punta di Maiata and/or the larger sampling spacing together with increased weathering in Punta Piccola during this interval may be responsible for this slight discrepancy. Current research on detailed polarity reversal records in the Trubi, however, is likely to resolve this problem.

5. Ages of bioevents in the Punta di Maiata section

The correlation of the polarity sequence of the Punta di Maiata section to the Geomagnetic Polarity Time Scale [23] enables us to calculate the ages of bioevents by linear interpolation between paleomagnetic datum levels.

The FO of *G. puncticulata* arrives at 4.12–4.13 Ma. This age perfectly agrees with earlier obtained ages of 4.13 and 4.15 Ma in Trubi sections from adjacent southern Calabria [6,8] and confirms once more that this bioevent represents a useful chronohorizon in the Mediterranean.

As far as the last occurrence of *G. margaritae* is concerned, a distinction can be made between the last common occurrence (LCO) of this species and its actual last occurrence (LO, see Fig. 3). Age constraints for both biohorizons, however, are less straightforward because they occur in a polarity interval which contains two (of the three) slump levels (Fig. 3). Linear interpolation would give ages that are slightly too old because these slumps are located higher in the succession than these biohorizons. A more correct age estimate is obtained if these slumps are excluded from the stratigraphic record. Linear interpolation, in that case, yields ages of 3.72 ($\pm$0.01) and 3.59 ($\pm$0.01) Ma for these datum planes. Approximately the same

ages—3.71 (±0.01) and 3.56–3.59 Ma, respectively—are obtained if we use the Rossello composite section in which the interval containing the slumps has been avoided (Fig. 6). This age of 3.56–3.59 Ma for the LO of *G. margaritae* corresponds well to previous, indirect age estimates for this biohorizon in the Mediterranean (3.60 Ma, [3]), but it does not agree with the direct age estimate of 3.50 Ma obtained from Site 652 in the Tyrrhenian Sea (ODP Leg 107, [14]). Our current age shows that the LO of *G. margaritae* in the Mediterranean slightly predates its extinction in the open ocean (3.40 Ma, [25,3]).

Finally, the ages of 3.41 (±0.01) and 3.39 (±0.01) Ma found for the FO of *G. crassaformis* and the temporary disappearance level of *G. puncticulata* at Punta di Maiata confirm earlier results from the Punta Piccola section (3.40 and 3.38 Ma, [9]). The exact position and inferred age of all planktonic foraminiferal biohorizons in the Rossello composite have been summarized in Table 1.

6. The Zanclean/Piacenzian boundary

The age of 3.56–3.59 Ma for the LO of *G. margaritae* also provides an accurate, first-order age estimate for the Zanclean–Piacenzian (Z/P) stage boundary. In recent years there has been almost unanimous consensus in the literature in the use of Barbieri's [26] redefinition of the Piacenzian and to consider the LO of *G. margaritae* as delimiting the Zanclean and Piacenzian stages because this biohorizon coincides with the base of the Piacenzian in its stratotype section [3,12,13]. Since the type Zanclean extended well above the LO of *G. margaritae*, Mazzei et al. [13] redefined its top at the disappearance level of this species, thereby following the recommendations in the International Stratigraphic Guide [27] according to which the top of a stage is defined by the bottom of the next one.

Very recently, however, detailed biostratigraphic studies revealed that a hiatus is present at the base of the type Piacenzian and, as a consequence, that this base does not coincide with the true last occurrence of *G. margaritae* but actually post-dates it (see [14]). This stratigraphic complication evidently demands a revaluation of the Z/P boundary definition.

If the generally accepted, but not formally defined, physical boundary, i.e. the base of the type Piacenzian, is maintained, all sediments spanning the break are automatically assigned to the older Zanclean stage (see [28], p. 111). This approach is rather unfortunate because it hampers easy recognition of the boundary in sections other than the Piacenzian stratotype. The only alternative is to redefine the base of the Piacenzian, in which case the LO of *G. margaritae* may be maintained as a criterion for this boundary. This option implies that the basal part of the Piacenzian is missing in its stratotype and that the boundary should be redefined at the level of the LO of *G. margaritae* in a continuous, well-dated succession. From a biostratigraphical point of view, however, objections can be raised against the use of this biohorizon. The intermittent and rare manifestation of *G. margaritae* above its last level of common occurrence (see Fig. 3) undeniably reduces the accuracy of this bioevent for time-stratigraphic correlations, even within the Mediterranean. Moreover, this biohorizon is demonstrably diachronous from high to low latitudes in the open ocean [29]. Although the LO of *G. margaritae* from the Mediterranean roughly coincides with its final extinction around the G/G boundary [25,30], it actually seems to slightly pre-date it, as previously suggested by Rio et al. [3]. This relatively small age discrepancy—of the order of 150–200 ka—may well be explained by the observed latitudinal diachroneity of this biohorizon.

Rio et al. [14], following the discovery of the hiatus in the Piacenzian stratotype, suggested redefinition of the Z/P boundary close to the G/G boundary to facilitate worldwide recognition. In this case, the FO of *G. crassaformis* is the most suitable planktonic foraminiferal biohorizon for defining this boundary in the Mediterranean. This horizon is accurately dated at 3.40 Ma both at Punta Piccola [9] and Punta di Maiata, and, although it only represents a first, temporary influx of this species in the Mediterranean, it has been recognized in a large number of sections both on Sicily and Crete (see also [18]). Its entry with respect to the adjacent Atlantic Ocean, however, is clearly delayed [9], which greatly reduces its use in long-distance correlations. The only alternative planktonic foraminiferal event in the G/G boundary interval is the LO of *G. puncticulata* (s.s.

Spaak, 1983 [18]) dated at 3.38 Ma. However, according to present taxonomic views, *G. puncticulata* is only temporarily absent from the Mediterranean until its re-appearance at 3.16 Ma in the form of assemblages which are dominated by its eco-morphotype *G. bononiensis*. The final disappearance of *G. puncticulata* from the Mediterranean is much later (2.31 Ma, [10]) and is coincident with the extinction of this species in the open ocean [10,31].

By far the most practical solution, therefore, is to define the Z/P boundary at the level which corresponds with the G/G reversal boundary. Whatever level will finally be proposed to delimit the Zanclean and Piacenzian stages, it is clear that this boundary can best be "stratotypified" in the Rossello composite section. This section contains an excellent and continuous faunal and polarity record across the critical time interval. In addition, the presence of astronomically controlled sedimentary cycles can further be employed to provide highly accurate age constraints for this boundary, as will be dealt with in the next section.

7. The Rossello composite: a Mediterranean and global reference section for the Early to early Late Pliocene

Irrespective of its potential suitability as neostratotype for the Z/P boundary, the Rossello composite section is of global importance because of its significant role in establishing an astronomically calibrated (polarity) time scale.

Hilgen and Langereis [19] provided an alternative polarity time scale for the major part of the Gilbert and Gauss Chrons by using the average (21.7 ka [32]) quasi-period of the precession cycle as the periodicity for the sedimentary cycles in the Rossello composite section. The G/G boundary, dated radiometrically at 3.40 Ma [33], was used as an age reference point.

More recently Hilgen [34] (in this issue in fact) presented an astronomically calibrated (polarity) time scale for the late Gauss to Matuyama by correlating cyclic patterns of sapropels in the Mediterranean to the astronomical records based on the new solutions of Berger and Loutre [35]. This time scale has only one reversal boundary, the upper Kaena, in common with the time scale of Hilgen and Langereis [19]. The new astronomically calibrated time scale can be extended back to the Miocene/Pliocene boundary by adding the age difference of 180 ka observed for this reversal boundary to the ages provided by Hilgen and Langereis [19] for the older polarity reversals. The resultant ages for the reversal boundaries as well as those for the planktonic foraminiferal biohorizons in the Rossello composite are presented in Table 1. These ages must be considered preliminary pending a more exact calibration of the sedimentary cycles in the Trubi to the astronomical record. The employment of the Rossello composite section in constructing the definite version of this time scale is further enhanced by the detailed research carried out on the reversal boundaries in this section (and in other sections of the Trubi—[36] and unpublished data). Although because of their preliminary nature the results of this research have not been incorporated in the present study, it is envisaged that eventually the position of all reversal boundaries in the Trubi will be accurately known with a resolution of at most a few thousand years.

We conclude that the Rossello composite section provides an unprecedented, high-quality reference section for the Early to early Late Pliocene. This reference section does not show the drawbacks of the one based on Site 653 from ODP Leg 107 in the Tyrrhenian Sea, which was drilled with the main purpose of recovering a continuous succession of deep marine sediments that would serve as a "deep-sea type section" for both stratigraphic and paleoenvironmental studies [37]. Unfortunately, Site 653 did not yield a reliable magnetostratigraphy due to unsuitable magnetic properties [38]. Consequently, the chronostratigraphy of Site 653 is mainly based on biostratigraphic correlations to (a very limited number of) magnetostratigraphically controlled sections elsewhere in the Mediterranean [14]. Distinct cyclic bedding has apparently not been observed in the major part of the Pliocene at this site. Moreover, no serious attempts have been made so far to cross-correlate Sites 653A and B. This will be necessary to overcome problematic core recovery at core breaks [see 39] and to obtain a real, continuous succession.

8. Conclusions

The integrated magnetostratigraphy (planktonic foraminiferal) biostratigraphy and cyclostratigraphy of the Rossello composite section of Hilgen [1] has been completed with the present study of the Punta di Maiata subsection. This Rossello composite section contains a complete succession of open, deep-marine sediments, which extends from below the Thvera Subchron into the Matuyama Chron. It provides an unprecedented, high-quality standard reference section for the Early to early Late Pliocene.

Semi-quantitative biostratigraphic data from the Punta di Maiata section allow a distinction to be made between the last common occurrence and the actual last occurrence of *G. margaritae*. Linear interpolation between reversal boundaries yield accurate age estimates of 3.72 and 3.59 Ma for these biohorizons.

The Punta di Maiata section (in the case the LOD of *G. margaritae* being maintained as the boundary criterion) and the Punta Piccola section (in the case of a horizon chosen close to or at the Gilbert–Gauss reversal boundary) are at present the most suitable sections for formally designating the Zanclean–Piacenzian stage boundary.

The global significance of the Rossello composite is greatly enhanced by the fact that a major part of the astronomically calibrated (polarity) time scale for the last 5.5 Ma is based on this section.

To further improve the importance of the Rossello composite, additional studies, for example on stable isotopes and calcareous nannofossils, should be carried out. Sampling or resampling of this section will be greatly facilitated by the characteristic succession of the sedimentary cycles in the Trubi.

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