



ELSEVIER

Tectonophysics 298 (1998) 243–258

TECTONOPHYSICS

# Astronomical dating of a tectonic rotation on Sicily and consequences for the timing and extent of a middle Pliocene deformation phase

C.E. Duermeijer\*, C.G. Langereis

*Paleomagnetic Laboratory, Fort Hoofddijk, Budapestlaan 17, 3584 CD Utrecht, Netherlands*

Accepted 16 July 1998

## Abstract

A detailed palaeomagnetic study of long and continuous middle Pliocene sections from the Caltanissetta basin on Sicily reveals a differential clockwise rotation occurring around 3.21 Ma. The rotation appears to be a rapid event (80,000–100,000 years) which suggests that the responsible tectonic processes also occur rapidly. Its timing corresponds closely to the transition from the Trubi to the Narbone Formation at 3.19 Ma. This transition marks a major change in sedimentary environment on Sicily and in Calabria, and it is coeval, for instance, with the onset of sapropel formation in the eastern Mediterranean. Apparently it marks a synchronous and central–eastern Mediterranean-wide event. Data from the oldest sediments overlying the Tyrrhenian basement (ODP Leg 107) suggest an acceleration in opening of the Tyrrhenian Sea during the middle Pliocene. We speculate that this acceleration is related to a transpressional event in the Sicilian fold-and-thrust belt and extension which formed troughs in the foreland, the Strait of Sicily. Thrust imbrication accompanying the transpressional event on Sicily induced the middle Pliocene clockwise rotation and resulted in shallowing of the Caltanissetta basin causing the change in sedimentation regime characterised by the Trubi–Narbone transition. Following this middle Pliocene tectonic phase, no rotation took place in the southern Apennines, Calabria and Sicily until the middle Pleistocene (1.0–0.7 Ma). © 1998 Elsevier Science B.V. All rights reserved.

*Keywords:* paleomagnetism; tectonic rotation; Mediterranean; Sicily; Pliocene; astronomical dating

## 1. Introduction

During the last decade, detailed studies of the sedimentary cyclicity of Pliocene sequences on Sicily and in Calabria have resulted in high-resolution chronostratigraphic correlations (Zijderveld et al., 1986, 1991; Hilgen, 1987). Integrated magnetostratigraphy, biostratigraphy and cyclostratigraphy have provided a reference framework for the Mediterranean Pliocene (i.e. the Rossello Composite

section; Langereis and Hilgen, 1991). This framework underlies the astronomical polarity time scale (APTS) for the Pliocene (Hilgen, 1991a,b), which is based on the correlation of sedimentary cycles to quasi-periodic variations of precession. Here, we use the most recent APTS of Lourens et al. (1996). The palaeomagnetic data set of the Rossello Composite was used by Scheepers and Langereis (1993) to suggest that a differential rotation of 10° occurred ‘approximately at Kaena times’. The exact timing of this rotation could not be established since the mean directions of the normal and reversed subchrons of the Rossello Composite were not antipodal. Contrary

\* Corresponding author. Fax: +31 (30) 253-1677; E-mail: duermeij@geo.uu.nl

to the older (Gilbert Chron) part of the Rossello Composite, the samples from the younger (Gauss Chron) part showed no or little normal overprint. Their 'overprint correction', which was successfully applied to the older part, could not be used in the younger part since the sense of the non-antipodality was contrary to what was expected from a secondary, present-day overprint (see Scheepers and Langereis, 1993).

The Pliocene is a period of regional contraction within the Sicilian fold-and-thrust belt (Oldow et al., 1990) and extension in the foreland, the Strait of Sicily (Argnani, 1990). Oldow et al. (1990) have demonstrated that large-scale clockwise block rotations during the late Cenozoic accompany the migration of a thrust front towards the Sicilian foreland. Our objective is firstly to confirm the middle Pliocene tectonic differential rotation found in the Rossello Composite and, secondly, to date it more accurately by using the APTS on sections which show no unexplained non-antipodality and were sampled in much greater detail than the previous magnetostratigraphic sampling. We will investi-

gate further whether this rotation phase was a local phenomenon or caused by a major tectonic event with a regional expression. Therefore, two additional middle Pliocene sections containing the Trubi and Narbone formations, Secca Grande and Punta Secca, were selected. The new results are compared to those of the Rossello Composite. Finally, we link this rotation to the geodynamic processes affecting the Sicilian fold-and-thrust belt, the Strait of Sicily and the Tyrrhenian basin during the Pliocene.

## 2. Sections and sampling

Sicily is composed of five main tectonic units: (1) the Ragusa platform which is part of the Apulian plate; (2) the Gela–Catania foredeep; (3) the Caltanissetta basin; (4) the northern Sicilian fold-and-thrust belt; and (5) the Peloritani units which belong to the Calabro–Peloritani block (Fig. 1). The Rossello Composite is located in the Caltanissetta basin and is composed of three cliff sections along the southwest coast of Sicily, i.e. the Eraclea Minoa, Punta di Ma-

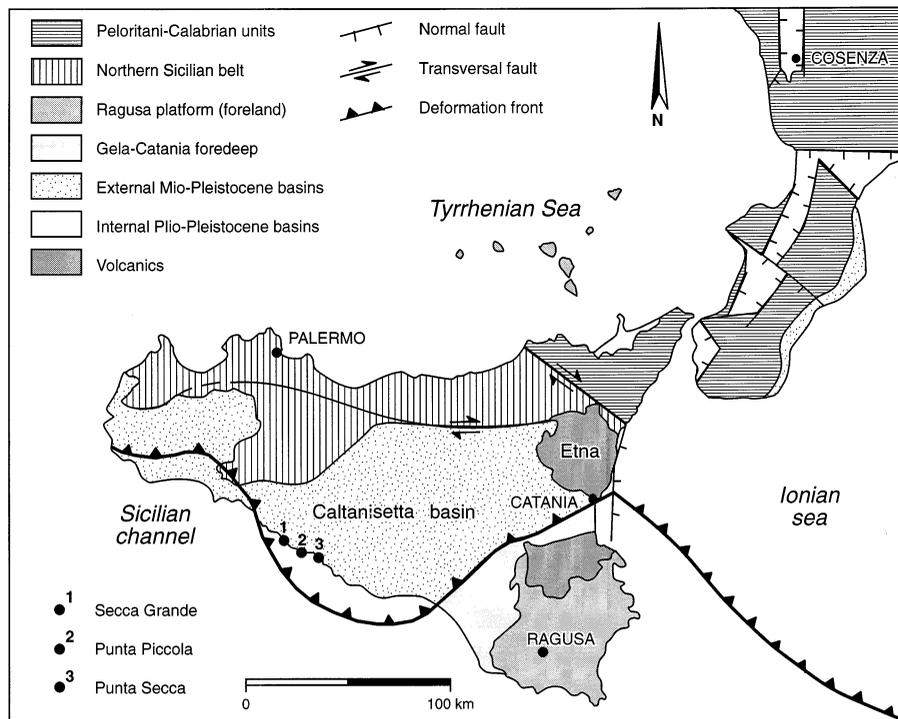


Fig. 1. Structural map of Sicily with the sections studied: Secca Grande, Punta Secca, and Punta Piccola.

iata and Punta Piccola sections. The Rossello Composite contains the Trubi and Narbone formations. The Lower to middle Pliocene Trubi Formation consists of carbonate-rich, rhythmically bedded grey to white marine marls (Hilgen, 1987). Fossil assemblages indicate that these sediments were deposited at a depth of 500–800 m (Brolsma, 1978). The Trubi Formation is overlain by the Upper Pliocene to Lower Pleistocene Narbone Formation represented by rhythmically bedded, relatively carbonate-poor, marly clay with sapropel layers, deposited at shallower depths of 100–400 m (Brolsma, 1978). Both formations were studied in two additional sections: Punta Secca and Secca Grande (Fig. 1). Punta Secca is a cliff section along the southwest coast of Sicily in the Caltanissetta basin, near the village of Siculiana. The section contains a small, well constrained fault, approximately at the Gauss–Matuyama boundary. The Secca Grande section is located between the village of Ribera and the coast. The top of the Secca Grande section is locally formed by an olistostrome. Therefore, it was extended upward at the opposite side of the valley, near the village of Ribera, where no olistostrome is present. During a first field visit the Secca Grande and Punta Secca section were sampled with two levels per sedimentary (precession-related) cycle, corresponding to a resolution of approximately 10,000 years. During a second visit, the Trubi–Narbone boundary interval was sampled in Secca Grande (with a 10 cm spacing) to date accurately any differential rotation. Palaeomagnetic coring was carried out following routine procedures, using an electric, water-cooled drill and a generator as power supply. Care was taken to remove the weathered surface and to drill fresh sediments.

### 3. Palaeomagnetic results

#### 3.1. Rock magnetic properties

Some rock magnetic tests were performed to identify the carriers of the remanent magnetisation. Bulk susceptibilities were measured on a KLY-2 Kappabridge; they were typically  $200 \times 10^{-6}$  SI and are quite constant throughout the Secca Grande and Punta Secca sections. Acquisition of an isothermal remanent magnetisation (IRM) was measured on a

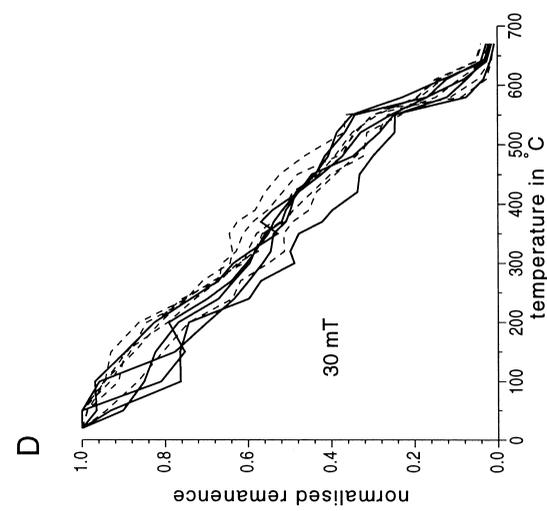
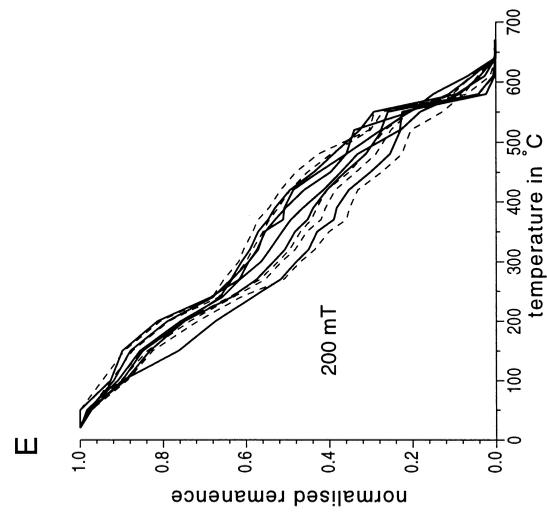
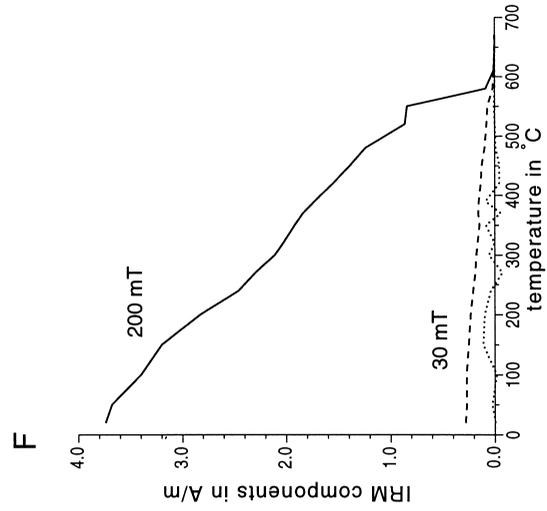
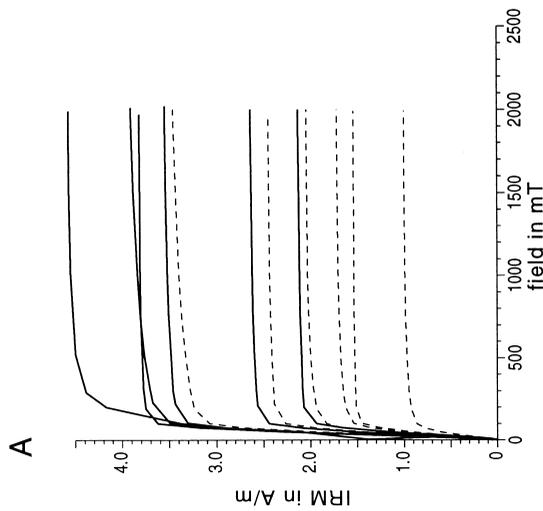
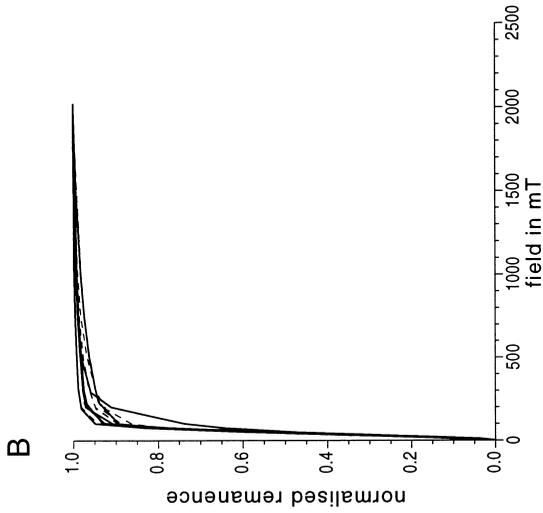
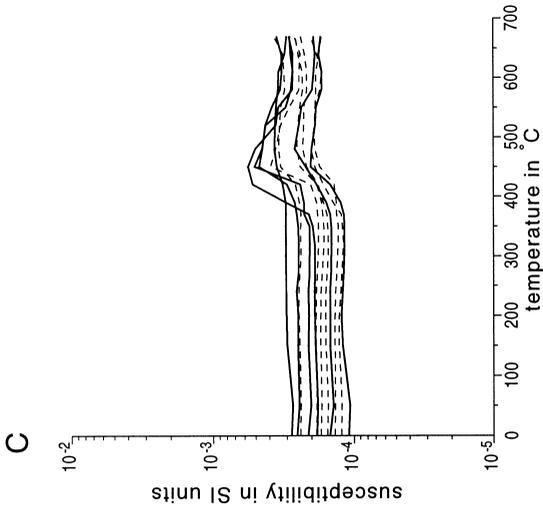
digitised spinner magnetometer based on a Jelinek JR3 driver unit. An IRM was induced in three orthogonal directions (Lowrie, 1990) using fields of 30 mT, 200 mT and 2 T in a pulse magnetiser, and subsequently thermally demagnetised. These fields were chosen as most appropriate on the basis of the typical magnetic characteristics of these marine marls (e.g. van Velzen and Zijdeveld, 1990). After each temperature step the low-field susceptibility was measured.

The Secca Grande and Punta Secca sections reveal the same magnetic carriers. The steep initial rise and the acquisition of 90–95% of the saturation IRM (SIRM) at 100 mT (Fig. 2A,B) indicates magnetite to be the dominant magnetic carrier. A small percentage (~5%) of the SIRM is acquired at fields higher than 300 mT and indicates that a high-coercivity mineral is also present. All samples show an increase in low-field susceptibility (Fig. 2C), just below 400°C caused by oxidation of pyrite which produces magnetite. Thermal demagnetisation of the 3-axis IRM (Fig. 2D–F) shows that the remanence is mostly carried along the 200 mT axis. Typically, samples show maximum unblocking temperatures close to 580°C and indicative of magnetite, but often temperatures are above 600°C, indicating the presence of maghemite.

#### 3.2. Thermal demagnetisation

Thermal demagnetisation of the natural remanent magnetisation (NRM) was performed using a magnetically shielded, laboratory-built furnace; measurements were done on a 2G Enterprises DC SQUID cryogenic magnetometer. A total of 679 specimens from the Punta Secca and Secca Grande section was demagnetised, using small temperature increments between 30° and 50°C. Demagnetisation diagrams (Zijderveld, 1967) and least-square fitting of lines (Kirschvink, 1980) through selected data points were used to determine the NRM components. The magnetisation vectors were averaged using Fisher (1953) statistics to calculate mean directions per interval/polarity zone.

The demagnetisation behaviour of the sections studied is similar. Representative demagnetisation diagrams show a small randomly oriented laboratory-induced component removed at 100°C (Fig. 3).



Occasionally, a secondary component caused by weathering and with a present-day field direction before bedding tilt correction is present; it is removed at temperatures between 100° and 250°C. A characteristic remanent magnetisation (ChRM) component is removed at temperatures between 570° and 600°C. It shows both normal and reversed polarities and a linear decay towards the origin. In the Secca Grande section, almost all NRM intensities (30–170 mA/m) of the ChRM-component are one order of magnitude larger than the NRM intensities found in the Punta Secca section. This difference is related to the fact that Secca Grande consists of the Trubi Formation and lower part of the Narbone Formation, with typically high intensities and a stable magnetite-dominated magnetomineralogy (Langereis and Hilgen, 1991), while most of the Punta Secca is much younger and consists of the upper part of the Narbone Formation (shallower marine). Intensities are typically as those found by Zijdeveld et al. (1991) in the time- and facies-equivalent Narbone Formation in southern Calabria. The differences in intensities are caused by the different sedimentary environment (see also van Velzen et al., 1993). Demagnetisation of the NRM above approximately 390°C may result in randomly directed components (Fig. 3E,F) which were not used for the calculations.

The ChRM directions and polarity zones of the Secca Grande section (Fig. 4) show that five polarity intervals are recorded. In the Punta Secca section (Fig. 5) the ChRM directions reveal seven polarity zones, where the Punta Piccola section (Scheepers and Langereis, 1993) contains six zones.

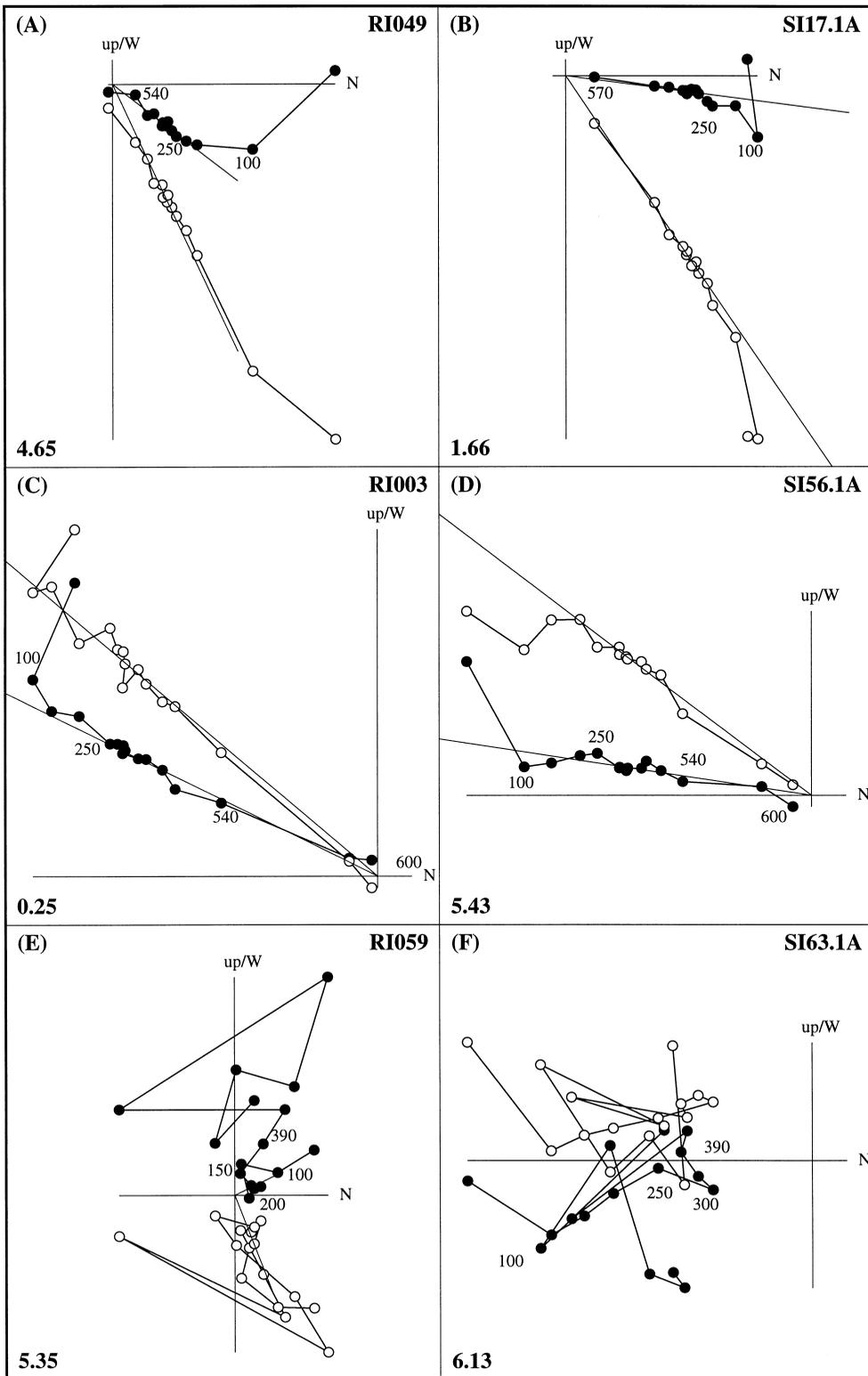
### 3.3. Differential rotations

Scheepers and Langereis (1993) found a differential clockwise rotation of 10° in the Punta Piccola section of the Rossello Composite. Their data revealed an uncertainty in age of the rotation between the Gilbert–Gauss boundary and the youngest normal subchron (C2An.1n) of the Gauss. Although

the normal and reversed mean ChRM directions were not antipodal, they suggested approximately Kaena times as the best age estimate. This is slightly younger than the transition from Trubi to Narbone between cycle 95 and 96 at an age of 3.19 Ma in subchron C2An.2n (Langereis and Hilgen, 1991; Lourens et al., 1996). The Punta Piccola section covers the uppermost part of the Gilbert Chron to the lowermost part of the Matuyama Chron. The Secca Grande and Punta Secca sections can be correlated bed-by-bed to the Rossello Composite on the basis of their cyclostratigraphy and magnetostratigraphy. The reversals in the two sections are located in the same cycles as in the Rossello Composite. The lowermost normal polarity zone of the Secca Grande section is subchron C2An.3n, the uppermost zone represents subchron C2An.1n, whereas the reversed zones are the Mammoth and Kaena subchrons (Fig. 4). Even though the Punta Secca section contains a small fault approximately at the Gauss–Matuyama boundary, the results confirm that, from bottom to top, the subchrons Mammoth to C1r.2r are present (Fig. 5).

The palaeomagnetic results from the Secca Grande section indicate a differential clockwise rotation of 10°, from 32° in the Mammoth subchron to on average 22° in the C2An.2n and Kaena subchrons (Figs. 6 and 7). The mean declinations of C2An.2n and Kaena are exactly antipodal, although the inclinations slightly differ. The upward extension of the Secca Grande section, at the opposite side of the valley, has a significantly larger absolute rotation (declination is 35° and inclination is 42.9°;  $N = 39$ ,  $k = 92.6$ ,  $\alpha_{95} = 2.4$ ) than the post-Mammoth part of the Secca Grande section (22°). The results of Secca Grande indicate that the differential clockwise rotation must have taken place in a short time considering the change in the average declination over a small interval that encompasses the Mammoth–C2An.2n boundary. The rotation can thus be accurately dated, within an interval of approximately four or five cycles (80,000–100,000 years) around the boundary between the Mammoth and subchron

Fig. 2. (A and B) Examples of IRM acquisition of samples from the Secca Grande (solid lines) and Punta Secca (dashed lines) section. (C) The low-field susceptibility measured during stepwise thermal demagnetisation. (D and E) Thermal demagnetisation along the 30 mT and 200 mT axis, respectively. (F) An example of thermal demagnetisation of the 30 mT (dashed line), 200 mT (solid) and 2.0 T (dotted) orthogonal induced IRM components. Note that the remanence mainly resides in the 200 mT axis.



C2An.2n which has an astronomically dated age of 3.21 Ma. The Trubi–Narbone transition, astronomically dated at 3.19 Ma, falls within this rotational interval. These results from Secca Grande agree with the earlier estimate (between 2.58 and 3.60 Ma) of the tectonic rotation in the Rossello Composite.

In the Punta Secca section, a differential rotation could not be substantiated because only a very limited number of samples could be taken from the Trubi. Furthermore, no differential rotation in the Punta Secca section was found up to the Early Pleistocene, if we exclude the palaeomagnetic data near the observed fault (i.e. all data below 40 m; Fig. 4). The mean direction is  $D_{\text{mean}} = 21.9^\circ$ ,  $I_{\text{mean}} = 44.0^\circ$  ( $N = 15$ ,  $k = 110.4$  and  $\alpha_{95} = 3.7$ ).

### 3.4. Anisotropy of magnetic susceptibility

Analysis of the anisotropy of the magnetic susceptibility (AMS) can be used to establish the sedimentary and tectonic history in weakly deformed sediments (Tarling and Hrouda, 1993). Basically, the AMS of a rock is described by a second-order tensor, visualised as an ellipsoid having three principal axes ( $k_{\text{max}}$ ,  $k_{\text{int}}$  and  $k_{\text{min}}$ ). In undeformed sediments, the magnetic susceptibility is characterised by an oblate ellipsoid, with foliation coinciding with the bedding plane. Hence, the magnetic fabric is purely depositional or related to compactional loading with the  $k_{\text{min}}$  axes perpendicular to the bedding plane and the  $k_{\text{max}}$  and  $k_{\text{int}}$  axes scattered in the bedding plane itself. In case of small deformation acting on the rock, the  $k_{\text{max}}$  axes cluster in the direction of maximum extension, or perpendicular to the maximum compression and the  $k_{\text{min}}$  is still perpendicular to the bedding plane. An increase of strain changes the oblate ellipsoid into a prolate structure. Therefore, oblateness (here  $L-1/F-1$ ; with  $L/F$  as lineation/foliation) is used to indicate deformation, and the clustering of the  $k_{\text{max}}$  axes to indicate the direction of extension (and indirectly the compression-direction).

The AMS fabric in the Secca Grande, Punta Secca and Punta Piccola sections has oblate ellipsoids for

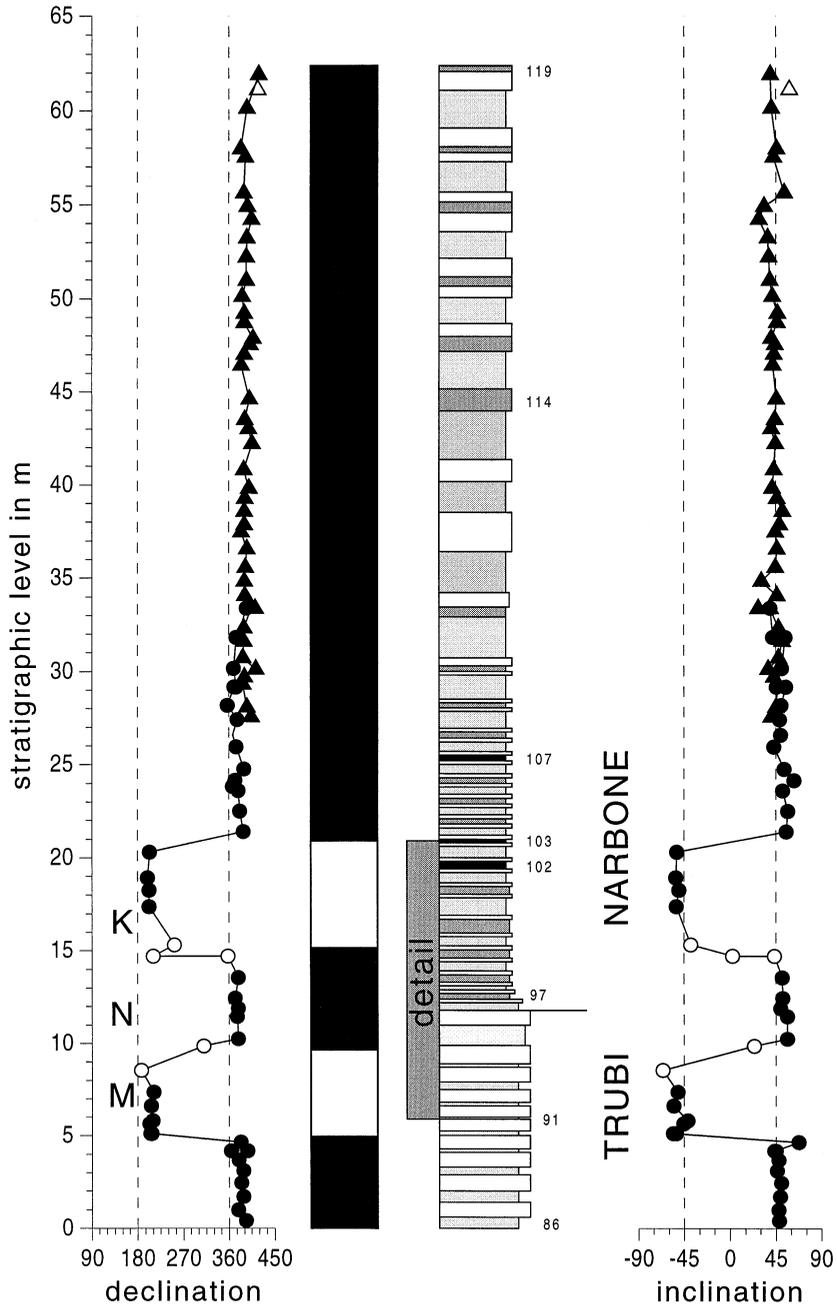
nearly all samples. The lineation and foliation are rather constant throughout the three sections (Secca Grande  $L_{\text{mean}}$  and  $F_{\text{mean}}$  both 1%; Punta Secca and Punta Piccola both  $L_{\text{mean}} = 0.5\%$ ,  $F_{\text{mean}} = 2\%$ ). The AMS ellipsoid in both the Trubi and the Narbone formations of the Secca Grande and Punta Secca sections display  $k_{\text{max}}$  axes aligning E–W, indicating a N–S compression, and (sub)vertical  $k_{\text{min}}$  axes (Fig. 8). In the Punta Piccola section the  $k_{\text{max}}$  axes align NE–SW indicating a NW–SE compression. Although the  $k_{\text{max}}$  directions in Secca Grande (166 samples) seem more dispersed than in Punta Secca (73), there is a clear clustering of the vast majority of the samples, giving small error ellipses and a well defined average lineation direction. In all three sections no noticeable change in compression/extension direction is present around the interval where the differential rotations occur.

## 4. Discussion

The previous palaeomagnetic study by Scheepers and Langereis (1993) indicated a clockwise rotation ‘approximately at Kaena times’. The better constrained clockwise rotation around 3.21 ( $\pm 0.05$ ) Ma in the Secca Grande section replaces their earlier estimate. Our results imply a middle Pliocene regional event in the Caltanissetta basin where a tectonic rotation coincides with a change towards a more shallow environment. This tectonic phase is not restricted to Sicily; elsewhere in the Mediterranean there is evidence for major changes at the time of the Trubi–Narbone transition. For example, in ODP Leg 160 Sites 967 and 969 in the eastern Mediterranean, the formation of the first sapropels starts directly after the Trubi–Narbone boundary (Kroon et al., 1998), representing a change to periodic anoxic bottom water conditions. The first sapropels at Punta Piccola, Punta Secca and Secca Grande are slightly younger ( $\pm 100,000$  years) which may be caused by a higher threshold value for sapropel formation in the Caltanissetta basin. The transitions (i.e. both the Trubi–

Fig. 3. Orthogonal projections of stepwise thermal demagnetisation of selected samples from the Secca Grande (RI) and Punta Secca (SI) section. Closed (open) circles represent the projection of the NRM vector endpoint on the horizontal (vertical) plane. Values indicate temperatures in °C; stratigraphic levels are shown in the lower left corners.

# Secca Grande ChRM-directions



Narbone transition and the first sapropel formation in the eastern Mediterranean) point to a major reorganisation in basin configuration and/or a fundamental change in climatically induced palaeoceanographic conditions. Around the same time, a major tectonic event caused an increase in uplift rates and large-scale tilting to the north on Crete (Meulenkamp et al., 1994). In northern Italy, Mary et al. (1993) found a hiatus between the upper part of the Gilbert up to the lower part of the Kaena. Their ChRM directions imply a rotation phase falling within this hiatus; the part below the hiatus shows a considerable counterclockwise rotation, whereas the younger part has no significant rotation, roughly constraining the age of this differential rotation. These regional tectonic events, seemingly unrelated, can now be correlated on the basis of an accurate chronology.

The ChRM directions from the long, continuous Punta Secca section indicate no differential rotation until the Early Pleistocene. Also in Calabria and in the southern Apennines (Scheepers et al., 1993, 1994) no evidence of any differential rotation was found, from the middle Pliocene to the early-middle Pleistocene. Scheepers (1994) suggested that an additional clockwise rotation phase must have occurred between the middle Pliocene and early-middle Pleistocene on Sicily, because he found smaller clockwise rotations in the early-middle Pleistocene ( $15^\circ$ ) than in the middle Pliocene ( $25^\circ$ ). This is not conclusive, however, because local tectonics may disturb recognition of regional tectonic effects. A good example is the extension of Secca Grande on the opposite side of the valley: ChRM directions show a statistically different absolute rotation, which can only be explained by local tectonics. This demonstrates the importance of establishing a differential rotation within a continuous section rather than from isolated outcrops. Finally, Scheepers (1994) finds a rotation phase between 1.0 and 0.7 Ma in Sicily, Calabria and the southern Apennines. We conclude that no rotation occurred along the entire Tyrrhenian arc

between the middle Pliocene (3.2 Ma) and middle Pleistocene (1.0–0.7 Ma).

Previous palaeomagnetic research on the Trubi and Narbone formations (Van Hoof and Langereis, 1991) has shown that delayed NRM acquisition may significantly disturb a record of rapid geomagnetic field changes that occur during a polarity reversal. Since delayed acquisition may cause a reversal to appear older, the timing of the rotation phase may be in error by one or two precession cycles (20,000–40,000 years). The reversals of the Secca Grande and Punta Secca sections are located, however, in the same cycles as in the Rossello Composite. There is no age discrepancy with the APTS which is based on the Rossello Composite and has been corrected for delayed NRM acquisition (Lourens et al., 1996). Thus, the results show a true differential clockwise rotation phase around 3.21 Ma and this age replaces the earlier estimate of Scheepers and Langereis (1993). Furthermore, there is no geographical trend in timing of the differential clockwise rotation phase from Secca Grande to Punta Secca and finally to Punta Piccola.

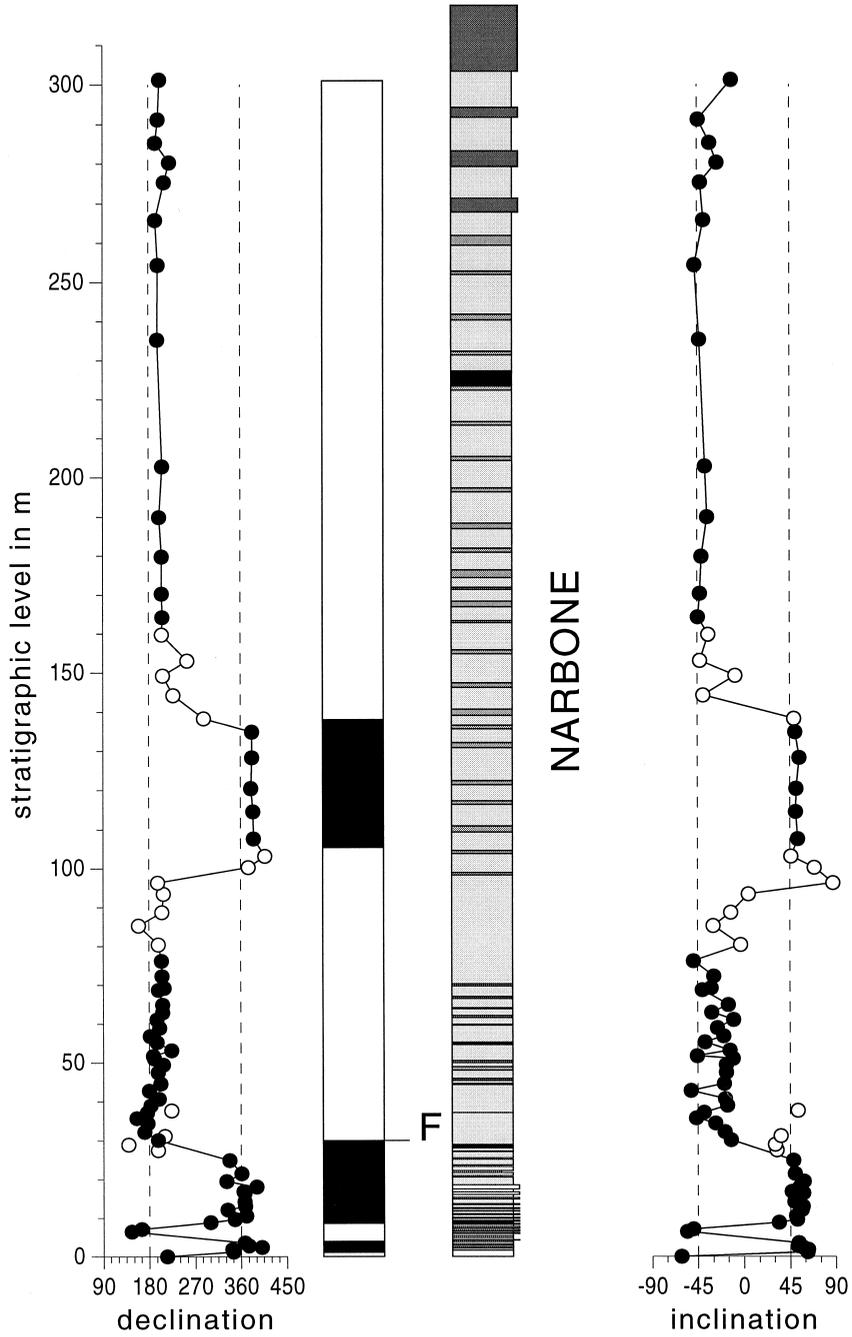
#### 4.1. Geodynamics

A structural study associated with palaeomagnetic data (Oldow et al., 1990) indicated that large-scale clockwise rotations of thrust sheets on Sicily occurred during the Late Miocene–Pliocene. This was accompanied by a progressive shift in tectonic transport direction from east to south (Oldow et al., 1990). The timing of thrust imbrication and rotations was closely bracketed. Moreover, detailed seismic and structural studies have revealed a Pliocene transpressional event for the Sicilian fold-and-thrust belt (Catalano et al., 1976, 1996). The Strait of Sicily forms the foreland of Sicily and also reveals evidence of middle Pliocene tectonics (Catalano et al., 1995). This foreland contains half-grabens opened by extension, later filled and structurally inverted

Fig. 4. Magnetostratigraphy of the Secca Grande section, including the upward extension (triangles) and detail set (shaded area with 166 samples); *K* = Kaena; *N* = normal, C2An.2n; *M* = Mammoth); see also Figs. 6 and 7. Closed circles represent reliable directions, open circles represent low-intensity samples and no linear decay towards the origin (see text). In the polarity column black (white) denotes normal (reversed) polarity zones. In the lithological column grey shading indicates beige marls in the Trubi Formation, whereas in the Narbone Formation dark grey/black represents brown sapropels; white indicates white marls. Numbers represent cycle numbers of the correlative small-scale cycles in the Rossello Composite section (Langereis and Hilgen, 1991).

# Punta Secca

## ChRM - directions



### Secca Grande detail

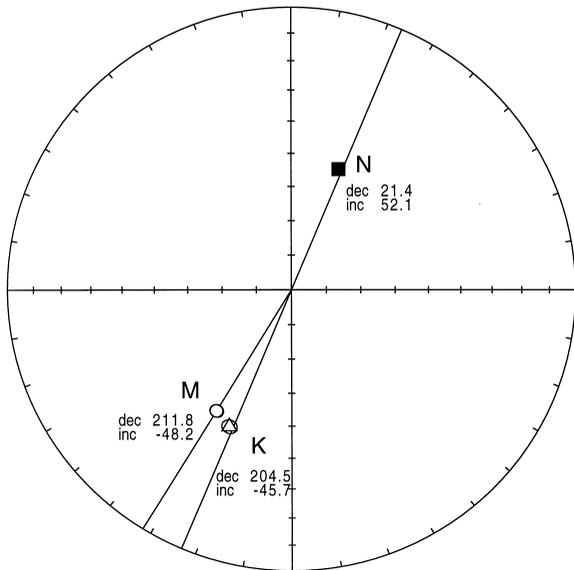


Fig. 6. Mean directions of ChRM-components (the Secca Grande set) are shown in an equal-area projection, indicating a 9° differential clockwise rotation; K = Kaena ( $N = 34$ ,  $k = 140.7$ ,  $\alpha_{95} = 2.1$ ); N = normal, C2An.2n ( $N = 58$ ,  $k = 161.6$ ,  $\alpha_{95} = 1.5$ ); M = Mammoth ( $N = 35$ ,  $k = 166.9$ ,  $\alpha_{95} = 1.9$ ) see also Figs. 4 and 7. *Dec (inc)* indicates declination (inclination); combined Kaena and normal: declination 22.4°, inclination 49.7°;  $N = 92$ ,  $k = 103$ ,  $\alpha_{95} = 1.5$ .

because of a change in stress field implying compression along a N–S axis (Catalano et al., 1993). Contractural structures on Sicily and extensional structures in the Sicilian foreland are coeval (Oldow et al., 1990). Contractural deformation of the Sicilian fold-and-thrust belt (Catalano et al., 1996) and extension in the Strait of Sicily (Argnani, 1990) is linked to extension in the Tyrrhenian Sea. Between

Fig. 5. Magnetostratigraphy of the Punta Secca section. Closed circles represent reliable directions, open circles represent low-intensity samples and no linear decay towards the origin (see text). In the polarity column black (white) denotes normal (reversed) polarity zones. In the lithological column light (dark) grey represents beige (grey) marls; in the top part of the section, dark grey indicates sand layers. *F* = a small fault (see text). The lowermost reversed zone represents the Mammoth, the second the Kaena. The uppermost normal zone represents the Olduvai, wherein we find the Plio–Pleistocene boundary.

### Secca Grande detail

#### ChRM - directions

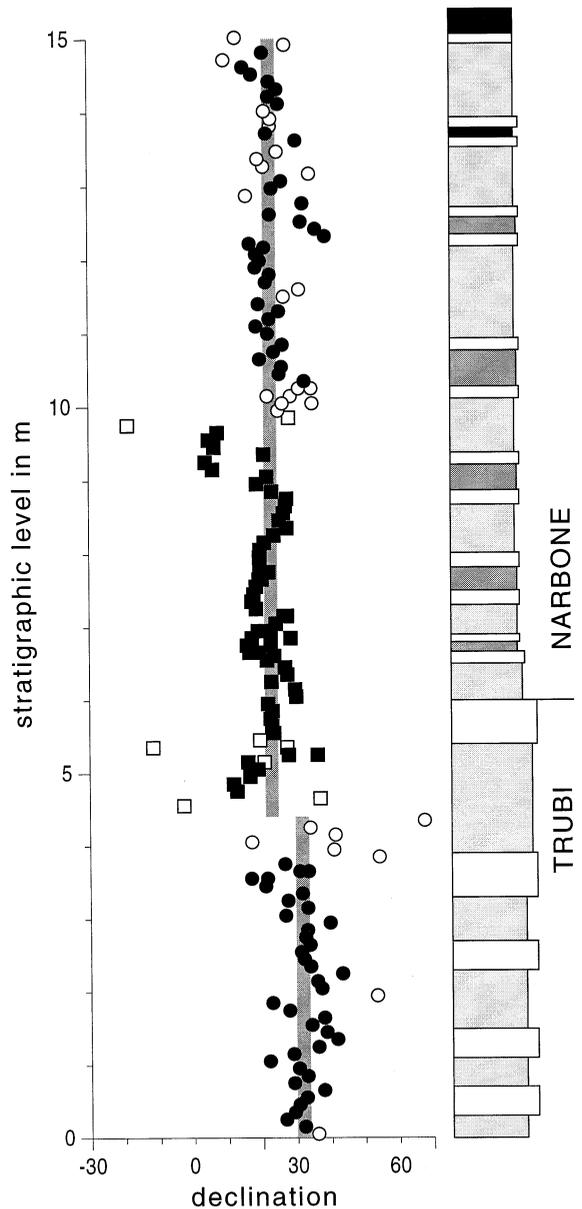


Fig. 7. Declinations of the ChRM directions of the Secca Grande detail set (see also Figs. 4 and 6). Shaded bands are the mean directions with their  $\alpha_{95}$  for the Mammoth subchron and the normal + Kaena subchrons, respectively. Open symbols indicate the low-intensity samples; circles are the inverted ChRM directions. Lithological column see caption Fig. 4.

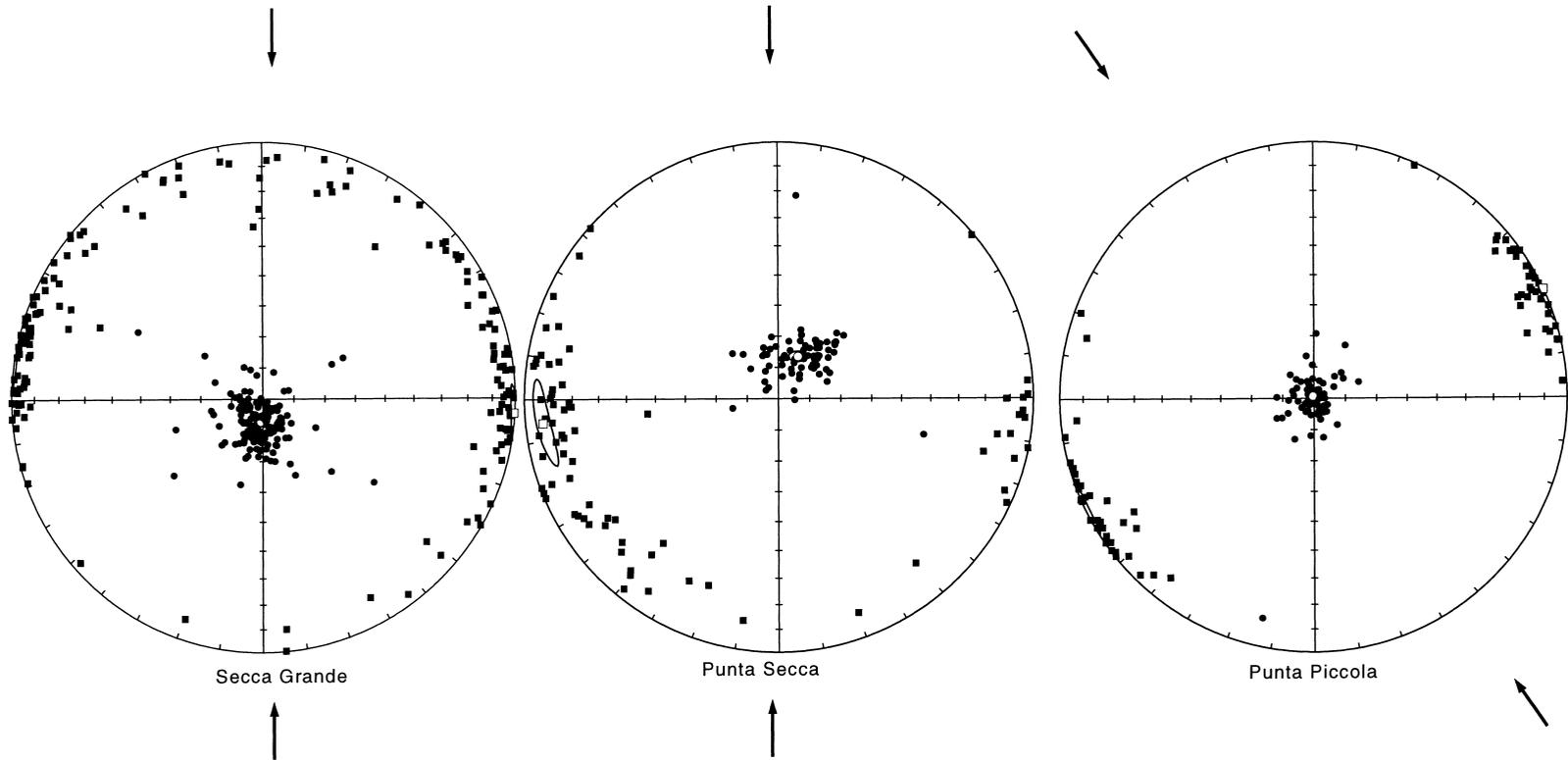


Fig. 8. The equal-area projections (after bedding correction) show the anisotropy of the sections with  $k_{\min}$  (circles) and  $k_{\max}$  (squares). Arrow indicates compression direction.

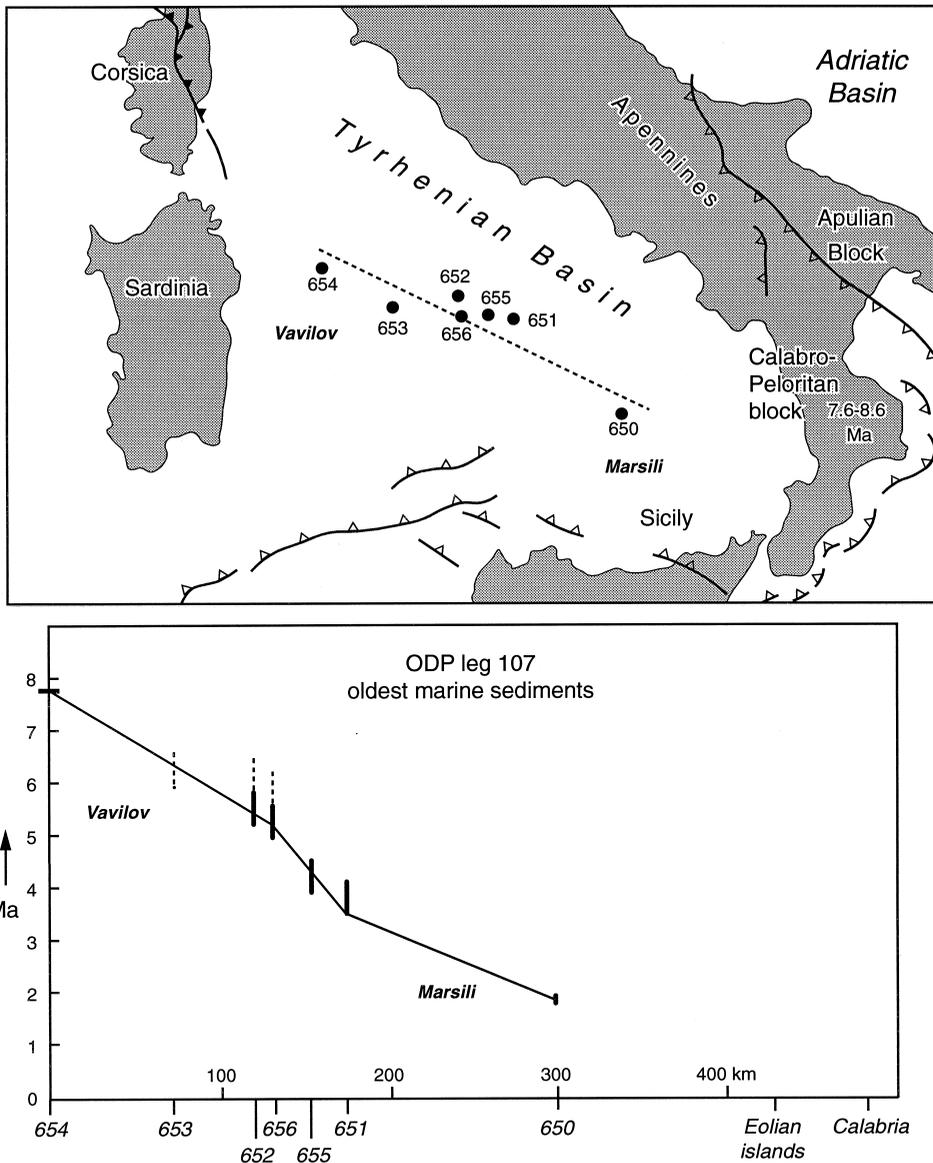


Fig. 9. Ages of oldest marine sediments overlying the basement versus distance in km throughout the Tyrrhenian Sea are shown. Location of ODP sites from Leg 107. Note that rapid intervals of opening correspond to the location of the Vavilov and Marsili basins. Sites (ages) are based on re-dating of results from Kastens et al. (1987) and Flores et al. (1992) and are as follows: Site 654 (7.89 Ma), 653\* (5.9 Ma), 652\* (5.95–5.23 Ma), 656\* (5.6–5.02 Ma), 655 (3.98–4.52 Ma), 651 (4.1–3.6 Ma) and 650 (2.0–1.8 Ma); \* = no basement recovered, and therefore represents minimum age.

8.6 and 7.8 Ma (Duermeijer et al., 1998) the Tyrrhenian Sea opened as back-arc basin (Robertson and Grasso, 1995) caused by extension resulting from SE roll-back of the subducting slab. The oldest marine sediments overlying the basement of the Tyrrhenian Sea (Kastens et al., 1987; Flores et al., 1992; Fig. 9)

were re-dated using astronomical ages of biostratigraphic markers (from Lourens et al., 1996). The resulting new ages suggest an acceleration in opening of the Tyrrhenian Sea between 3.5 and 2 Ma. Some ODP cores did not recover basement, and for these wells minimum ages are used (Fig. 9). This leads

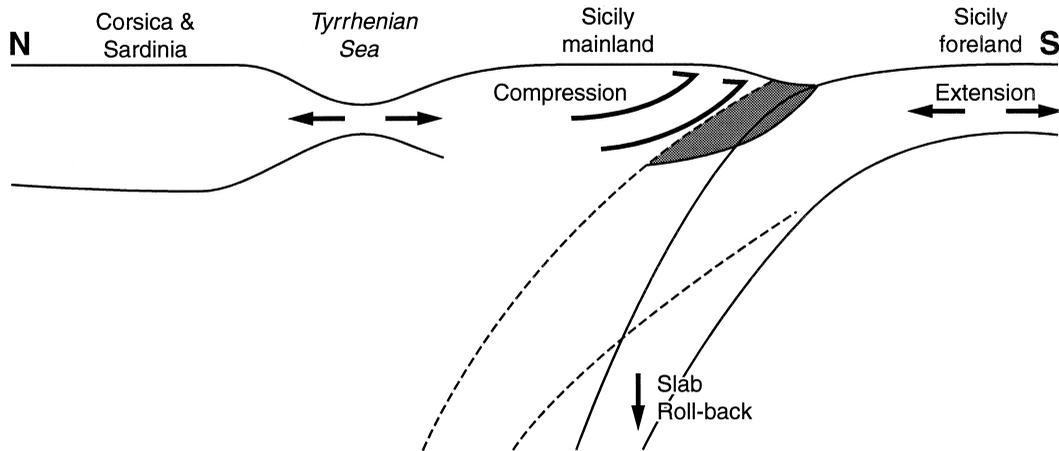


Fig. 10. Schematic image of the geodynamic process accounting for compression on Sicily and extension in the foreland as a result of acceleration in opening in the Tyrrhenian Sea.

to a simplified model of the geodynamic processes (Fig. 10) in which the acceleration caused a wave of contraction throughout Sicily, resulting in southward tectonic transport. In the case of locked continental collision, ridge push can be significantly reduced and extension becomes important, as in the Sicilian foreland (Argnani, 1990). Compressional systems on Sicily occur because of an acceleration in opening of the Tyrrhenian Sea, i.e. the movement of the overriding plate, advances trenchward faster than trench roll-back (see Busby and Ingersoll, 1995). Grasso and Butler (1991) and Butler et al. (1995) consider the Caltanissetta basin as a series of basins developed across the frontal part of the thrust belt. Thrusting generated anticlines and synclines which created sediment traps. Therefore, flexural subsidence was of increasing importance during the late Neogene.

The anisotropy of the magnetic susceptibility (AMS) indicates N–S compression for the Secca Grande and Punta Secca sections, whereas the AMS data of the Punta Piccola show a NW–SE compression direction. The AMS data are consistent throughout the Trubi and Narbone formations and hence throughout the rotation interval. This implies that the clockwise rotation event is recorded before the AMS ellipsoid was deformed as a consequence of N–S compression. Furthermore, our AMS data and structural studies of Catalano et al. (1993) imply a N–S compression direction for both the Sicilian fold-and-thrust belt and its foreland. Therefore, the AMS data of the Punta Piccola section, implying NW–SE com-

pression, must be regarded as a younger or local overprint.

Because rotations are associated with thrust imbrication (Oldow et al., 1990) and as such with the Pliocene transpressional event, we propose this event to have occurred around  $3.21 (\pm 0.05)$  Ma. Although most geological processes (e.g. opening of the Tyrrhenian Sea, thrusting, etc.) are believed to occur gradually, the data presented here indicate that at least some tectonic rotations may occur rather fast. If this rotation is indeed linked to an acceleration in opening of the Tyrrhenian Sea between 3.5 and 2 Ma, this could imply that the change in the rate of opening also occurred rather rapidly.

## 5. Conclusions

Palaeomagnetic results from three sections along the southwest coast in the Caltanissetta basin, reveal a rapid differential ( $10^\circ$ ) clockwise rotation phase dated around 3.21 Ma, close to the Trubi–Narbone boundary.

The age of the Pliocene differential clockwise rotation phase found on Sicily can be linked to the transpressional event in the Sicilian fold-and-thrust belt and to the extensional event in the Sicilian foreland. We conclude that both the transpression and extension are related to an acceleration in opening of the Tyrrhenian basin between 3.5 and 2 Ma, this being derived from the oldest (recovered) marine

sediments overlying the Tyrrhenian basement. The Trubi–Narbone boundary marks a shallowing in the Caltanissetta basin and, thus, a change in the sedimentary environment of the entire basin caused by this transpressional event. This boundary is probably not the expression of a regional (Sicilian) event, because time-equivalent events are central–eastern Mediterranean-wide, as can be concluded from ODP Leg 160 (eastern Mediterranean). On Crete an increase in uplift and large-scale thrusting phase is observed and in northern Italy a hiatus and tectonic rotation are documented as additional evidence.

Evidence for phases of non-rotation were identified between the middle Pliocene (3.21 Ma) and middle Pleistocene (1.0–0.7 Ma) throughout the entire Tyrrhenian region (i.e. southern Apennines, Calabria and Sicily).

## Acknowledgements

We thank Johan Meulenkamp, Michiel van der Meulen, Wout Krijgsman, Frits Hilgen and Lucas Lourens for their help in the field and fruitful discussions. The comments of the reviewers, H.D. Talling and M. Mattei and those of Lisa Tauxe were very helpful in improving the manuscript. H. Meijer is thanked for measuring many of the samples. Si ringraziano Ernesto Ragusa et famiglia, del ristorante ‘Il Gabbiano’ ad Eraclea Minoa (Sicilia), per la loro ospitalità ed il loro aiuto quando si sono rotti la nostra macchina e due generatori. This work was conducted under the programme of the Dutch national research school, the Vening Meinesz Research School of Geodynamics.

## References

- Argnani, A., 1990. The Strait of Sicily rift zone: foreland deformation related to the evolution of a back-arc basin. *J. Geodyn.* 12, 311–331.
- Brolsma, M.J., 1978. Quantitative foraminiferal analysis and environmental interpretation of the Pliocene and topmost Miocene on the south coast of Sicily. *Utrecht Micropaleontol. Bull.* 18, 1–159.
- Busby, C.J., Ingersoll, R.V., 1995. *Tectonics of Sedimentary basins*, Blackwell, Oxford, 580 pp.
- Butler, R.W.H., Lickorish, W.H., Grasso, M., Pedley, H.M., Ramberti, L., 1995. Tectonics and sequence stratigraphy in Messinian basins, Sicily: constraints on the initiation and termination of the Mediterranean salinity crisis. *Geol. Soc. Am. Bull.* 107, 425–439.
- Catalano, R., Channell, J.E.T., D’Argenio, B., Napoleone, G., 1976. Mesozoic Paleogeography of the southern Apennines and Sicily. Problems of paleotectonics and paleomagnetism. *Mem. Soc. Geol. Ital.* 15, 95–118.
- Catalano, R., Infuso, S., Sulli, A., 1993. The Pelagian foreland and its northward foredeep. Plio-Pleistocene structural evolution. In: Max, M.D., Colantoni, P. (Eds.), *Geological Development of the Sicilian–Tunisian Platform*. UNESCO Rep. Mar. Sci. 58, 37–42.
- Catalano, R., Infuso, S., Sulli, A., 1995. Tectonic history of the submerged Maghrebian Chain from the southern Tyrrhenian Sea to the Pelagian foreland. *Terra Nova* 7 (2), 179–188.
- Catalano, R., Di Stefano, P., Sulli, A., Vitale, F.P., 1996. Paleogeography and structure of the central Mediterranean: Sicily and its offshore area. *Tectonophysics* 260, 291–323.
- Duermeijer, C.E., Van Vugt, N., Langereis, C.G., Meulenkamp, J.E., Zachariasse, W.J., 1998. A major late Tortonian rotation phase of the Crotona Basin; implications using AMS as tectonic tilt correction and first indication of timing in opening of the Tyrrhenian Basin. *Tectonophysics* 287 (1–4), 233–249.
- Fisher, R.A., 1953. Dispersion on a sphere. *Proc. R. Soc. London A* 217, 295–305.
- Flores, J.A., Sierro, F.J., Glaçon, G., 1992. Calcareous plankton analysis in the pre-evaporitic sediments of ODP Site 654 (Tyrrhenian Sea, Western Mediterranean). *Micropaleontology* 38 (3), 279–288.
- Grasso, M., Butler, R.W.H., 1991. Tectonic controls on the deposition of late Tortonian sediments in the Caltanissetta Basin of Central Sicily. *Mem. Soc. Geol. Ital.* 47, 313–324.
- Hilgen, F.J., 1987. Sedimentary cycles and high-resolution chronostratigraphic correlations in the Mediterranean Pliocene. *Newsl. Stratigr.* 17, 109–127.
- Hilgen, F.J., 1991a. Astronomical calibration of Gauss to Matuyama sapropels in the Mediterranean and implication for the Geomagnetic Polarity Time Scale. *Earth Planet. Sci. Lett.* 104, 226–244.
- Hilgen, F.J., 1991b. Extension of the astronomically calibrated (polarity) time scale to the Miocene/Pliocene boundary. *Earth Planet. Sci. Lett.* 107, 349–368.
- Kastens, K.A., Mascle, J., Auroux, C. et al. (Eds.), 1987. *Proc. ODP, Init. Rep. 107*. College Station, TX (Ocean Drilling Program).
- Kirschvink, J.L., 1980. The least-squares line and plane and the analysis of paleomagnetic data. *Geophys. J. R. Astron. Soc.* 62, 699–718.
- Kroon, D., Alexander, I., Little, M., Lourens, L.J., Matthewson, A., Robertson, A.H.F., Sakamoto, T., 1998. Oxygen isotope and sapropel stratigraphy in the eastern Mediterranean during the last 3.2 million years. *Proc. ODP, Sci. Results* 160, in press.
- Langereis, C.G., Hilgen, F.J., 1991. The Rossello Composite: a Mediterranean and global reference section for the Early to early-Late Pliocene. *Earth Planet. Sci. Lett.* 104, 211–225.
- Lourens, L.J., Antonarakou, A., Hilgen, F.J., van Hoof, A.A.M.,

- Vergnaud-Grazzini, C., Zachariasse, W.J., 1996. Evaluation of the Plio-Pleistocene astronomical timescale. *Paleoceanography* 11 (4), 391–413.
- Lowrie, W., 1990. Identification of ferromagnetic minerals in a rock by coercivity and unblocking temperature properties. *Geophys. Res. Lett.* 17 (2), 159–162.
- Mary, C., Iaccarino, S., Courtillot, V., Besse, J., Aissaoui, M., 1993. Magnetostratigraphy of Pliocene sediments from the Stirone River (Po Valley). *Geophys. J. Int.* 112, 359–380.
- Meulenkamp, J.E., van der Zwaan, G.J., van Wamel, W.A., 1994. On Late Miocene to Recent vertical motions in the Cretan segment of the Hellenic arc. *Tectonophysics* 234, 53–72.
- Oldow, J.S., Channel, J.E.T., Catalano, R., D'Argenio, B., 1990. Contemporaneous thrusting and large-scale rotations in the western Sicilian fold and thrust belt. *Tectonics* 9 (4), 661–681.
- Robertson, A.H.F., Grasso, M., 1995. Overview of the Late Tertiary–Recent tectonic and palaeo-environmental development of the Mediterranean region. *Terra Nova* 7 (2), 114–127.
- Scheepers, P.J.J., 1994. Some paleomagnetic evidence for clockwise rotations in the Sicilian fold-and-thrust belt during the late Pliocene and the middle Pleistocene. *Geol. Ultraiectina* 112, 251–265.
- Scheepers, P.J.J., Langereis, C.G., 1993. Analysis of NRM directions from the Rossello Composite: implications for tectonic rotations of the Caltanissetta basin (Sicily). *Earth Planet. Sci. Lett.* 119, 243–258.
- Scheepers, P.J.J., Langereis, C.G., Hilgen, F.J., 1993. Counter-clockwise rotations in the southern Apennines during the Pleistocene: paleomagnetic evidence from the Matera area. *Tectonophysics* 225 (4) 379–410.
- Scheepers, P.J.J., Langereis, C.G., Zijdeveld, J.D.A., Hilgen, F.J., 1994. Paleomagnetic evidence for a Pleistocene clockwise rotation of the Calabro–Peloritani block (southern Italy). *Tectonophysics* 230, 19–48.
- Tarling, D.H., Hrouda, F., 1993. *The Magnetic Anisotropy of Rocks*. Chapman and Hall, London, 217 pp.
- Van Hoof, A.A.M., Langereis, C.G., 1991. Reversal records in marine marls and delayed acquisition of remanent magnetization. *Nature* 351, 223–225.
- Van Velzen, A., Zijdeveld, J.D.A., 1990. Rock magnetism of the Early Pliocene Trubi formation (Sicily). *Geophys. Res. Lett.* 17, 791–794.
- Van Velzen, A.J., Dekkers, M.J., Zijdeveld, J.D.A., 1993. Magnetic iron–nickel sulphides in Plio-Pleistocene marine sediments from the Vrica section (Calabria, Italy). *Earth Planet. Sci. Lett.* 115, 43–56.
- Zijdeveld, J.D.A., 1967. Demagnetisation of rock: analysis of results. Collinson, D.W., Creer, K.M., Runcorn, S.K. (Eds.), *Methods in Paleomagnetism*. Elsevier, Amsterdam, pp. 254–286.
- Zijdeveld, J.D.A., Zachariasse, W.J., Verhallen, P.J.J.M., Hilgen, F.J., 1986. The age of the Miocene–Pliocene boundary. *Newsl. Stratigr.* 16, 169–181.
- Zijdeveld, J.D.A., Hilgen, F.J., Langereis, C.G., Verhallen, P.J.J.M., Zachariasse, W.J., 1991. Integrated magnetostratigraphy and biostratigraphy of the upper Pliocene–lower Pleistocene from the Monte Singa and Crotona areas in Calabria, Italy. *Earth Planet. Sci. Lett.* 107, 697–714.