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The upper and lower Thvera sedimentary geomagnetic reversal records from southern Sicily

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ABSTRACT

Detailed paleomagnetic records of the upper and lower Thvera polarity transitions have been determined from Pliocene marine marls in southern Sicily. The dominant magnetic mineral is fine grained magnetite. The two transitions have VGP paths following a great circle passing South America and the west coast of North America. There are strong indications that the VGP paths result from smoothing of the non-antipodal stable directions before and after the transitions. The upper Thvera transitional record is preceded by two excursions and followed by a third one. The first excursion is a sedimentary artefact caused by post-depositional migration of magnetic minerals and the third one by is caused by weathering of the sediment. The upper Thvera transition from Sicily is compared with the record from Calabria, about 250 km away. The two records show similarities as well as differences: both transitions have identical VGP paths, but in Calabria the transition is recorded lower in the sediment, the first and third excursions have different characters and the second one is not present. Apparently the registration of transitions of the Earth's magnetic field in sediments is strongly influenced by smoothing and diagenetic processes after deposition.

1. Introduction

The Earth's magnetic field has reversed its polarity many times in the geological past, but the mechanism which causes this feature still remains largely unresolved. An aid in solving this problem is the detailed paleomagnetic study of the behaviour of the Earth's magnetic field during these transitions. Detailed records of geomagnetic transitions have been obtained from different sources, the most important of which are those recorded in lava sequences and those in sedimentary sequences. Although sedimentary sequences concern appropriate time control and continuous registration of the geomagnetic signal, the recording mechanism in sediments is still badly understood and may easily lead to sedimentary artefacts [3–6]. However, Laj et al. [7] and Tric et al. [8] concluded, from studies of the VGP paths of several transitions (showing a wide distribution in both time and place) that the VGP paths are predominantly confined to a longitudinal band over the Americas or its antipode, and that there may have been a strong dipolar field during transitions. However, Valet et al. [9] pointed out that the transitional fields cannot be dipolar and that the longitudinal confinement found by Laj et al. [7] and Tric et al. [8] is statistically insufficiently constrained. Mary and Courtillot [10] found that, in many reversals, the reversing fields decrease and subsequently increase along the dipole direction on which a random noise is superposed. In addition, Langereis et al. [6] have shown that the longitudinal confinement of the VGP paths from sedimentary records can also be explained by a process of smoothing of the stable non-antipodal directions before and after the transitions. Clearly, many more transitional records from both lavas and sediments are required before there is a consensus on this matter.

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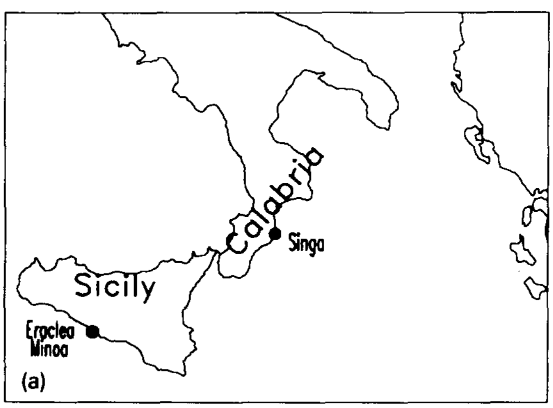
One important aspect when making a contribution to the number of known and (highly) detailed records is to ensure that the reversal(s) are well identified. This makes it possible to compare the same reversal from different geographical locations, and from different sedimentary (or volcanic) environments. In this paper we present the detailed reversal records of the lower and upper boundaries of the Thvera subchron from marine marls in southern Sicily. The results of five successive transition records from the Lower Pliocene in Calabria, in the Gilbert Chron, which range from the upper Thvera to the upper Nunivak, have already been reported by Linssen [2]. For the present work the upper Thvera transitional record from Sicily, together with the record of the lower Thvera, were sampled in considerably more detail and both are presented here.

2. Geological setting and sampling

The Thvera subchronozone in the Gilbert Chronozone was identified by a detailed magnetostratigraphic study of the Eraclea Minoa section in the Caltanisetta basin of Southern Sicily (Fig. 1) [11]. The Eraclea Minoa section forms the basal part of the Rossello composite section [12] and it consists of marine marls of the Pliocene Trubi Formation (Fig. 2); the bedding plane at the sampling locality has a strike and a dip of 267°W and 14°N. The average sedimentation rate can be accurately determined on the basis of the astronomically calibrated polarity time scale (APTS) [13] and is 5.0 cm/kyr in the lower Thvera section and 4.4 cm/kyr in the upper Thvera section. The marls of the Trubi formation mainly consist of carbonates (60–80% $CaCO_3$) and a mixture of clay minerals [14]. Hilgen [15] recognized a long succession of small-scale sedimentary cycles—the so-called quadruplets. The weathering profile of these quadruplets form a repetition of grey, white, beige and white coloured beds (Fig. 2), which were deposited during cyclic sedimentation periods of approximately 19–23 ka. These sedimentary cycles are clearly related to the precessional cycle of the Earth's orbit [16]. Although the weathering profile shows quite sharp changes in colour and induration, the changes in fresh, unweathered sediment are much more gradual. Considerable effort was taken to remove the weathered surface (up to 1 m) in order to expose the fresh (dark grey, light and dark blue) sediment. This method proved successful for almost the entire intervals sampled, except for the top part of the upper Thvera interval where the uppermost white layer remained visibly and strongly weathered. In the lower Thvera interval the colour layering was not as clear as in the higher part of the section. Only a greyish and a beige layer could be distinguished, while between these two layers there was a somewhat lighter coloured (white?) layer.

Sampling was carried out by taking oriented cores, 25 mm in diameter, more or less parallel to the bedding plane at very close intervals (~ 1 cm), from a freshly cut, near-vertical plane. Each core was divided into specimens 22 mm long. The



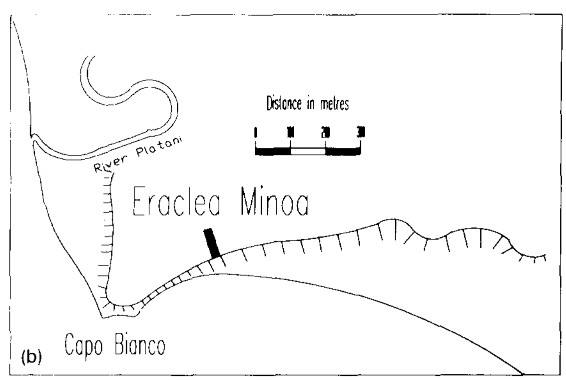


Fig. 1. (a) Map of Sicily and Calabria. The transitions described in this paper were sampled at the Eraclea Minoa Section. The upper Thvera transition will be compared with the same transition sampled in the Singa section in Calabria, some 250 km away from Eraclea Minoa. (b) Location of the Eraclea Minoa section in Sicily (Italy).

stratigraphic position of each specimen was accurately determined by taking into account drilling orientation, bedding plane and width of the saw cut. The resolution of these records is of the order of a few millimetres; hence it is better than 100 years. Variations in the parameter within a sample will, therefore, in principle only smooth the high frequency signal of the secular variation [17].

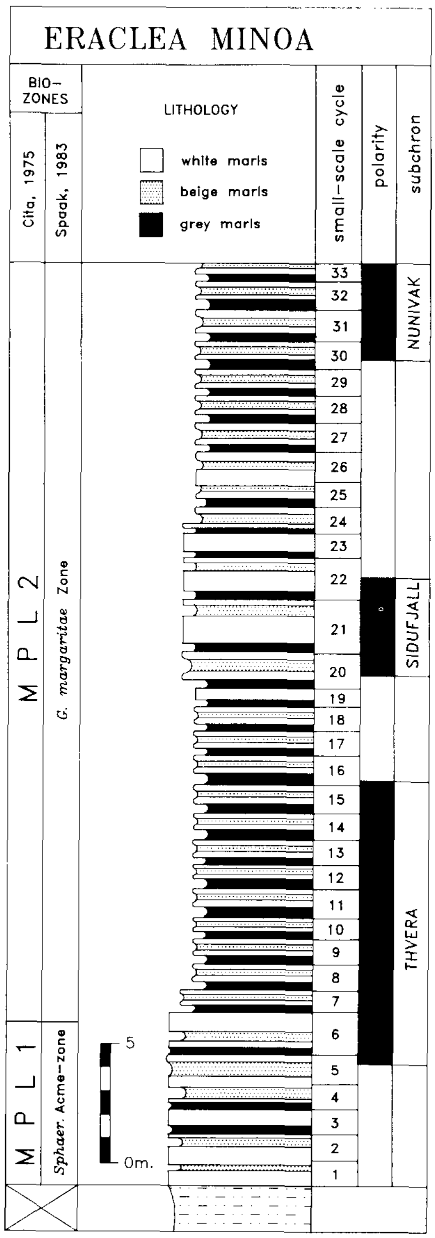


Fig. 2. Lithostratigraphy and magnetostratigraphy of the Trubi formation at the Eraclea Minoa section [12,15]. The lower Thvera transition was identified in small-scale cycle 5 and was sampled in detail over an interval of 1 m. The upper Thvera transition was identified in small-scale cycle 16 and was samples over 1.75 m. In this paper the zero levels of the two transition records are arbitrary, and were chosen at pronounced layer-parallel sedimentary lines. For the lower Thvera this zero level was chosen at a line in the beige layer of cycle 5. The zero level of the upper Thvera record is at the top of the gray layer of cycle 15. The white marls have a higher carbonate content, while the grey and beige marls are relatively poor in carbonate [16], probably due to increased continental run-off (grey) or increased African wind-blown input (beige) [14].

3. Rock magnetism

The acquisition of a stable remanence may take place at a certain depth below the sediment–water interface, resulting in a time lag between the deposition of the sediment and the acquisition of the remanence. Usually this is referred to as a post-depositional detrital remanent magnetization (pDRM) and the corresponding time lag is directly related to the lock-in depth, which, in turn, depends for a major part on sediment compaction. A typical value of the lock-in depth for relatively slowly deposited sediments (1–8 cm/kyr) is approximately 16 cm [18]. In the case of authigenic (biogenic) formation of magnetic minerals, however, a chemical remanent magnetization (CRM) may be acquired at depths or in depth intervals that depend on redox conditions rather than mainly on compaction. The "lock-in depth" or depth lag may then be considerably larger [5]. Post-depositional diagenetic processes controlled by changing redox conditions, may, in addition, lead to the migration of Fe ions, which can cause a CRM at a depth of more than 1 m below the sediment–water interface [1,16]. Rock magnetic parameters may give an indication of the change in the character and concentration of the magnetic minerals. Therefore, we determined the initial susceptibility (χ_0) and the (remanent) saturation magnetization (J_{rs}, J_s) and the (remanent) coercivity (H_{cr}, H_c).

The acquisition of an isothermal remanent magnetization (IRM) for a number of samples from different lithologies up to a maximum DC field of 2 T (Fig. 3a) reveals that there are deflection points at fields of 100–200 mT, indicating that a low coercivity mineral has reached the saturation remanence. The increase in the IRM in higher fields, of mainly the white lithology, records, in addition, the presence of a high coercivity mineral. The saturation IRM (J_{rs}) at 2 T was thermally demagnetized. The relative intensity decrease at 120°C as a percentage of the initial J_{rs} of the upper Thvera section is shown in Fig. 3b. The samples with a relatively large amount of highly coercive minerals during IRM acquisition are from the same sedimentary interval (mainly white marls) as samples with the strongest decay at 120°C. This suggests that the highly coercive, low unblocking temperature mineral is goethite, which is a typical product of weathering. A strong indication of the presence of goethite is the brown and strongly oxidized layer at level 135 of the upper Thvera section. At this level the decrease in the J_{rs} intensity between room temperature and 120°C is at a maximum of 40% (Fig. 3b). From the NRM demagnetization results, any remanence carried by goethite is not evident.

J_{rs} seems to show a lithological dependence. Correction for the amount of goethite is made by subtracting the part of the J_{rs} demagnetized at 120°C from the total J_{rs} (Fig. 4). This correction lowers the J_{rs} values somewhat but the lithology dependence remains. There are maxima in the beige layers, and minima in the lower part of the grey layers and in the white layers above the grey layers. The maxima are up to 3.5 A/m for the upper Thvera section and 1.5 A/m for the lower.

As observed in the entire section [cf., 1], the initial susceptibility (χ_0) is strongly dependent on the lithology; the beige layers consistently show maxima (here the maximum is 250×10^{-6} SI), while minimum values are found at the transition from white to grey.

The ratio J_{rs}/χ_0 is largely independent of concentration (provided that the dominant magnetic mineral is magnetite) and it may give an indication of the grain size. The ratio shows typical

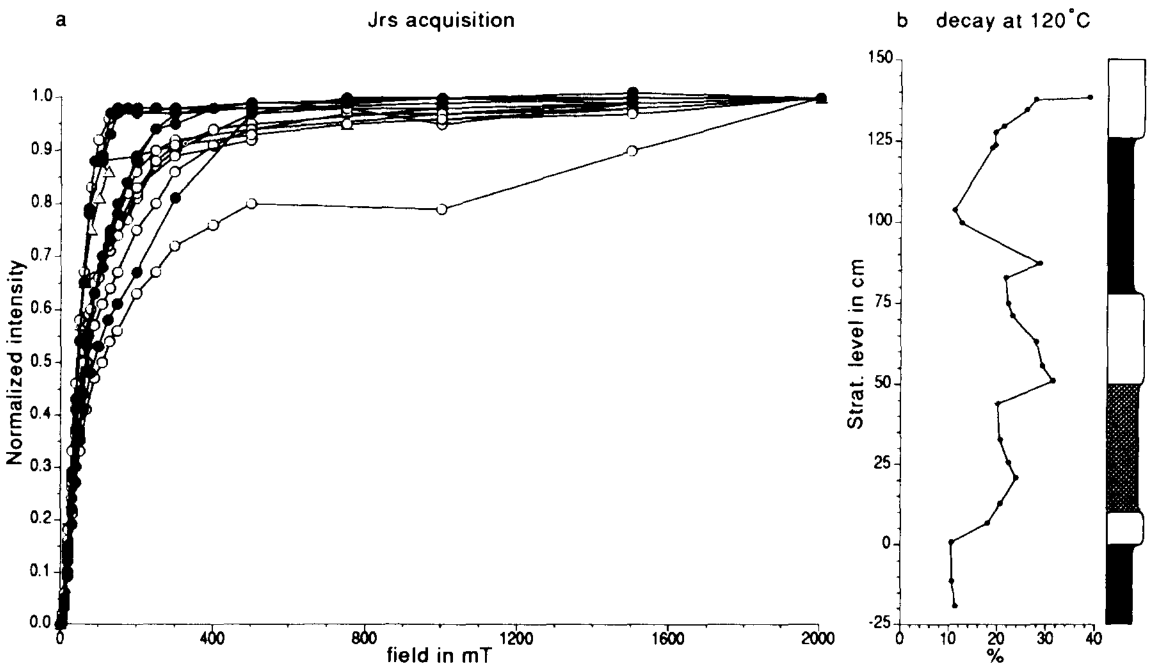


Fig. 3. (a) Normalized IRM acquisition curves of samples from different lithologies, up to a maximum field of 2T. Most samples from the grey (black points) and beige (triangles) lithologies and one from the white (circles) lithology are saturated at fields lower than 400 mT. The rest of the white samples and one grey sample are saturated in higher fields. (b) During thermal demagnetization of samples from the upper Thvera section with a saturation IRM (J_{rs}) the relative decrease in intensity up to 120°C is determined as a function of stratigraphic level. The samples having the strongest decay got their saturation remanence at higher fields, which indicates the presence of goethite, especially at level 135, which was a brown coloured part of the lithology.

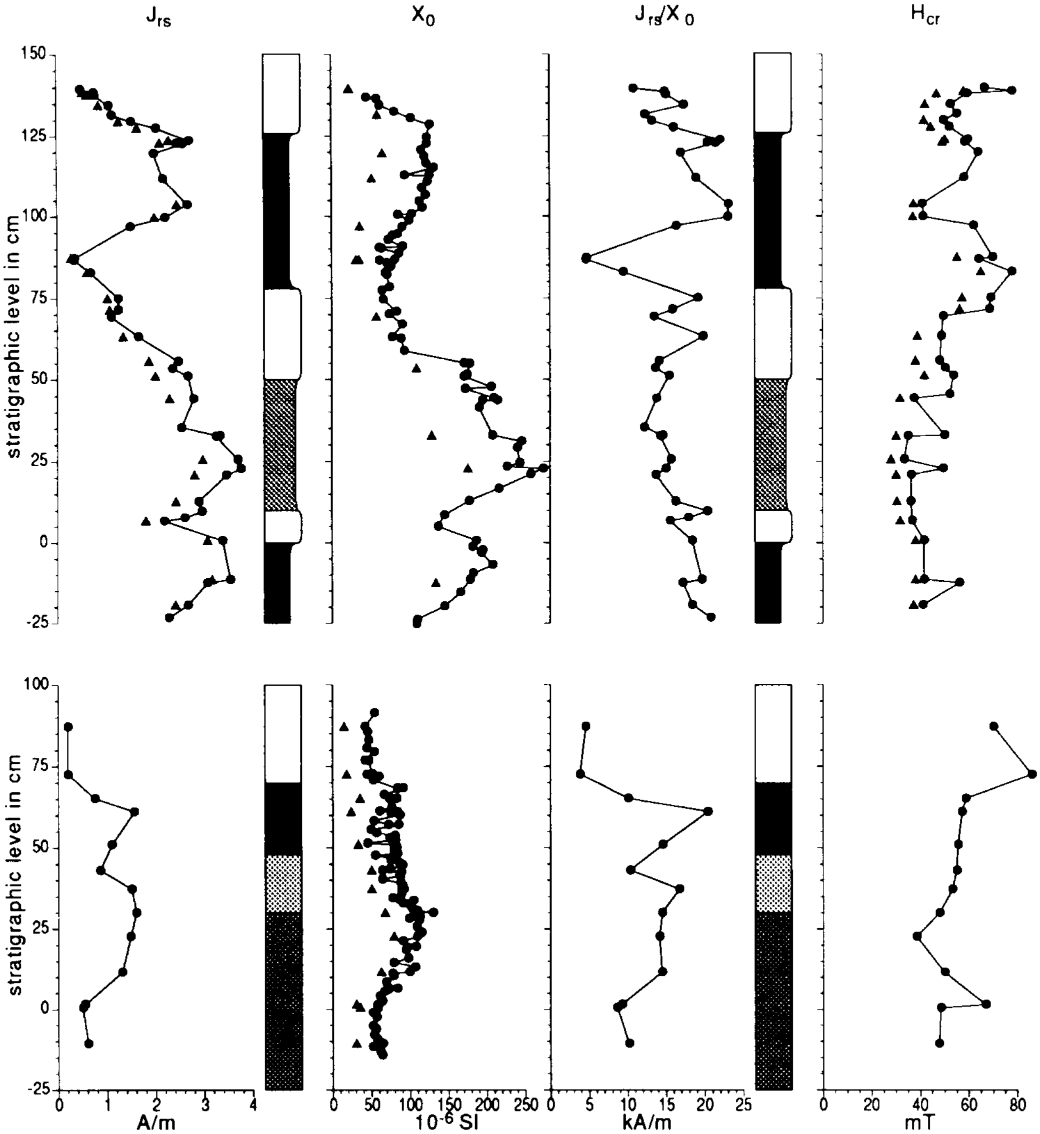


Fig. 4. Variation in the magnetic parameters saturation IRM (J_{rs}), initial susceptibility (χ_0), the ratio J_{rs}/χ_0 and remanent coercive force (H_{cr}) as functions of the stratigraphical levels and lithology. The upper part of the figure is the upper Thvera section; the lower is the lower Thvera section. The legend of the lithological column of the upper Thvera section is the same as in Fig. 2. In the lower Thvera section the differences between layers were hard to distinguish. The colours in this column are, from bottom to top: beige, whitish, greyish and white. Triangles in the J_{rs} diagrams denote the intensities of J_{rs} at 120°C. At this temperature it is assumed that only goethite fraction has been demagnetized. Triangles in the χ_0 diagrams are the corrections for the high field susceptibility. In the H_{cr} diagram the triangles denote the high coercive mineral correction (goethite), see also text. J_{rs} and χ_0 have maxima in the beige parts of the lithology. The ratios of both parameters lie in the range of fine grained magnetite. The remanent coercive forces H_{cr} lie in the range of fine grained magnetite and maghemite.

values of 15–20 kA/m, except for a clear minimum in the bottom part of grey. Fine-grained magnetites have values larger than 20 kA/m [19] and they are presumably of single domain size [20,21]. The clay fraction of the lithology has a strong paramagnetic contribution and will increase the bulk susceptibility, χ_0. Hysteresis loop experiments quantify the amount of the paramagnetic contribution (Fig. 5). Correction of χ_0 for the paramagnetic susceptibility increases the ratio

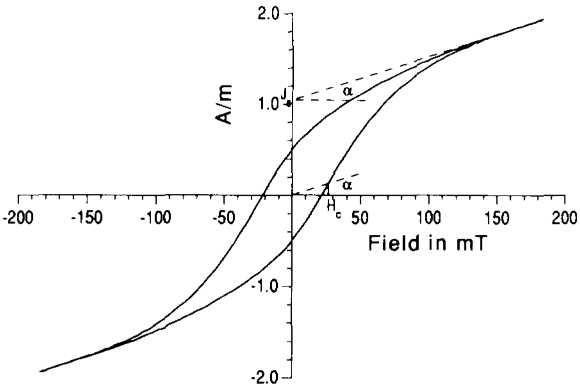


Fig. 5. Hysteresis loop. The linear trend at higher fields (dashed lines) is due to the paramagnetic susceptibility of the clay minerals. It can be derived from the curve as the tangent (of α). Horizontal axis = inducing field; vertical axis = induced remanence; J_s = saturation remanence determined where the dashed line crosses the vertical axis; H_c = coercive force determined where the loop crosses the horizontal axis after correction for the paramagnetic susceptibility.

J_{rs}/χ_0 to values typical of fine grained magnetites.

The remanent coercivity, H_{cr}, in natural sediments is independent of the concentration of magnetic material and is not influenced by paramagnetic clay minerals. Assuming that there is only one mineral present, H_{cr} is measured by a stepwise increase in the DC field in a direction opposite to J_{rs}, where H_{cr} is the DC field strength required to decrease J_{rs} to zero. However, in a mixture of a low coercivity mineral (magnetite) and a high coercivity mineral (goethite), a correction for the goethite must be made. The J_{rs} of the mixture, gained at a 2 T field, will consist of the IRM's of both minerals. While determining the H_{cr} of the low coercivity mineral occurring in this mixture, the DC field opposite to J_{rs} will not decrease the IRM of goethite. Therefore, the DC field must be increased until the IRM intensity of goethite is reached, instead of the zero intensity for a sample containing only one mineral. In order to obtain an approximation of the goethite fraction, we assume that the IRM intensity of goethite is the part of J_{rs} that is demagnetized between room temperature and 120°C. Typical H_{cr} values of fine grained magnetites are 40–60 mT [20,22,23], which are the values observed in the upper Thvera section (Fig. 4). After the goethite correction the data show a better fit to the fine-grained magnetite values. In the lower Thvera section the H_{cr} data are somewhat high for fine-grained magnetite values between levels 0 and 75, but here no goethite correction was made.

In their rock magnetic study of the Trubi marls from Eraclea Minoa [20], using the ratios H_{cr}/H_c and J_{rs}/J_s, Van Velzen and Zijderveld concluded that the magnetic minerals were dominated by fine grained (SD) magnetites. A small discrepancy between their data and those from Dunlop [23] was explained by the presence of some goethite, and possibly some super paramagnetic magnetite. Our H_{cr}/H_c and J_{rs}/J_s data are the same as those of Van Velzen and Zijderveld [20] (Fig. 6).

On the basis of the rock magnetic properties we conclude that, in spite of a presumed dependence of the rock magnetic parameters on lithology, the dominant magnetic mineral is fine grained magnetite throughout the sedimentary

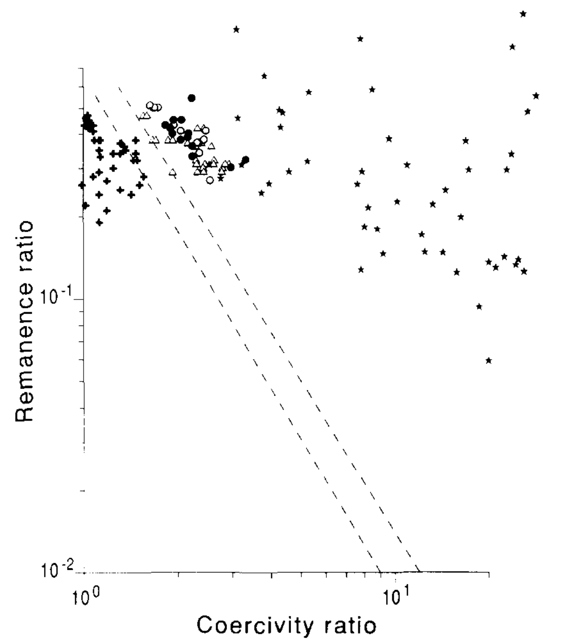


Fig. 6. Double logarithmic plot of coercivity ratio H_{cr}/H_c versus remanence ratio J_{rs}/J_s after [20]. Literature data for magnetite of known grain sizes fall on a single trend indicated by two dashed lines [23]. Stars = data from goethite; crosses = data from pyrrhotite [33]; circles = data from this study, which fit the values from the Trubi sediments (triangles) by van Velzen and Zijderveld [20] very well. These authors concluded that fine SD magnetites were the most important magnetic minerals in the sediment.

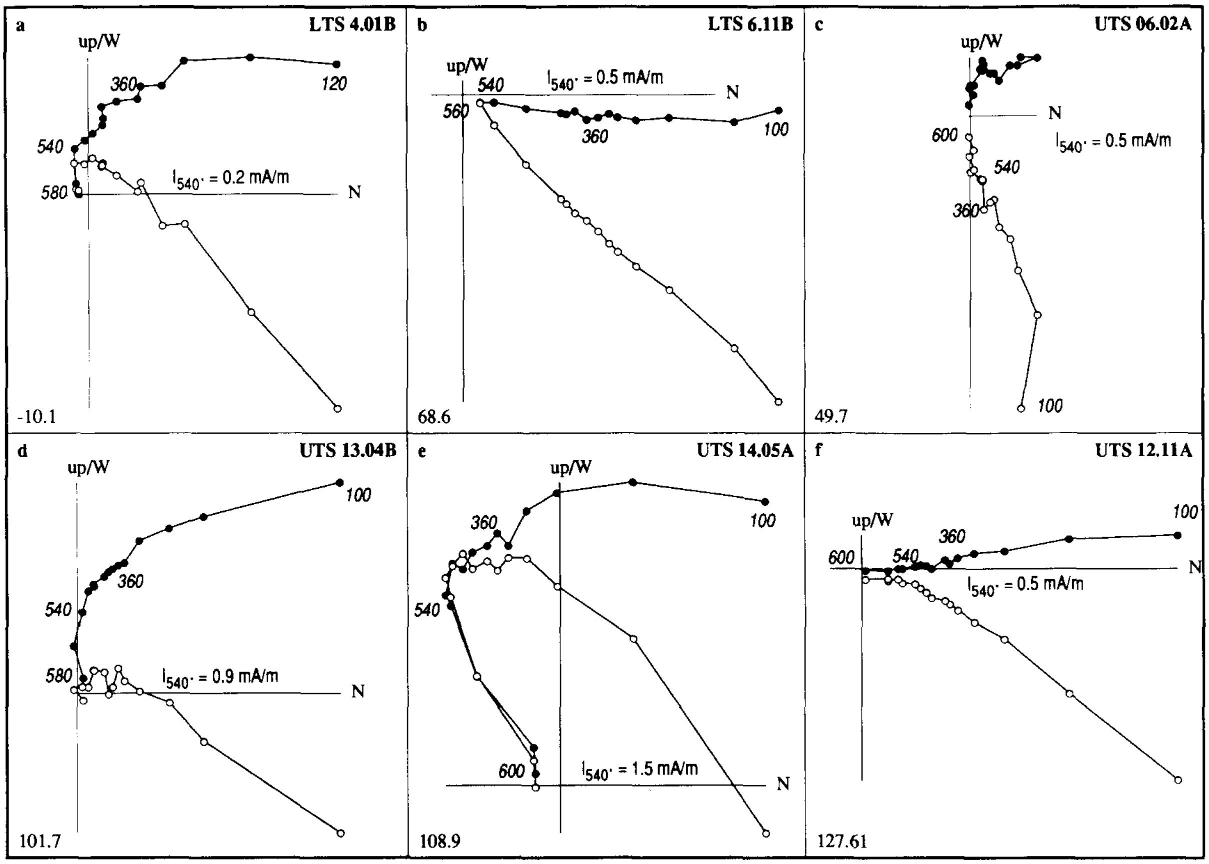


Fig. 7. Thermal demagnetization diagrams. (a) and (b) Lower Thvera. (c)–(f) Upper Thvera. (c) and (d) Intermediate directions. Up to temperatures of 250°C the directions are normal. Between 300 and 480°C the decay is small. The maximum unblocking range is from 580°C to 600°C, indicating that magnetite is the carrier of the ChRM.

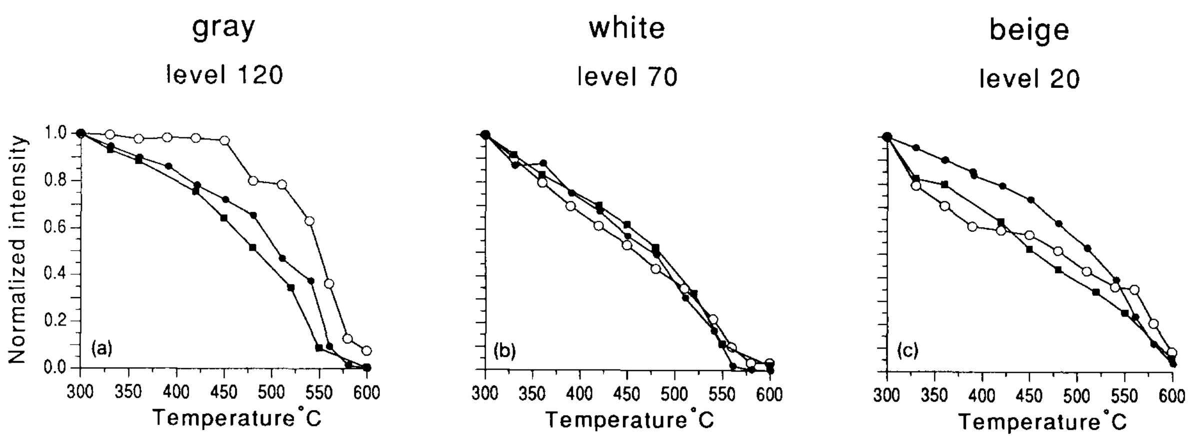


Fig. 8. Normalized thermal demagnetization decay curves of ChRM (circles), IRM(2T) (squares) and ARM (dots) for (a) level 120 (gray); (b) level 70 (white); and (c) level 20 (beige) from the upper Thvera section. Intensities are normalized with respect to 300°C, after removal of the secondary component. Generally, at temperatures above 500°C the relative decrease in the ARM intensities is more similar to ChRM behaviour than that of IRM. Therefore, the ARM is considered to be representative of the ChRM.

interval. A small amount of goethite and possibly some super paramagnetic material is present.

4. NRM components

In almost all paleomagnetic studies of the Pliocene Trubi marls the NRM generally shows a secondary magnetization (removed at temperatures below 300–330°C) but, more importantly, two other prominent magnetization components: a low temperature (LT) component, removed between 360 and 480–510°C, and a high temperature (HT) component, removed between 480–510°C and 600°C [4,17]. The LT and HT components were obvious because in some parts of the records the two components were completely anti-parallel; in addition, these two components have also been observed in other sediments [24]. In the case of the Thvera transitions from the Trubi sediments on Sicily the LT component is less obvious (Fig. 7); however, for reasons of consistency the LT component has nevertheless been determined as the component removed in the temperature trajectory 360–480°C.

The directions of all components are determined by fitting a least squares line [25], usually through five or more demagnetization steps. The secondary magnetization has a typical present day field direction; it probably resides in MD magnetite [20]. In the Trubi marls, this secondary magnetization is removed at 200–250°C, but in the Thvera records a substantial part persists to higher temperatures resulting in LT components intermediate between the secondary and HT components (Fig. 10). During demagnetization of the LT component fluctuations in the remanence are sometimes observed, especially during a corresponding "plateau" in the decay curves (Fig. 8). Finally, the HT component, or characteristic remanent magnetization (ChRM), is removed at

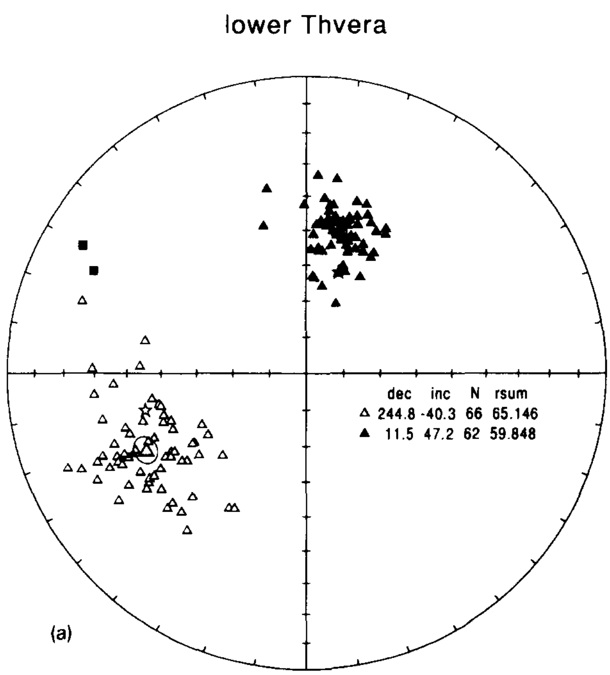


Fig. 9. Stable HT directions just before and after the transitions (triangles). Reversed directions of the lower Thvera transition were determined from the interval −15–16 cm and normal direction from 57 to 90 cm. Normal directions of the upper Thvera transition were determined from the interval 85–95 cm and reversed directions from the interval 108–125 cm. The mean directions of these stable, near-transitional directions before and after the transitions show a clear offset. Circles = calculated stable normal directions between −25 and 0 cm, preceeding two excursions in the lowermost part of the upper Thvera transition; asterisks = mean directions before tectonic correction; squares = mean directions of LT component before and after tectonic correction, averaged over trajectories where the HT component is reversed. Before tectonic correction the LT component is steeper and more westerly. The normal LT component is almost parallel to the normal HT component.

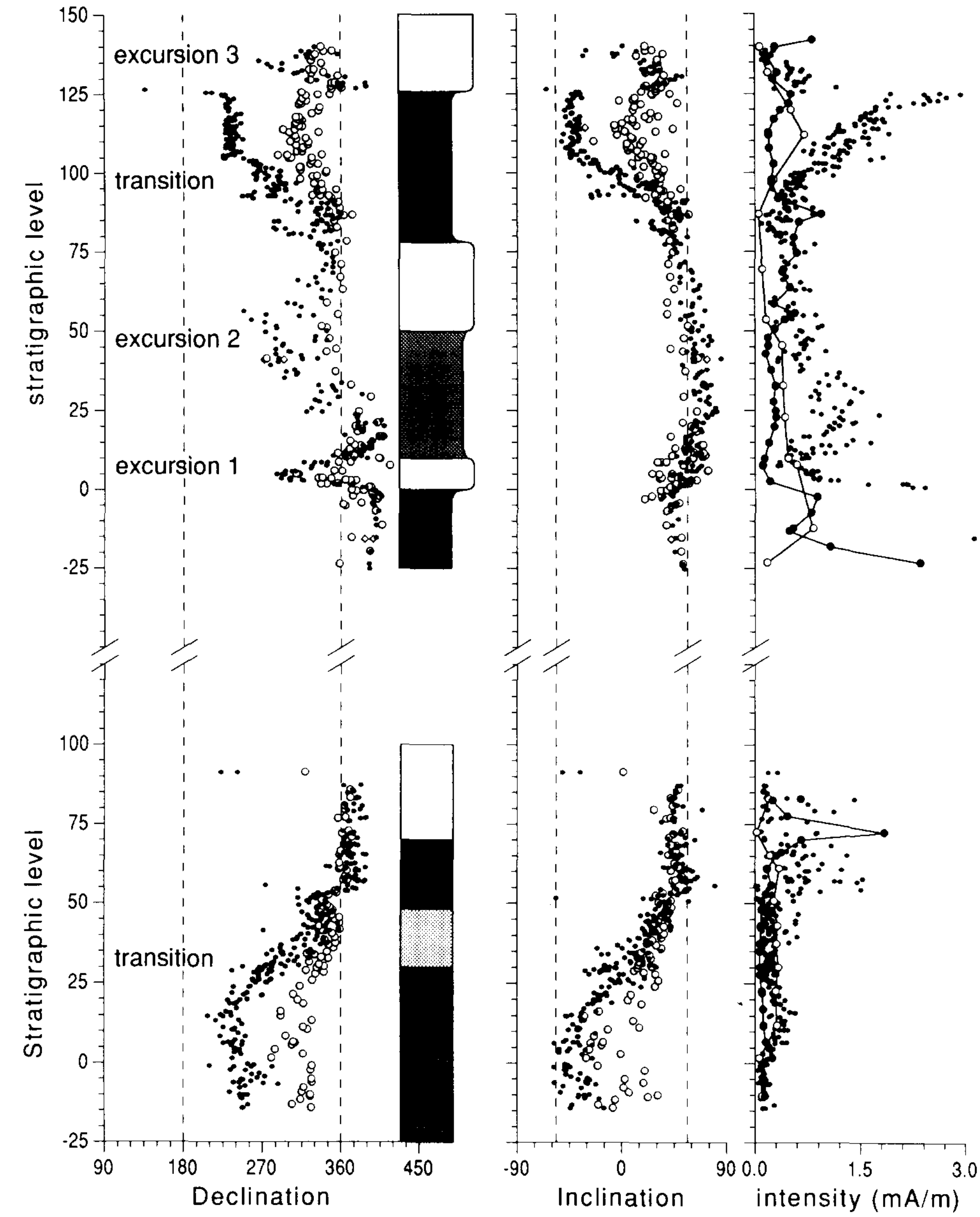


Fig. 10. Records of the declination, inclination and intensity obtained after thermal demagnetization of the upper and lower Thvera transitions. For legend of sedimentary column see Fig. 4. Circles = the LT component; dots = the HT component; dashed lines = declination and inclination (57.5°) of the geocentric axial dipole for the present latitude of the locality. The lower Thvera transition is gradual. The upper Thvera record has, besides the actual transition at level 95 cm, three intervals with major directional changes: between level 0 and 15, where the declination swings to almost 270° west, with a minor steepening of the inclination (excursion 1); between levels 25 and 90, in which the declination again swings to 270° west while the inclination steepens slowly (excursion 2) and then becomes more shallow again, back to its initial value at level −5. The declination does not return back to its initial values (35°E). Excursion 3 is at level 125, where the ChRM directions jumps from reversed to normal directions coinciding with a (sharp) lithological change, followed by a slower change back to reversed directions. Small dots = the record of ChRM intensities at 510°C in mA/m; circles = ARM(510°C); dots connected by a line = the smoothed record of the ratio ChRM/ARM(510°C), both are in arbitrary units. Data were smoothed by a 5 cm spatial window. ChRM data larger than 3 mA/m below the zero level of the upper Thvera record were not plotted in order to enlarge horizontal scale. The changes in the ratio are mainly caused by changes in the ARM(510°C).

temperatures higher than 450°C, but the most rapid decay is observed only at temperatures higher than 510°C. It is also at these highest temperatures that this component shows a (more or less) linear decrease towards the origin.

The (mean) normal and reversed directions before and after the transitions are not anti-podal but show a clear offset (Fig. 9). An overlap in the blocking temperature spectrum of the secondary component with the spectrum of the HT component is probably quite persistent up to the highest temperatures [21] and may therefore introduce an offset in HT directions: the reversed HT component is expected to have a southwest declination and the normal component a northeast declintion due to the rotation of the basin and a relatively shallow inclination caused by compaction. A secondary component will offset the reversed declination to west and decrease the inclination, conversely the normal declination will be offset to the north and the inclination increased, as is seen in Fig. 9. Therefore, the offset may be caused by the geomagnetic field but is more likely due to the secondary overprint. The offset in the normal declinations of the lowermost part of the upper Thvera transition has an average clockwise rotation of rotation of 38.5°, which is more easterly than expected for the secondary overprint. As was expected, the inclinations in the normal directions are steeper than in the reversed directions. The stable directions before and after the two transitions show negative reversal tests [26]. Uncorrected for the bedding plane, the mean normal HT directions deflect further from the north and inclinations are steeper, while the mean reversed HT directions tend to more westerly directions and inclinations also steepen (Fig. 9). The mean "reversed" LT component shows, before tectonic correction, a more westerly declination and a steeper inclination.

Scheepers and Langereis [27] also find differences between normal and reversed directions (30° and 40°, respectively) for the entire Thvera subchronozone and the overlying reversed subchronozone. They suggest that this is probably related to the higher carbonate content (and thus higher porosity) of the basal part (i.e., the Eraclea Minoa section) of the Rossello composite section [12,16]. A higher porosity may result in increased weathering of SD magnetite, which causes a secondary component that persists up to the highest temperatures [21]. The non-transitional ChRM directions show an inclination error of 7–16°(Fig. 9) and it is stronger in the reversed directions. Hence, there is probably a bias in inclination due to a secondary component. The most important cause of the inclination error, however, is most likely due to compaction and its magnitude is clearly related to the carbonate content [27], a result which is known from earlier studies [28,29].

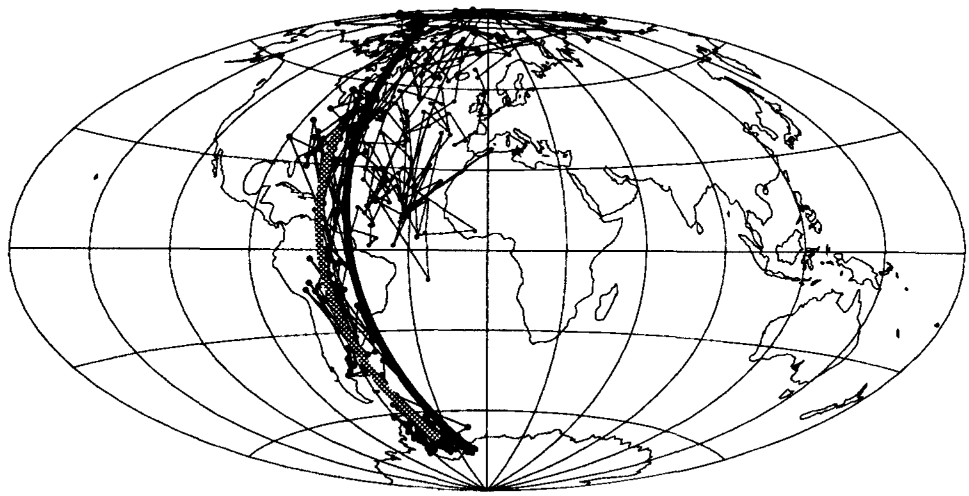
5. The transition records

The registration of the lower Thvera transition record in the HT component (Fig. 10) shows a smooth reversal from reversed to normal directions, starting at level 15 cm. At the end of the transition between levels 50 and 55 cm, a small "acceleration" to normal declinations (including the rotation) can be seen in the lower part of the (supposedly) grey layer. The directional changes of the entire transition take place in 40 cm. This interval would represent some 8.0 kyr using a sedimentation rate of 5.0 cm/kyr.

The upper Thvera record, on the other hand, appears to be complicated and essentially four main features can be recognized (Fig. 10): two excursions in the lower part, the transition itself and one more excursion in the upper part. Excursion 1 (between 0 and 15 cm) shows a large swing of, in total, more than 100° in declination to the west, and even some 70° within 2.5 cm. This excursion is rapid and is consistently recorded in the declination. There is no corresponding swing in inclination, only a slight steepening can be seen. After the return to stable declinations (again including the 35° rotation) there is a second swing in declination: excursion 2 in the interval between 25 and 70 cm. The inclinations remain steep. The return to normal directions does not include the 35° rotation. The third feature is the actual transition. This takes place between levels 80 and 105 cm (within the grey layer), although at levels 80–85 cm some rapid changes can be seen. Using a sedimentation rate of 4.4 cm/kyr, this interval represents some 8.0 kyr. During the transition at level 93 there are some rapid changes in declination as well as inclination.

The stable, post-transitional reversed directions are followed by excursion 3. This excursion coincides with the boundary between the grey and white lithology. Moreover, the main part of the excursion is in a brown coloured part of the white layer, the part of the lithology where in the rock magnetic section the maximum in goethite was found. This makes it a priori very unlikely that excursion 3 was caused by directional changes of the geomagnetic field.

upper Thvera



lower Thvera

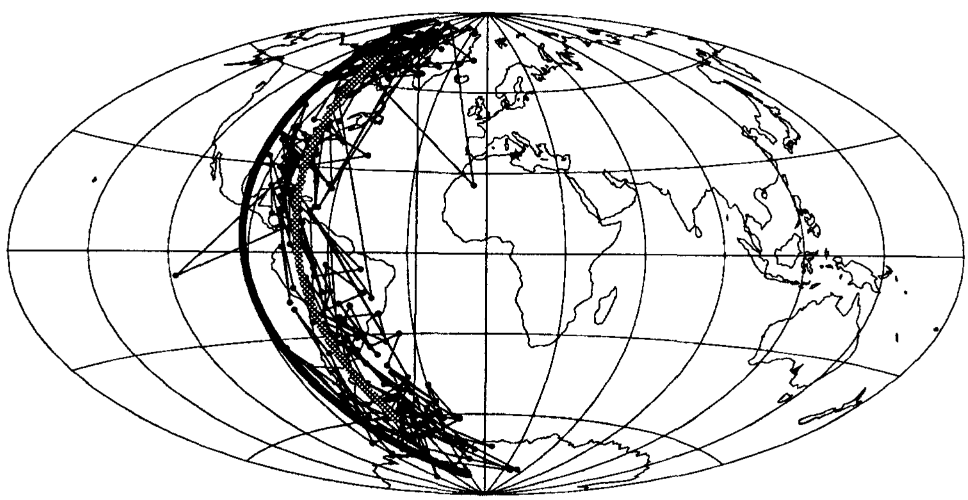


Fig. 11. Aitoff projection VGP paths of the transitions show a strong confinement to a great circle over North and South America. The excursions preceding the upper Thvera transition (smaller symbols) have their VGP's north of the equator in the Atlantic. Star = location of the site; solid line = the VGP path obtained by filtering the mean directions of under/overlying polarity zones resulting from magnetostratigraphy [12]; shaded line = filtering of near-transitional directions determined from the reversal records. The near-transitional directions are the same as in Fig. 9, except for the normal directions preceding the upper Thvera transition. There the mean direction of the ChRM's between levels 85 and 92 cm was used.

5.1 Intensity

The observed changes in magnetic mineralogy over the transition records do not allow the intensities of the ChRM (510°C) to be used as a measure of the relative paleointensity of the geomagnetic field during the transition. For a magnetite-dominated magnetic mineralogy like the Trubi sediments [21], King et al. [30] proposed a method which uses the ARM intensity as the normalizing factor for the abundance of magnetite carrying the remanence. Since the ChRM was determined at temperatures higher than 510°C, we used the ARM intensity at 510°C as a normalizing factor, although the NRM and ChRM demagnetization curves are somewhat different (Fig. 8). The number of data points of the ChRM exceeds the number of ARM points, therefore a linear interpolation was used between the subsequent ARM data points. The ratios ChRM (510°C)/ARM(510°C) were calculated by first smoothing the ChRM intensity record with a 5 cm wide rectangular moving window and normalizing it with the interpolated ARM data points.

The normalized intensity of the lower Thvera record shows a clear maximum at level 75 cm (Fig. 10). There are small local maxima at levels 2 and 57 cm, respectively. The upper Thvera record starts with very high values of 23 mA/m (not shown in Fig. 10 to enhance variations in the lower intensities), and it has a minimum of 0.15 at level 8 cm. This minimum coincides with excursion 1. The ChRM/ARM ratio increases gradually to 1 at level 85, which is at the onset of the actual transition. The intensity minimum between 100 and 115 cm is followed by a local maximum at level 125. Above level 125 there is another decrease in intensity. This decrease occurs at excursion 3, which is most likely caused by a lithological change at that level.

6. Discussion

6.1 The Sicilian lower and upper Thvera records

The average sedimentation rate during the Thvera subchronozone has been established at 4.4 (upper Thvera) to 5.0 (lower Thvera) cm/kyr [11,13,16]. The sedimentation rate during the deposition of the grey and beige marls could be somewhat higher due to increased continental run-off and a constant carbonate flux [14], or somewhat lower due to increased carbonate production in the white marls while the flux of the non-carbonate fraction is constant [31]. The difference in ages between the midpoints of two subsequent grey layers [13] is the time during which one quadruplet is deposited. By considering this deposition time, the thickness and carbonate content of each individual layer, we can compute the average sedimentation rate of each individual layer. This results (with the assumption of a constant carbonate production with a varying non-carbonate fraction, or a constant non-carbonate fraction with a varying carbonate production) in a variation in sedimentation rate from 3.9 (resp. 3.5) cm/kyr in the white (beige) layers to 5.3 (resp. 6.2) cm/kyr in the beige (white) layer and from 3.5 cm/kyr in the beige layers to 6.2 cm/kyr in the white layer. These values will not significantly alter any conclusions about the duration of the record, so sedimentation rates of 5.0 and 4.4 cm/kyr are assumed for the lower and upper Thvera records, respectively.

The VGPs were calculated after applying a 35° correction for the clockwise rotation of the location. The VGP paths of the two transitions are very strongly confined to meridians over both the Americas (Fig. 11). The VGP paths of the two excursions preceding the upper Thvera transition lie in the northern Atlantic. Tric et al. [8] showed that VGP paths of two-thirds of recently obtained transitions behave very similarly to those of the lower and upper Thvera. Laj et al. [7] pointed out that the same bands of longitude are important in other geophysical observations, such as the pattern of fluid motion in the outer core and regions of higher seismic velocities in the lower mantle, suggesting a causal relationship. However, Rochette [4] showed that smoothing of the non-antipodal directions before and after a transition will also result in VGP paths with a strong longitudinal confinement. By smoothing the mean stable directions before and after late Miocene and Pliocene transitions sampled in the Mediterranean, Langereis et al. [6] found synthetic VGP paths confined to the Americas which were identical to the observed VGP paths.

Mean stable directions were determined (Fig. 9) by averaging the directions over a sedimentary interval just before or after the transitions where the changes in directions are due to noise. The stable directions of the polarity zones before, during and after the Thvera subchronozone from the magnetostratigraphic study of the Eraclea Minoa by Hilgen and Langereis [11] are shown in Table 1, together with the near transitional directions. The mean directions of the previous reversed polarity zone and the Thvera subchronozone show a marginally positive reversal test (class C) [26], while the mean directions of the subsequent polarity zone and the Thvera subchronozone, as well as the near transitional directions, have negative reversal tests. Synthetic VGP paths were calculated by smoothing the mean stable magnetostratigraphic directions (Table 1) before and after each transition, using the method of Rochette [4] (thick lines, Fig. 11). The lower Thvera synthetic VGP path is some 30° away from the observed VGP path of the lower Thvera transition. The upper Thvera synthetic VGP path has the same band of longitude as the observed upper Thvera VGP path.

Using the same procedure, the synthetic VGP paths were also calculated by smoothing the mean stable directions just before and after the transitions (Fig. 9). The coincidence of the observed VGP paths with these synthetic VGP paths is even more striking (shaded lines, Fig. 11). The smoothing may well be due to the filtering mechanism of remanence acquisition in these sediments. The coincidence of the transitional data and the smoothed non-transitional directions is also apparent in several other transitional records from the Sicilian Trubi marls [6]. This strongly indicates that the filtering mechanism of the acquisition of the sediment obscures the real geomagnetic transitional directions.

Hoffman [32] found, in transitional records from lava sequences (which are not or hardly smoothed), long-lived VGP positions clustering at spots on the globe that coincide with the preferential longitudinal bands over the Americas or its antipode found earlier [7,8]. These recurring clusters are still highly hypothetical and they may only reflect short periods of active volcanism during transitions. On the other hand, if these clusters do represent a stage of a dipolar transitional configuration, the VGP will be independent of the sampling site on the globe. Filtering of this record by a sedimentary NRM acquisition will result in a VGP path that includes the spot of these long-lived VGP positions and (if the filter width is large relative to the time of the transition) the longitudinal bands that contain these spots. Therefore, depending on the relative filter width of the sediment, some information about the transitional path may be registered by sediments and the synthetic VGP path will be confined to the Americas or its antipode.

Since the demagnetization curves of ARM and ChRM are slightly different, calculation of the relative paleointensity may not be meaningful. Indeed, the absolute maxima in the relative paleointensity records are due to high ChRM intensities as well as extremely low ARM(510°) intensities. A high geomagnetic field intensity cannot change the magnetic parameters such as the ARM(510°), so the paleointensity records must be considered unreliable. Similarly, since the demagnetization curves of J_{rs} and ChRM are different (Fig. 8), J_{rs} is also unsuitable as a normalizing factor. Another commonly used method for determining paleointensities is the ChRM/χ_0 ratio. The χ_0 records of both transitions (Fig. 4) show the same tendency as the ARM(510°) records,

TABLE 1

Mean declinations (dec) and inclinations (inc) of subchronozones before, during and after the Thvera suchcronozone

Subchrononzone	dec	inc	N	$r$sum	Length (cm)	Angle	Critical angle	Results
4.47–4.57	187.1	−41.4	7	6.93	500			
						10.3	8.0	neg
Thvera	−4.6	47.4	11	10.86	1200			
						7.8	10.7	C
4.77–4.86	186.5	−50.3	4	3.96	500			

Figures in first column are the ages of the boundaries of the subchronozones. N = number of samples; length = length of subchronozone; $r$sum, angle, critical angle and results (negative or class C) are parameters from the reversal test [26].

and the ChRM/χ_0 ratio will, therefore, result in the same maxima as those shown in Fig. 10.

6.2 *Comparison of the upper Thvera records from Sicily and Calabria*

We have compared the Sicilian and Calabrian records from the same upper Thvera transition in the Mediterranean region, because both records should be identical up to very high order coefficients. The upper Thvera transition record was earlier reported as one of five successive transitions [2]. These transitions were sampled at the Singa section, some 250 km from Eraclea Minoa (Fig. 1) in the Calabrian Trubi sediments. The grey–white–beige–white sequence in the Sicilian Trubi is equivalent to a grey–white sequence in the Calabrian Trubi [15]. Therefore, the vertical scales have been stretched linearly so that the boundaries from grey to white at levels 0 and 125 cm in the Sicilian record are almost coincident with the same boundaries in the Calabrian record (Fig. 12). Although the stratigraphic resolution of the Calabrian upper Thvera record is in the order of a few centimetres (a much lower resolution than obtained in Sicily) the excursions and transition should be identical. It appears, however, that the first two excursions from the Sicilian record are either different (excursion 1) or absent (excursion 2) in the Calabrian record. Steep inclinations after excursion 1 occur in both records. The excursions cannot be caused by recent overprints because a recent overprint would have normal directions, whereas excursion 1 in the Calabrian record is even fully reversed; also showing, in addition to the Sicilian record, negative inclination values.

On the other hand, one could argue that the (tendency to) normal directions between excursion 1 and the transition are caused by a recent overprint. This seems rather unlikely because the rock magnetic parameters do not indicate secondary minerals in this part of the record. Recently, Van Hoof and Langereis [5] showed that the HT (and LT) component can acquire their remanence at a considerable depth below the sediment–water interface and that this depth lag was not constant throughout the lithology. It was suggested that the magnetic minerals carrying the components were authigenically formed under

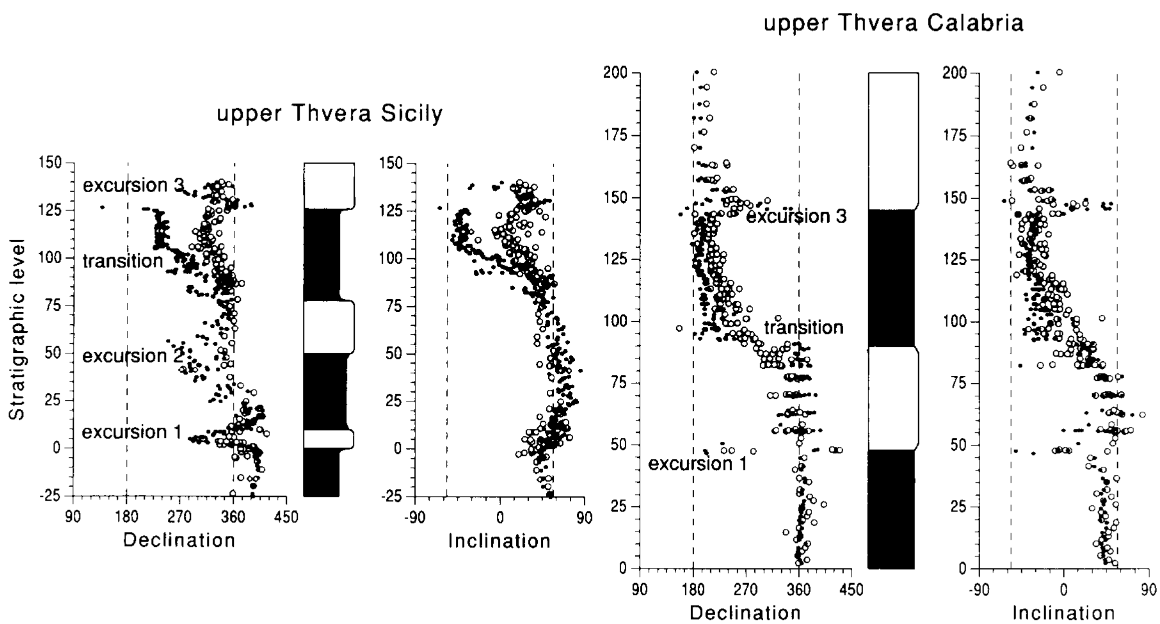


Fig. 12. Comparison of the upper Thvera record from the Sicilian Trubi Formation and the one from the Calabrian Trubi Formation [2]. The vertical scale is changed calibrate the same lithological boundaries from grey to white. In the Calabrian sampling excursion 1 is present as full reversed directions, excursion 2 is absent, the transition takes place lower and faster in the sediment and transition 3 is similar to that in the Sicilian record.

different and cyclically fluctuating paleoredox conditions. This mechanism does explain excursion 1 if it is assumed that, in the Calabrian record, the white layer has totally acquired the post-transitional, reversed direction, while the Sicilian record has only partially acquired the post-transitional directions in excursions 1 and 2.

Van Hoof et al. [1] have suggested that, due to the changing paleoredox conditions, a migration of Fe^{2+} and Mn into mainly the lower white (i.e., on top of grey and below beige) layers will take place, leading to the formation of secondary magnetite. Therefore, a maximum delay in the lower white layer is most likely. The transition itself in the Calabrian record is somewhat lower in the sediment and somewhat "faster". In spite of some small differences in the transitions, the VGP paths of both upper Thvera records are confined within the very same great circle over North and South America. Langereis et al. [6] indicate that the VGP path of the Calabrian record may also be attributed to a smoothing process of the sediment, similar to the VGP paths of the transitions in this paper.

Excursion 3 is also recorded in the Calabrian Trubi as fully normal directions; it is more or less identical in both records but, in both cases, we attribute this feature to a very recent overprint caused by weathering. Contrary to the Sicilian record, the LT component in the Calabrian sediment has clearly recorded the transition. This indicates that this component in the Sicilian record (if present at all), has an different origin from than in the Calabrian record.

7. Conclusion

We have identified magnetites as the most important carrier of the HT and LT components in records of the lower and upper Thvera reversal boundaries recorded in the Trubi marls of Sicily. The lower Thvera transition is recorded as a smooth change from reversed to normal directions. The actual upper Thvera transition is preceded by two "excursions" and followed by another. This last "excursion" is most probably caused by a recent overprint due to weathering. The two excursions preceding the transitions are considered to be sedimentary artefacts due to early diagenetic processes. The directions of the excursions are inferred to be caused by the post-transitional reversed geomagnetic field. The observed HT (and LT) components in this sediment interval most probably acquired post-transitional directions due to the formation of secondary magnetite, while outside the excursion the sediment had already acquired the pre-transitional directions. The upper Thvera transition, itself, is a smooth change from normal to reversed directions.

The relative paleointensity record was obtained by normalizing the ChRM(510°C) with ARM(510°C). The minima and maxima are not only due to changes in ChRM(510°C) but also to the (lithology dependent) ARM(510°C), indicating that the normalizing procedure (with ARM(510°C)) is probably not suitable for determining paleomagnetic field changes in intensity. In addition, if the ChRM is the vector sum of normal and reversed directions caused by smoothing, then the intensity is low while the geomagnetic field intensity during the normal and reversed directions may be strong. The VGP paths of the upper and lower Thvera are most probably the result of smoothing of the stable directions before and after the transition [3,5]. In addition, it is unlikely that the complex behaviour of the upper Thvera record is a registration of the transitional geomagnetic field because the directional changes do not completely match directional changes of the Calabrian upper Thvera record only about 250 km away.

For a study of the long-term geomagnetic behaviour (magnetostratigraphy), these sediments are very suitable, since they match the geomagnetic polarity time scale very well [cf., 11]. Any study of polarity transitions however, necessitates an extremely good understanding of remanence acquisition in sediments and requires ample rock magnetic and geochemical studies.

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