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Carlo Laj, Sylvie Guitton, Catherine Kissel, Alain Mazaud, Sylvie Gultron. Complex Behavior of the Geomagnetic Field During Three Successive Polarity Reversals, 11 -12 m.y.B.P. Journal of Geophysical Research, 1988, 93 (B10), pp.11655. 10.1029/JB093iB10p11655 . hal-03551036

HAL Id: hal-03551036

<https://hal.science/hal-03551036>

Submitted on 1 Feb 2022

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Complex Behavior of the Geomagnetic Field During Three Successive Polarity Reversals, 11 - 12 m.y. B.P.

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Detailed paleomagnetic records of both the directional and relative field intensity changes occurring during three sequential polarity reversals have been obtained from marine clays of Serravallian-Tortonian boundary age in the island of Zakinthos (Greece). The three reversals are characterized by a complicated geometrical and temporal structure. Periods of rapid changes of the geomagnetic field vector alternate with periods of near stationarity. Different episodes of collapse and recovery of the field intensity and the presence of "rebounds" have been documented. Overall the records obtained here are reminiscent of volcanic records and appear much more complex and quite different from those previously obtained from upper Tortonian marine clays in Crete, in the same geographical area. The bearing of these results on some of the published reversal models is discussed, and it is also suggested that the greater complexity of the Zakinthos records might be related to the fact that they are exactly coeval with the last reversal spurt documented by reversal frequency analyses.

INTRODUCTION

The first suggestion that the geomagnetic field might have changed polarity in the past was advanced at the beginning of our century [Brunhes, 1906]. However the reality of the phenomenon and its planetary character was definitively proved only in the early 1960s, when Cox *et al.* [1964] used the newly developed K/Ar isotopic dating method to establish a one-to-one correlation between the magnetic polarity and the age of rocks of different nature and geographical origin.

Since this brilliant demonstration of the existence of one of the most unpredictable and dramatic properties of the geomagnetic field, records of polarity reversals obtained from a wide variety of rock types have provided important insight into the mechanisms of the Earth's dynamo. Comparing the records of the Matuyama-Brunhes transition obtained at Lake Tecopa in California and at the Boso Peninsula in Japan, for instance, Hillhouse and Cox [1976] demonstrated the non dipole character of the transitional field. Although a very recent work [Valet *et al.*, 1988a] indicates that the paleomagnetic directions of the original work are somewhat overprinted, Hillhouse and Cox's paper has been one of the major steps and has provided a guideline in the study of magnetic reversals. Subsequently, the analysis of a large number of sedimentary and volcanic records has documented some of the geometrical and time dependent characteristics of the reversing geomagnetic field [Fuller *et al.*, 1979; Hoffman, 1984; Bogue and Hoffman, 1987].

Many of the published studies concern single records of different reversals recorded at different sites. Recently it has been shown that valuable information can be obtained from

studies of sequential reversals recorded at a single site, which allow observation of the evolution of the transitional field characteristics over a period of time [Valet and Laj, 1984; Bogue and Coe, 1982; Valet *et al.*, 1988b; Clement and Kent, 1985; Theyer *et al.*, 1985; Clement, 1987]. These sequences have provided evidence that some of the characteristics of the reversal process may persist unchanged for periods spanning several polarity chrons, and also that transitional fields may vary dramatically after such periods of invariance.

Up to now, however, studies of sequential reversals have concerned periods of time of the order of 1 m.y. or so. New theories, arisen in geophysics in the most recent years, consider the Earth as a single system in which all the phenomena occurring from the core to the mantle and the upper crust are interrelated. In view of these theories, it is now interesting to explore the characteristics of the reversal process over longer periods of time, of the order of the time constants of mantle overturn.

In this paper we report the results obtained on three sequential reversals recorded in marine clays of Serravallian-Tortonian boundary age in the Island of Zakinthos (Greece). A preliminary report on one of these reversals has already been given elsewhere [Laj *et al.*, 1987]. Here we give the complete results and compare the characteristics of these reversals with those of four sequential reversals of late Tortonian age already reported from western Crete in the same geographical area [Valet and Laj, 1984; Valet *et al.*, 1988b]. The two sequences are thus separated by an interval of some 5 m.y., a first step to study the characteristics of the reversal process over long periods of time.

GEOLOGICAL SETTING AND SAMPLING

The sampled section of Serravallian-Tortonian boundary age (11-12 m.y.) as determined by nannofossil stratigraphy [Jamet, 1982] is situated near the village of Maherado on the flank of a major monocline in the island of Zakinthos

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Paper number 7B3071.
0148-0227/88/007B-3071\$05.00

Fig. 1. Schematic geological map of the island of Zakynthos showing the location of the village of Maherado. Age of the geological formations are: 1, Triassic; 2, Cretaceous; 3, Eocene; 4, Oligocene; 5, Miocene; 6, Pliocene; 7, Quaternary; and 8, axis of the anticline.

in Greece (Figure 1). Because of the geodynamical evolution of the Aegean area, this island has undergone a 26° clockwise rotation and a $3\text{--}4^\circ$ northward drift since the deposition of the sediments [Laj *et al.*, 1982; Kissel, 1986]. Recent bulldozer leveling of the section has uncovered a well-exposed fresh outcrop consisting of 20 m of fine blue gray marine clays, with a very regular bedding tilting $30^\circ \pm 5^\circ$ toward the northeast. A preliminary magnetostratigraphic study of 27 different horizons regularly spaced over the entire section allowed us to locate three polarity reversals, named ZM01, ZM02, and ZM03 from the bottom upward, at levels 8.8, 11.8, and 17 m, respectively. A marked discontinuity in the ZM03 transitional zone indicates the most probable existence of a sedimentary hiatus at this level.

Three field trips were necessary for the sampling. The cores were obtained with an electric drill powered by a portable generator, using a 25-mm barrel with a sintered diamond cutting edge. Water or sometimes pressurized air was used as a coolant. The drill was hand held in some cases for obtaining cores about 12–15 cm long. In other cases, and especially for sampling ZM01, a 26-cm corer was used and the drill installed on a sliding frame perpendicular to the bedding. Cores up to 24.5 cm long were recovered. Most of the cores were cut into 22x25 mm cylindrical specimens directly in the field. The long ones however were brought back to the laboratory without cutting.

Careful attention was paid to the determination of the stratigraphic position of the cores. In the case of ZM03 the

sampled transition zone is situated on an almost vertical slope, and we used a method described elsewhere [Valet, 1985]. For the ZM01 and ZM02 transitional zones a reference frame oriented parallel to the bedding plane was placed on the sampled portion of the section, and the position of the top of each core was measured with a ruler carefully oriented perpendicular to the frame. Multiple measurements gave the same results within 0.5 to 1 cm between cores, depending on their position. The stratigraphic position of the different specimens obtained from each core was calculated taking into account the stratigraphic position of the top of each core and its orientation parameters and the width of the saw used to cut the cores. Each of the very long cores drilled perpendicular to the bedding covers an appreciable fraction of the transitional zone with no relative stratigraphic error among the different specimens issued from it. In some cases up to eight 22-mm-long specimens or sixteen 11-mm-long ones, were obtained from a single long core.

SEDIMENTARY AND MAGNETIC CHARACTERISTICS OF THE CLAYS

The main sedimentary and magnetic characteristics of the section have already been investigated in previous geodynamical studies [Laj *et al.*, 1982]. Nevertheless, we have done additional analyses not only to verify that these clays are suitable for a paleomagnetic study of reversals, but also to a certain extent, to establish their close similarity with those of upper Tortonian age already studied in western Crete [Valet, 1985; Valet *et al.*, 1988b].

TABLE 1. Mean Concentration of Major Minerals Obtained by Microprobe Analysis for Each Transition.

	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	K ₂ O	CaCO ₃	TiO ₂	MnO ₂	Fe ₂ O ₃
ZM01	34.41	31.94	11.29	5.40	3.03	2.14	0.89	0.56	
ZM02	43.32	32.37	11.32	5.98	3.79	2.16	0.94	0.59	0.39
ZM03	47.53	29.63	10.32	5.61	3.87	2.00		0.59	0.41

Sedimentary Characteristics

X ray diffraction analyses show that the mineralogy comprises detrital quartz, clay minerals, some feldspars, and carbonate. Chlorite, illite, and kaolinite dominate the clay fraction. The relative abundances of these components are quite constant over the entire stratigraphic height of the section, and their mean values are very close to those previously reported from Crete [Vale, 1985; Vale *et al.*, 1988b]. Furthermore, a microprobe examination of a series of samples shows that the concentration of the major elements Ca, Si, Al, and Fe, in order of decreasing abundance, is also quite constant over the entire section. The mean values for each transitional zone, reported in Table 1, are also very close to those observed in Crete. Thus there is a very marked similarity between the sedimentary mineralogy of the Serravallian-Tortonian Maherado section and that of the upper Tortonian sections studied in Crete.

Measurements of the anisotropy of the magnetic susceptibility show that in the lower part of the section (which includes the ZM01 and ZM02 transition zones) the magnetic fabric is characterized by an oblate ellipsoid with the minimum axis, K_3 , perpendicular to the bedding, typical of calm water sedimentation. A well-defined lineation exists with the maximum susceptibility axes K_1 horizontal and tightly grouped about the axis of the structure (N165°E). In the upper part of the section the susceptibility ellipsoid is prolate, K_2 and K_3 are very close in magnitude and form a girdle around the K_1 axis which is also aligned along N165°E. This form of the susceptibility ellipsoid is typical of the very early stages of deformation in consolidated sedimentary rocks [Lowrie and Hirt, 1987] and it has been interpreted in this way in a recent investigation of the magnetic fabric of sedimentary formations in northwestern Greece [Kissel *et al.*, 1986]. Visually however the sediments do not appear at all deformed or in any way different from those of the lower part of the section. The perfectly opposed normal and reverse directions obtained outside the transition zones are coherent with those obtained from coeval sites in Zackynthos and the surrounding regions indicating that the directions are not significantly affected by the deformation.

Magnetic Mineralogy

Measurements of the isothermal remanent magnetization (IRM) acquired stepwise in fields up to 1.5 T, of the low field magnetic susceptibility χ , and of the anhysteretic susceptibility $\chi(\text{ARM})$ (anhysteretic magnetization acquired

in a 100 mT AF and 1 mT direct fields), were used to identify the magnetic minerals.

The results indicate that $95 \pm 5\%$ of the saturation isothermal magnetization (SIRM) is acquired in a field of 0.2 T. Subsequent alternating fields or thermal demagnetization shows that the median destructive field of the SIRM is 25 mT and that complete removal of the magnetization is obtained by heating at temperatures between 500° and 580 °C, indicating that magnetite is the dominant magnetic mineral.

The χ/SIRM ratios are grouped around the mean value of 7×10^{-5} m/A over the entire section. The $\chi(\text{ARM})/\chi$ ratios of different samples, distributed along a single regression line (Figure 2), are consistent with a magnetic mineralogy dominated by magnetite with grain size of less than 10 nm [Hastra, 1982; King *et al.*, 1983].

In summary, the sediments from the Maherado section are quite suitable for a paleomagnetic study and, in particular, meet the requirements for determining the relative variations in field intensity with methods using anhysteretic remanent magnetization as a normalizing factor [King *et al.*, 1983]. The close similarity of these sediments with those of Crete is also clearly established.

Fig. 2. Relation between the anhysteretic susceptibility ($\chi(\text{ARM})$) and the low field susceptibility (χ) showing the homogeneous size of the magnetic grains.

Fig. 3. Typical demagnetization diagrams. The stratigraphic height of the samples, reported in each diagram (H in meters), identifies their position in the stratigraphic column of Figures 4 and 9. The solid and open symbols represent the projection of the magnetic vector on the horizontal and on the N-S vertical plane, respectively. The NRM intensity, M_0 , is given in units 10^{-6} A/m.

The constancy of all the sedimentary and magnetic parameters over the entire section is an indication of a uniform, undisturbed sedimentary environment, so that one may assume that no drastic changes of the sedimentation rate have occurred during the deposition of the section. The hypothesis of a constant sedimentation rate appears as a good first-order approximation.

STABLE PALEOMAGNETIC DIRECTIONS

All the measurements were made using a LETI three-axes cryogenic magnetometer. Alternating field and thermal demagnetization used on pilot samples isolated the same stable paleomagnetic directions. The thermal treatment was however preferred because the results obtained by this method on groups of samples from the same horizon were systematically better grouped. Each sample has been stepwise demagnetized with a minimum of 10 steps from room temperature to the limit of reproducible results, which ranges between 500° and 580°C, depending on samples. At each step the magnetic susceptibility was measured with a susceptibility bridge. No significant changes in magnetic susceptibility were observed up to the highest temperatures, indicating that the magnetic minerals were not seriously affected by the thermal treatment. The stable paleomagnetic directions, isolated after 250-300°C, were accurately determined by hand fitting a straight line

through at least five or six points of orthogonal demagnetization diagrams, some of which are shown in Figure 3.

The final directions are reported as a function of the stratigraphic height in Figure 4 after correction for tectonic tilt. In these plots each point corresponds to one sample, either a 22x25 or a 11x25 mm cylinder, except in the interval 8.50-8.60 m, where 5x25 mm samples were used. The values of the declination have been corrected by subtracting 26° to account for the rotation of the island. The mean inclination value well outside the transition zones is 45°, about 12° shallower than the value expected at this latitude. Inclination anomalies of about 8-9° have been observed in similar sediments from the Hellenic Arc and ascribed to compaction [Laj *et al.*, 1982]. The inclination anomaly observed in Zackynthos most probably results in part from compaction and in part from the mentioned northward displacement of some 3-4° in latitude, documented by previous geodynamical studies [Kissel, 1986].

The sedimentation rate, which is necessary for a precise description of the time dependence of the transitional fields, can be obtained only if a correlation of the results to the polarity time scale can be established. In spite of the biostratigraphic dating at the Serravallian-Tortonian boundary, this correlation is not entirely straightforward because of the short time span of the sampled section.

Nevertheless, when such a correlation is attempted in the interval 12 ± 3 Ma, the highest correlation coefficient observed, using either the *Lowrie and Alvarez* [1981] or the *Berggren et al.* [1985] polarity scales, corresponds to correlating the observed magnetostratigraphic column to chron C5A. This yields an average sedimentation rate between 2 and 3 cm/1000 years, which is a reasonable figure for sediments of this nature in the Hellenic sedimentary arc.

INTERPRETATION OF THE RESULTS IN TERMS OF TRANSITIONAL FIELDS

The different laboratory experiments described above have demonstrated the stability and the primary character of the magnetization. Before undertaking an interpretation of the results in terms of transitional reversing fields, it is however necessary to establish that the relatively slowly deposited sediments of the Maherado section have correctly recorded the fast changing field directions. Indeed it has been shown [Salloway, 1983; Valet, 1985; Hoffman and Slade, 1986] that time averaging of the vector field may sometimes not only smooth, but also significantly alter the paleomagnetic signal. We thus examine this question before discussing the characteristics of the records.

Time Resolution of the Records

A certain amount of smoothing is inherent to any sedimentary study, if only because of the stratigraphic thickness the samples. We believe, however, that in the blue gray clays of the Maherado section, a possible post depositional remanent magnetization (PDRM) does not introduce smoothing to such an extent that most of the information is altered or lost. On this matter, fine-scale features present on the records can be taken as evidence that the influence of PDRM is indeed quite limited [Valet, 1985; Hoffman and Slade, 1986].

It is clearly visible in Figure 4 that many time dependent fine structures are present in the Maherado records. For instance the very fast episode present in both the declination and inclination records at the onset of ZM01, and which represents a complete N-R-N transition, is only 8 cm wide. Another fast episode is present at the end of both ZM02 and ZM03. Also the sharp discontinuity, associated with the visual gap of sedimentation, observed in the record of the ZM03 reversal is convincing evidence that the record had not been smoothed as a result of a thick lock-in zone of the magnetization which would cause blocking of different magnetic grains from the same stratigraphic level at different times. Moreover, as will be discussed below, the Maherado transitions are characterized by different fast episodes of collapse and recovery of the field intensity. During the ZM02 transition, in particular, the intensity recovers to the totality of its non transitional value, and the entire process of recovery and collapse is only 4 cm wide at mid-height, ruling out the possibility of substantial smoothing by post depositional phenomena.

We have also examined the effect of reducing the sample size. When the stratigraphic thickness of the sediment concerned by the PDRM is greater than the size of the sample, smoothing results mainly from the PDRM itself, and no drastic increase of the time resolution is expected from reducing the size of samples. In the opposite case, the time resolution will be increased when small size samples are used. Two different series of samples were examined: the first concerns cores sampled well outside the transitional zones, where no large and rapid directional changes of the field are expected. The cores of the second series on the contrary overlap a zone where a very fast directional change occurs. In both cases the cores have been drilled perpendicular to the bedding plane, so that different slices correspond to distinct intervals of time.

Standard size samples of the two series were successively sliced into two subsamples 11 mm thick, then into four subsamples 5 mm thick. With the inferred sedimentation rate, each of the 5-mm samples represents about a 250-year average of the geomagnetic field. At each step the samples were slightly demagnetized in a 100-mT alternating field to avoid possible spurious components acquired during the sawing [Lauer, 1978], then measured with the cryogenic magnetometer. Even the smallest samples exhibited magnetizations of the order of 5×10^{-4} A/m and thus could be measured with accuracy. A typical result, shown in Figure 5a, shows that only a very small increase of scatter of the directions, consistent with the secular variation, is observed for successive sub samples from a nontransitional zone. Strongly divergent directions are observed on the contrary for the different sub samples from the fast changing zone (Figure 5a). In all cases, the magnetization vector of a sample is always equal, within noise limits, to the average vector magnetization of the two sub samples issued from it. Moreover the results obtained from the different subsamples exhibit a perfect serial correlation (Figure 6). This clearly indicates that the time resolution of the record is increased when small size samples are used, and yields an upper limit of the order of 5 mm for the width of the zone affected by a possible PDRM.

All these characteristics thus establish that the Maherado clays correctly record fast changing field directions and can be used for the study of geomagnetic reversals. Samples 11 mm thick have been used in zones where the direction of the magnetic field was changing rapidly. Samples 5 mm thick cut from a single core were used only to study the fast episode at the onset of the ZM01 reversal. In all other cases we did not use 5-mm samples because the relative stratigraphical position of the cores is determined with an accuracy of 0.5-1 cm, which consequently is the limiting value of the overall time resolution of the records.

Directional Changes of the Field During the Reversals

The complicated pattern of the transitional directions for the three reversals is best described in terms of VGP paths, which have been calculated taking into account the rotation

Fig. 4. Plots of the observed inclination and declination values as a function of the stratigraphic height for the three reversals. Concerning transition ZM01, the fluctuations on the declination record between 8.7 and 8.9 m correspond to a period of very high inclinations. Their amplitude is thus amplified by the projection.

of the island and assuming a paleoposition 4° south of its present one. A correction of the inclination error with a formula such as that suggested by King [1955] does not significantly change the results, so no correction was applied.

Transition ZM01. As shown in Figure 7a, the reversal starts with a very fast episode during which the VGP

moves all the way from the North to the South Pole. Although observed in all the cores drilled in this zone, this normal to reverse episode is so fast that it has been recorded in each core by only one or two 5-mm samples, so that it covers a maximum stratigraphic interval of 10 mm. The N-S path is thus quite ill-defined, the intermediate directions suggesting that the path lies somewhat east of the site's

Fig. 5. Stereographic projection showing the effect of reducing the size of samples (a) from the nontransitional zone and (b) from the fast changing zone (samples coordinates). The angular scatter in Figure 5a of the order of 10-15°, is consistent with a 250-year average of the secular variation.

longitude. A period of standstill at the South Pole is then recorded by a few samples, spanning a stratigraphic height of 5-6 cm, after which the VGP moves back to the North Pole. The corresponding S-N path is defined by a few samples (total duration 6-7 cm) and is situated approximately on a longitudinal band 90° west of the site.

The VGP then clusters about the North Pole for some time (~10 cm) and starts moving again toward the mid-latitudes more or less along the site meridian (Figure 7b). In contrast with the rapidity of the first N-R-N cycle, the VGP then lingers at northern mid-latitudes for a relatively long time (30% of the total stratigraphic height of the reversal) with quite a large scatter of the field directions both longitudinally and latitudinally. After this period of standstill the VGPs start moving again first to the west, then southward along a rather narrow longitudinal band centered about 90°W of the site. The South Pole is reached after a final oscillation which brings the VGP back to equatorial latitudes. The total stratigraphic height involved in the directional changes is 50 cm.

Transition ZM02. The second reversal starts with the

VGP moving from the South Pole along a meridian roughly 110° E from the site (i.e., more or less antipodal to the main part of the ZM01 path, Figure 8a). There is a severe lack of points in the equatorial latitudes, particularly in the northern hemisphere, and the path is defined again at 40° N, shifted some 60° eastward with respect to the first half of the transition (i.e., almost antipodal to the site). The VGPs are perfectly north for a while, then a rather fast episode (rebound) is recorded with the VGP shifting back to low southern latitudes and back to the North Pole, both ways along the same longitudinal part as the first half of the S-N section (Figure 8b).

Transition ZM03. The upper reversal of the section starts with a very fast episode during which the VGP shifts suddenly from a normal to a reverse dipole position in only 2-3 cm. There are no intermediate points between 60°N and 50°S (Figure 9a). This rapid shift corresponds to the discontinuity observed in the field, so that most probably it results from a small sedimentary hiatus and does not represent a fast geomagnetic change. Although the path for this episode is not precisely defined to the obtained accuracy, it coincides with that of the preceeding R-N transition ZM02.

After the fast N-R episode, the VGPs cluster about the South Pole for about 10 cm in stratigraphic height, then oscillations appear, and finally a well-defined rebound occurs, which brings back the VGPs to northern mid-latitudes. The rebound ends when the VGPs suddenly return to the South Pole. During the rebound the VGPs are largely constrained in the same longitudinal band as those for the N-R episode (Figure 9b).

Relative Changes of Field Intensity During Transitions

Although sediments are not suitable for determining absolute paleointensities, the magnetic properties of the Maherado clays, discussed above, meet the criteria for applying methods to determine relative paleointensity changes, using ARM to normalize the variations of the

Fig. 6. Plot of the VGPs obtained from a standard 22-mm sample and from the 5-mm subsamples issued from it, showing a perfect serial correlation during the fast episode of transition ZM01.

Fig. 7. Plot of the VGP path during the reversal ZM01. We have separated the path of (a) the first N-S-N cycle from that of (b) the final N-S change. This separation is entirely arbitrary and only intended to increase the clarity of the plot. There are very few points on the first N-S-N cycle in spite of the fact that 5-mm-thick samples from the same core were used, indicating a very fast rate of change of the geomagnetic field vector. This diagram is centered on the Greenwich longitude.

concentration of the magnetic minerals carrying the remanence [Levi and Banerjee, 1976; King et al., 1983]. At Maherado, the only reliable measurements of NRM intensity have been obtained after thermal demagnetization at 200-300°C. The normalizing ARM cannot be imposed on these heated samples. We have thus proceeded on "twin" samples, chosen as far as possible from exactly the same stratigraphic horizon and close to each other.

The results obtained using a 5×10^{-5} T direct and a 0.1 T - 400 Hz alternating field for imposing an ARM are shown in Figure 10, where for clarity a plot of the VGP latitudes as a function of the stratigraphic height is also reported for each reversal. If, in a general way, the paleointensity is decreased in the transitional zones to about 10-20% of its nontransitional value, each reversal has its own paleointensity characteristics, which are now described.

Transition ZM01. The initial paleointensity has about one half its posttransitional value, indicating that our sampling does not extend low enough in stratigraphic height and, more fundamentally, that the dipole strength has decreased prior to the onset of the directional changes. There is a sharp drop of the field intensity slightly before the beginning of the very fast N-S directional change. Then the intensity is reestablished to about half its posttransitional value for the brief period during which reverse dipolar directions are observed. The intensity then drops again while the VGP returns to the North Pole and does not

recover when the VGP is in a normal (north) dipole field position. There is a progressive increase of the field intensity, again to about one half its posttransitional value, during the period of time when intermediate directions occur (VGPs lingering at mid-latitudes). Finally the field intensity drops again during the last part of the reversal and is ultimately reestablished to nontransitional values after completion of the reversal.

Transition ZM02. As for ZM01 the initial intensity is low, about 1/3 of its posttransitional value, again indicating that the dipole field has significantly decreased before the onset of the directional changes. No drastic changes occur during the N-R transition; then the intensity quickly recovers to full nontransitional values, while the VGPs occupy a normal polarity dipole position. The total duration of this episode of recovery of the paleointensity is very short: as mentioned above, the intensity peak of Figure 10 is only 4 cm wide at mid-height. The intensity then drops sharply during the rebound and is finally reestablished after completion of the directional change.

Transition ZM03. In this case the intensity drops sharply to quite low values (15%) just before the onset of the directional change. The dipole strength is then partially reestablished to about one half its nontransitional value when usual reverse dipole directions are observed after the first N-R directional change. The intensity drops again during the rebound and is finally restored to nontransitional values well after the end of the directional changes.

For the three reversals the total duration of the intensity depression is thus longer than that necessary for the

Fig. 8. Plot of the VGP path (a) during the R-N reversal ZM02 and (b) during the rebound which occurs just after it. As in Figure 6, this separation is intended to increase the clarity of the plot. This diagram is centered on 120°E longitude.

Fig. 9. Plot of the VGP path during reversal ZM03. The very rapid shift that one can see on the first N-S episode (Figure 9a) corresponds probably to a sedimentary hiatus. Then a rebound (S-N mid latitude-N) is clearly visible (Figure 9b) as at the end of reversal ZM02. This diagram is centered on 120°E longitude.

directional changes. With the exception of the interval of normal dipole field configuration at the end of the fast episode in ZM01, periods of slow directional changes are associated with at least partial recovery of the paleointensity, and periods of fast changing directions with the lowest intensities.

DISCUSSION

When the transitional field is dominated by axisymmetric terms, the VGP paths lie along great circles either on the site longitude or antipodal to it ("near" or "far" sided paths) depending on the sense of the reversal [Hoffman, 1977]. This is not observed at Maherado: neglecting the ill-defined N-S part of the fast episode of ZM01, at mid- and low latitudes the paths are on average situated either 60-90° west (ZM01) or 60-110° east (ZM02 and ZM03) of the site, so that these transitions cannot be as simply classified as "near" or "far" sided. In this respect the paths for the Maherado transitions are quite similar to those of the upper Tortonian transitions already studied in western Crete whose paths are also situated roughly 90° west or east of the site depending on the sense of the transition [Valet and Laj, 1984; Valet et al., 1988b]. In both cases this is evidence for large asymmetries of the transitional field.

In most other respects, however, very significant differences are observed between the Cretan and the Maherado reversals. First of all, the Maherado records are not confined to narrow longitudinal bands as the Cretan

Fig. 10. Plots of the variation of the relative field intensity and the VGP latitude as a function of stratigraphic height for the three reversals. The intensity plots were obtained essentially using cores, broken when drilled, for which the orientation parameters were lost but a reliable stratigraphic control was available. The paleofield intensity decreases in the transitional zones to 10-20% of the nontransitional value, but each reversal has its own paleointensity characteristics which are described in the text.

ones: in the case of ZM01 there is a 60° shift in longitude between the onset and the termination of the final N-S path. A similar shift is observed for the S-N path of ZM02. This suggests that the nonzonal geometry of the transitional fields changes during the reversal process.

Furthermore, while the mean paths corresponding to ZM01 and ZM02 are to a first approximation antipodal, those for ZM02 and ZM03 virtually coincide, in spite of the fact that these last two reversals are of opposite sense. Thus the sequence of changing field directions is consistent with a flooding model when ZM01 and ZM02 are considered and with a standing field model in the case of ZM02 and ZM03. This is a marked difference with respect to the observations in Crete, where a significant longitudinal separation of the VGP paths of transitions of opposite sense was always observed. Contrary to Crete, where a period of invariant transitional field configuration for at least three successive reversals has been documented [Valet and Laj, 1984], the large changes observed in the VGP paths of the Maherado transitions indicate that in this case it is wrong to assume that a single type of transitional field is always present during the three reversals.

Another characteristic which distinguishes the Maherado from the Cretan sequence is the presence of "rebounds" in the ZM02 and ZM03 records. In both cases the two rebounds display VGP paths almost identical to those of the reversals. This similarity indicates a temporal dominance of a reversing field with an almost stationary transitional configuration, suggesting that in each case the rebound is closely related to the reversal process. The suggestion of a rebound following the main reversal and linked to it has already been advanced for the Steens Mountain reversal [Prévot *et al.*, 1985a, b], and indeed, consideration of both the directional and intensity changes during the ZM02 and ZM03 transitions yields a picture quite similar to the Steens Mountain volcanic record. In the Steens transition, however, the rebound is characterized by a large swing not related to the reversal path, indicating that different transitional geometries are involved successively. This difference between the Maherado and Steens Mountain records has led one of the authors, among others, to suggest that the reversal and the rebound of the Steens record might represent two different phenomena [Valet *et al.*, 1985]. Additional detailed volcanic records are certainly needed to establish whether this suggestion is correct or not, although recent work on sedimentary and volcanic sequences [Clement, 1987; M. Prévot, personal communication, 1987] certainly favors the original interpretation given by Prévot *et al.* [1985a, b]. The comparison of the Cretan records, where no evidence for rebounds is observed, with those from Maherado shows that the presence of highly damped, large oscillations of the field after the reversal is not a necessary characteristic of the reversal process.

From a dynamical point of view, the Maherado records are characterized by the presence of periods of rapid or very rapid changes alternating with periods of nearstationarity.

During the ZM01 reversal, for instance, the initial normal-to-reverse directional change is recorded over a maximum stratigraphic interval of 10 mm. With the inferred sedimentation rate, this corresponds to a duration of only 500 years, which is much shorter than those usually reported in the literature. Similar figures have however recently been reported for an R-N field reversal of Matuyama age recorded in lake sediments in Kashmir [Burbank *et al.*, 1986], and extremely rapid directional changes of the geomagnetic field occur during the Steens Mountain reversal [Prévot *et al.*, 1985a, b]. Thus the very rapid directional changes observed at Maherado are not inconsistent with some of the known characteristics of the reversing geomagnetic field.

The recovery and successive decay of the field intensity occurring during the three reversals are also rapid phenomena. Indeed, the entire process, which we interpret as a temporary reestablishment of a usual dipole configuration only lasts about 2000 years. A similar phenomenon has already been observed during the period of time between the two phases of the Steens Mountain reversal [Prévot *et al.*, 1985a, b].

For the ZM01 transition, it is noteworthy that no recovery of the field intensity is observed during the period characterized by a normal direction occurring after the first N-R-N cycle and lasting about 3000 years. Thus in spite of perfectly dipolar directions, this configuration cannot be considered as a reestablishment of a normal dipolar configuration, but is a transitional one. A similar transitional configuration has recently been observed during an N-S-N excursion recorded in a lava sequence in the southern hemisphere [Roperch and Chauvin, 1987]. A more stable configuration is observed in the rather long period characterized by intermediate directions and a progressive increase of the field intensity. The duration of this intermediate configuration (30% of the total duration of the reversal) indicates some degree of stability. The ZM01 record thus brings additional evidence for the existence of transient intermediate states of the geomagnetic field, characterized by nonnegligible intensity values and nondipolar directions. States with nonnegligible intensity and direction not axially dipolar have already been observed in lava sequences [Shaw, 1975]. Also, similar intermediate states exist during a two-stage process of reversal recently observed from southern hemisphere lavas [Hoffman, 1986].

Very large fluctuations in the rate of the field variations, such as those documented by this record, have already been observed elsewhere, particularly at Steens Mountain. In our opinion however, the much more continuous character of the sedimentation, when compared with the rate of extrusion of the lava flows, allows a more precise description of the time characteristics of the reversal.

CONCLUSIONS

As shown by visual inspection and by all the laboratory studies, the sediments used in both studies in Crete and

Maherado have very similar lithology, chemical composition, and sedimentation rate, so that it is very unlikely that the differences observed in the records arise from differences in the recording material. Rather, any observed difference most likely reflects differences in the transitional mechanisms of reversals occurring at different epochs, as no other major differences are expected for sites in the same geographical zone.

Comparison of the Maherado and Cretan records shows that the geometry and time dependent characteristics of the transitional field are more complicated at the Serravallian Tortonian boundary than in the upper Tortonian. This result thus underlines that it may be difficult to draw general conclusions from the study of single isolated records and stresses the importance of long sequences of reversals to improve our knowledge of the reversal mechanism.

Some of the characteristics of the complex Maherado records have a bearing on dynamo models. Indeed, it has already been observed that the occurrence of episodes of very rapid changes of the geomagnetic field support those models for reversal which involve large changes in the level of turbulence in the core under frozen-flux constraints [Prévot *et al.*, 1985b]. The time constants associated with the Maherado records are clearly at least an order of magnitude longer than those characteristics of the Steens Mountain reversal. However, they are shorter than the values usually reported in the literature for flux diffusion processes. A typical decay rate for the dipole field, assuming that the dynamo is switched off, is 10^4 years. Time constants for higher order harmonics are however shorter, as they drop with the inverse square of the order of the harmonic. Rapid phenomena, such as the fast episode observed at Maherado, can thus result from a flux diffusion dominated process, provided that this process involves only components of order higher than 5. However the initial state of the fast episode is a usual dipole, and a dipolar configuration is restored (in intensity and direction) at the end. Also there is some evidence that the transitional field can be described to a first approximation by low-order harmonics [Fuller *et al.*, 1979; Williams and Fuller, 1981]. Thus it seems very unlikely that flux diffusion processes play the dominant role in the fast episode of the Maherado reversal, which may in fact be largely related to a frozen-flux process.

Moreover the fact that widely different characteristics of the transitional field are observed over a period of only 5 m.y. appears as a negative test for a recently proposed model for geomagnetic reversals, which requires that all reversals from the same geographical zone be similar within the lifetime of mantle convection patterns [Gubbins, 1987].

Finally, one may wonder whether there is a link between the complexity of the Maherado records and the frequency of reversals. Recent analyses of the polarity time scale have shown that since 80 m.y. ago there has been a progressive increase of the reversal frequency [Lowrie and

Kent, 1983; Mazaud *et al.*, 1983; McFadden and Merrill, 1984]. Although the identification of an oscillating component superimposed on this trend has been a much debated problem [Mazaud *et al.*, 1983; McFadden, 1984; Pal and Creer, 1986], it can be checked directly on any modern polarity scale that, independently of any statistical study, the period 10-12 m.y. B.P., i.e., the Serravallian-Tortonian boundary is characterized by a high reversal frequency. It has also been shown theoretically that helicity fluctuations in a turbulent core may well trigger reversals [Olson, 1983], suggesting that periods of high reversal frequency may be in turn interpreted as periods of increased core turbulence. One may then reasonably wonder whether reversals occurring during such periods have the same morphology as those occurring during a calmer period.

From a methodological point of view, the Maherado records prove that very fine details of geomagnetic reversals can be recovered from carefully selected sedimentary sequences. These sequences, which combine an appropriate chronological control, a continuous recording and the possibility of correlation among reversals at different sites are in our opinion particularly well adapted for this kind of study, in spite of the complicated nature of their magnetization.

Acknowledgments. We wish to thank J. Tessier, P. Tucholka, and J.P. Valet for their constant help throughout this work. We are very indebted to Iannis and Katharina Notis for their warm Greek hospitality during the sampling, which took place in their back yard! The director of the IGME at Athens kindly provided the necessary permit. Financial support has been given by the CEA, the CNRS, and the INSU-ATP Noyau. CFR contribution 929.

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(Received November 20, 1987;
revised May 6, 1988;
accepted May 10, 1988.)