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New paleomagnetic results from the Aegean extensional province

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Abstract

Various Oligocene formations from NE Greece (ignimbrites from the Medousa area, rhyolites from Zagradenia, granodiorites from Elatia) show discordant paleomagnetic signatures, in each case indicating small cw (clockwise) rotation and also inclination flattening. Marls from Pithion were partly remagnetized in a present-day field. Samples that contain ancient magnetization components also indicate small cw rotation and inclination flattening. However, the magnetization of andesites from Peplos reflects a considerably larger rotation, likely owing to local tectonics.

In the context of previous work in the area, these results are used to propose a subdivision of NE Greece into four structural zones of distinctive rotational behaviour (from east to west): sites in zone 1, east of the Kavala-Xanthi-Komotini fault (KXK), show various cw and ccw (counterclockwise) rotation angles owing to complex kinematics resulting from the interaction of the KXK and the north-Anatolian fault zone. However, zone 2, between the KXK and the Strymon valley, is structurally homogeneous ($\sim 10°$ cw rotation). The paleomagnetic signature of the Vertiskos massif (zone 3) implies a larger ($> 30°$) cw rotation, whereas sites in the Vardar basin (zone 4) contain a paleomagnetic signature similar to that of zone 2. This suggests a motion of the Vertiscos massif, a meta-ophiolitic nappe, relative to underlying strata. Indeed, zones 2 and 4 may be parts of the same structural unit which underlies this nappe.

Introduction

We report new paleomagnetic data from five areas in north-eastern Greece. The results are mostly discordant and reflect post-Tortonian tectonic movements in the Aegean extensional province. The present study is part of an ongoing project which aims to contribute to the understanding of the paleogeodynamic development of the Balkan Peninsula. Specifically, establishing the dimensions of individually moving tectonic units and their motions relative to each other is of fundamental importance in order to understand better the tectonic processes responsible for the present structural situation.

Paleomagnetism is the most suitable tool for this objective, because deviations of obtained magnetic declinations from reference directions provide a measure for the rotations of tectonic units around vertical axes. The spatial distribution of such rotational values forms a framework to characterize the tectonic units within the study area.

Northeastern Greece has been (and is) the subject of many paleomagnetic investigations. Nevertheless, owing to the complex nappe tectonics within the area, a more detailed database within some units, and also new data from those units that were not studied before, are needed. Previous paleomagnetic work conducted in the area is not systematically reviewed here because Kondopoulou et al. (1996) already gave a recent review.

Geological setting

The Aegean extensional province consists of the North Aegean trough and northeastern mainland Greece ranging from the Vardar zone to Thrace. The complex structural appearance of the area reflects two major deformation phases: a predominantly compressive phase during the Mesozoic and early Cenozoic, and an extensional phase since the Miocene.

Owing to the collision of the Moesian continent to the northeast and the Rhodope to the southwest, Tethyan ocean floor was thrust upon continental units. Terranes within the nappe system are characterized by individual deformation and metamorphism histories. A crustal-scale duplex could be identified that consists of a meta-ophiolitic hanging wall (upper terrane) and a continental footwall (lower terrane). Four intermediate sheets of continental origin are stacked between these main units (Burg et al. 1996). Radiometric mineral dates from the area are mostly between 195 and 32 Ma and indicate the latest event of regional metamorphism and thus the end of the first deformation phase (Dixon & Dimitriadis 1984).

After the first deformation phase, an Eocene to Miocene thermal event resulted in abundant dikes and lava flows, and also plutons, that deformed the nappe system into dome and basin structures. Volcanic activity climaxed in the late Oligocene (Innocenti et al. 1984). Influx of water-bearing volatiles into the melting zones caused emplacement of voluminous ignimbrite sheets in the central Rhodope (Eleftheriadis 1995).

Crustal thickening causing gravitational instability resulted in the collapse of the orogen in the middle Miocene (Zagorčev 1992a). Thus, the neotectonic development of the area is dominated by extension that is accommodated in large NNW-trending basins (Vardar, Strymon, Drama, Thermaikos). The oldest syntectonic sedimentary units are some 15 Ma old (Dinter & Royden 1993). Miocene volcanics are commonly associated with these sedimentary basins. Moreover, intercalation of volcanoclastic rocks with sedimentary rocks implies that the volcanics formed in an extensional tectonic regime (Eleftheriadis 1995). The Rhodope metamorphic core complex (the lower terrane according to Burg et al. 1996) possibly became unroofed by southwestward translation of a part of Serbo-Macedonia by the Miocene Strymon valley detachment system (Dinter & Royden 1993). The detachment fault ranges from the Aegean coast near Kavala into the Bulgarian Struma valley, called Strymon valley in Greece (Figure 1). However, according to another model, this tectonic contact is not interpreted as a Neogene low-angle normal fault, but as a thrust fault (Strimon overthrust) of at least late Cretaceous age (Kockel & Walther 1965; Zagorčev 1992a, b, 1994).

The Kavala-Xanthi-Komotini (KXK) fault separates the Greek Rhodope from Thrace. It trends SSW-NNE, i.e. subparallel to the North Aegean trough system. Movement along this fault is right-lateral.

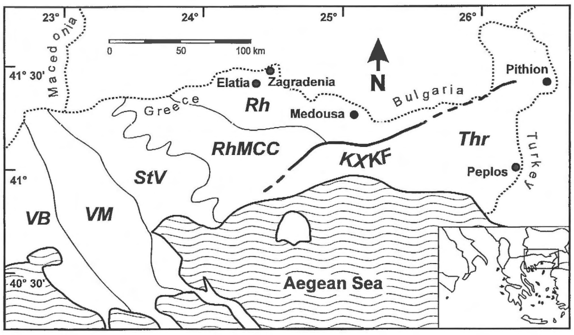

Figure 1. Study area. VB: Vardar basin, VM: Vertiskos massif, StV: Strymon valley, RhMCC: Rhodope metamorphic core complex. The Strymon valley detachment fault possibly separates the Strymon valley and the Rhodope metamorphic core complex (see text). Rh: Rhodope, KXKF: Kavala-Xanthi-Komotini fault, Thr: Thrace, dotted lines: political borders, •: areas sampled.

Sampling and procedures

A total of approximately 250 samples was taken from 23 sites in five areas (Figure 1, Table 1). In the Greek Rhodope, samples were taken from ignimbrites that crop out near Medousa, from rhyolites in the vicinity of Zagradenia, and from granodiorites of the Elatia pluton. Importantly, the ignimbrites of the Medousa area are associated with layered tuffs. For these rocks it was, thus, possible to determine the paleohorizontal. In southern Thrace, andesites were sampled near Peplos; and in northern Thrace, marls, partly intercalated with clays, were sampled near Pithion.

All of the sampled formations are of Oligocene age with the possible exception of the Elatia pluton, which probably is of late Cretaceous age but was reheated in the Eocene or Oligocene (References for age determinations are provided in Table 1). The age determination for the Elatia pluton (T. Soldatos, pers. comm. 1995) was conducted using the Rb-Sr method. Eight samples of biotite were dated 34 ± 1.0 Ma. However, one sample of muscovite yielded a date of 47 ± 1.4 Ma. Because of this discrepancy, the investigation is continued and will be published after consistent values are obtained. Likely, the pluton was pervasively remagnetized during the reheating, and, therefore, carries an Eocene or Oligocene magnetization.

Oriented cores of 2.5 cm diameter were collected using a portable coring apparatus with a non-magnetic

Table 1. Sampling data, age estimates (with references), and summary of paleomagnetic results.

Area	Lithology	n/n_0	Age [Ma]	
Medousa	ignimbrites	6/6	30 – 31	Innocenti et al. (1984)
Zagradenia	rhyolites	6/7	30 – 31	Eleftheriadis et al. (1984)
Elatia	granodiorites	6/10	39 – 47	T. Soldatos (1995, pers. comm.)
Peplos	andesites	2/4	23 – 33	Innocenti et al. (1984)
Pithion	marls	3/6	mid. Olig.	Goerlich & Gramann (1968)

Area	D/I		α_{95}	κ	R_{EA}/F_{EA}	$\Delta R_{EA}/\Delta F_{EA}$	R_{Af}/F_{Af}	$\Delta R_{Af}/\Delta F_{Af}$
Medousa	17/ 46	atc	5.4	152.8	6/11	7/5	9/9	7/5
Zagradenia	199/−49	ntc	4.5	221.6	8/9	6/4	12/7	6/4
Elatia	202/−39	ntc	11.2	36.5	11/19	12/9	15/17	12/9
Peplos	354/−27	ntc	–	–	166/28	–	163/31	–
Pithion	16/51	atc	8.8	197.1	5/7	11/7	8/5	11/7

n/n_0: sites used/total sites sampled; D/I: declination/inclination (area-mean); atc: after tilt correction; ntc: no tilt correction (paleohorizontal could not be determined); α_{95} and κ: statistical parameters of Fisher (1953); R_{EA}/F_{EA}, R_{Af}/F_{Af}: rotation and flattening with respect to Eurasian and African paleopole positions, respectively (Besse & Courtillot 1991); $\Delta R_{EA}/\Delta F_{EA}$, $\Delta R_{Af}/\Delta F_{Af}$: error limits for R and F (Beck 1980; Demarest 1983) with respect to Eurasian and African paleopole positions, respectively.

hollow drill bit. Samples were oriented in the outcrops with an orientation device consisting of a clinometer and a compass. Magnetic compass readings were compared with a sun compass. In no case NRM (natural remanent magnetization) intensitiy was high enough to influence the orientations. A standard 2.2-cm-long plug was cut from each core. Because some poorly consolidated sedimentary rocks could not be drilled, also oriented hand samples were collected. Lithological analysis was conducted at the outcrops and also on thin sections cut from representative specimens. During the sampling of the ignimbrites in the Medousa area, it was not always possible to distinguish different pyroclastic flows, due to outcrop conditions. Most likely, the six outcrops sampled represent three flow events. The same is true for the lava flows of the Zagradenia area. However, the stratigraphical and lateral distances between the outcrops sampled were sufficiently large to justify the assumption that the sites represent several flows.

Natural remanent magnetization was measured on a three-axes 2G-Enterprises cryogenic magnetometer. Specimens were subjected to a detailed stepwise demagnetization procedure by using alternating-field (AF) and/or thermal demagnetization in a shielded Shaw-furnace. During thermal demagnetization, the bulk susceptibility of the specimens was routinely measured to observe possible mineral transformations.

Paleomagnetic data analyses included principal component analysis (Kirschvink 1980) based on visual inspection of orthogonal projections (Zijderveld 1967). Site- and area-means were calculated and tested for statistical significance at a 95% probability level (Fisher 1953). To interpret the results in terms of possible discordance, the rotation (R) and flattening (F) were obtained by comparison of the area-mean values with expected magnetization directions calculated from polar wander paths for both Eurasia and Africa (Besse & Courtillot 1991). The rotation is the angular difference between observed and expected declination (positive values indicate clockwise rotation around a vertical axis), the flattening is the difference between observed and expected inclination (positive values indicate northward translation of the study area relative to a reference area). Error parameters were calculated for both R and F (Beck 1980; Demarest 1983).

Isothermal-remanent-magnetization (IRM) acquisition experiments aided identification of the magnetic mineral content of representative specimens.

Results

Ignimbrites from Medousa

The natural remanent magnetization typically decays towards the origin in a univectorial fashion. Figure 2 shows the typical behaviour of these specimens during AF demagnetization.

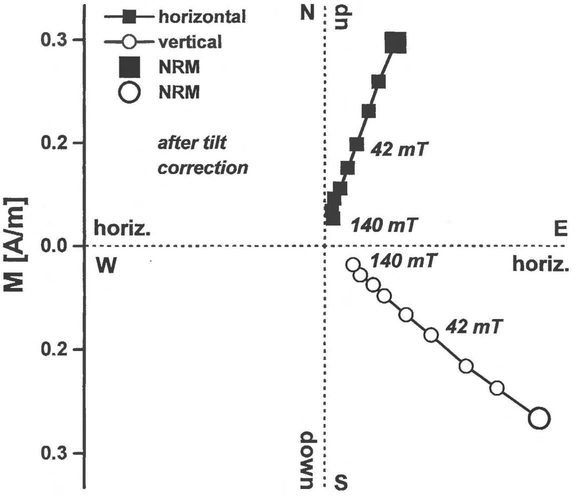

Figure 2. Representative modified Zijderveld diagram, Medousa ignimbrite. The vertical projection (open symbols) is drawn on a plane of undetermined azimuthal orientation. M: remanent magnetic intensity. mT: millitesla. The specimens contain only one NNE component of magnetization.

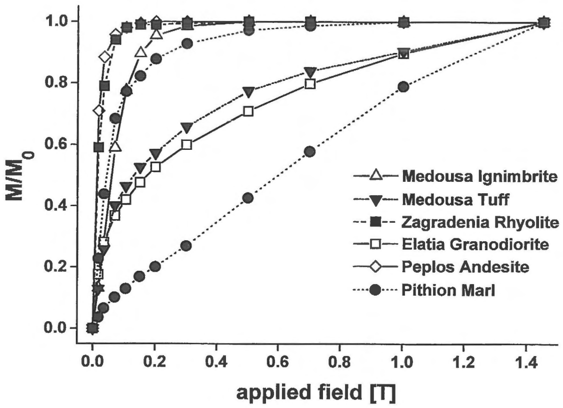

Figure 3. Representative plots of isothermal-remanent-magnetization (IRM) acquisition. M/M_0 normalized intensity. See text.

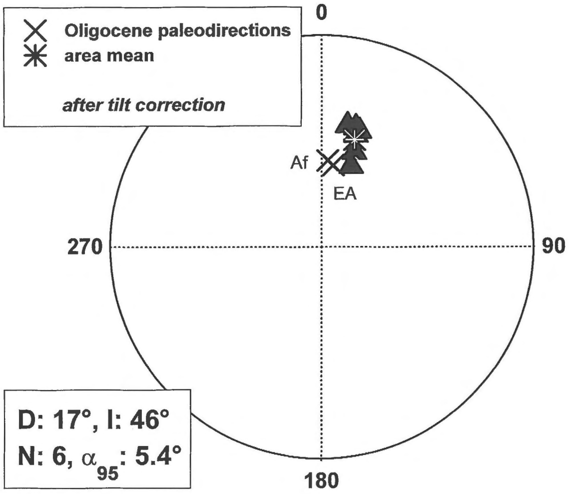

Figure 4. Site-mean magnetization directions, Medousa ignimbrites. Each triangle represents the average of the characteristic magnetization vectors of one site. The area-mean direction shows slight clockwise rotation and a flattened inclination when compared with the expected magnetization directions for Eurasia (EA) or Africa (Af). Paleopole positions from Besse & Courtillot (1991) were used. Full symbols: lower hemisphere, open symbols: upper hemisphere.

During thermal treatment most specimens do not show a good separation of the blocking temperatures; however, they typically lose approximately half of their initial NRM intensity when heated up to 500°C and completely unblock at less than 580°C. This unblocking behaviour indicates magnetite as the primary carrier of the remanence. Isothermal-remanence-acquisition experiments support this interpretation. Almost 80% of the saturation IRM is acquired when the specimen is exposed to an ambient field of 0.1 T, and saturation is achieved in an ambient field of 0.5 T (Figure 3).

The specimen directions group well within each site (κ between 129 and 264). The precision parameter κ (Fisher 1953) describes the dispersion of a population of directions. The following mean direction was obtained from the six sites after tilt correction: D = 17°, I = 46°, α_{95} = 5.4° (Figure 4, Table 1). Associated layers of tuffs were used to determine the paleohorizontal. It was not possible to conduct a fold test, because dips observed at the different outcrops were too similar. Before tilt correction is applied to the site-means, the area-mean is D = 350°, I = 60°, α_{95} = 5.6°.

Tuffs from Medousa

Unfortunately, massive welded tuffs from the Medousa area were pervasively remagnetized in a present-day field. The demagnetization behaviour indicates two magnetic phases, one of which unblocks below 150°C, suggesting goethite, whereas the other magnetic carrier unblocks at 550°C, indicating magnetite. Accordingly, IRM-acquisition curves reflect the presence of a minor low-coercivity phase and a major high-coercivity phase (Figure 3).

Rhyolites from Zagradenia

Orthogonal projections show only one southwesterly component of NRM with a negative inclination. Spec-

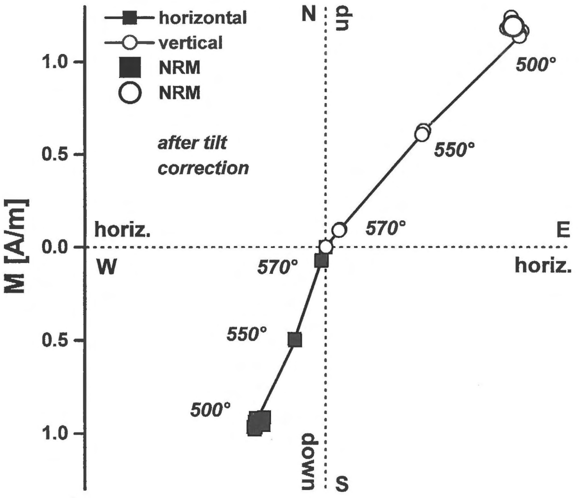

Figure 5. Representative modified Zijderveld diagram, Zagradenia rhyolite. The specimen contains only one SSW component of magnetization with reverse inclination. Cf. Figure 6.

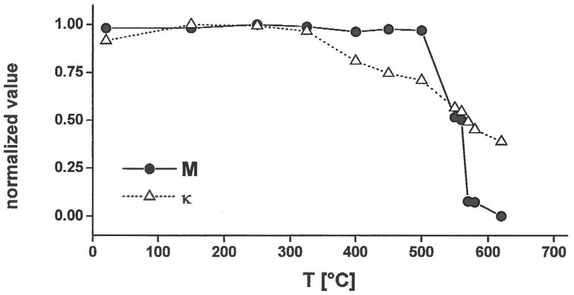

Figure 6. Change of remanent magnetization (M) and bulk susceptibility (κ) during thermal treatment, Zagradenia rhyolite. Samples typically unblock between 550 and 580°C indicating magnetite as the carrier of the NRM.

imens that were thermally demagnetized consistently show no or almost no intensity loss when heated up to 500°C and completely unblock at temperatures of less than 580°C (Figures 5, 6). This pattern indicates magnetite as the primary carrier of the NRM. IRM-acquisition experiments confirm this interpretation. In a magnetizing field of 0.1 T, the specimens typically acquire more than 95% of the saturation magnetization (Figure 3).

Again, specimen directions within each site show little dispersion (κ between 67 and 386). The area-mean was calculated using our present results and also site-means obtained by Atzemoglou et al. (1994). After rejection of one site with an outlying mean direction, the remaining six sites yielded a mean of D = 199°, I = $-49°$, α_{95} = 4.5° (Figure 7, Table 1). No tilt correction

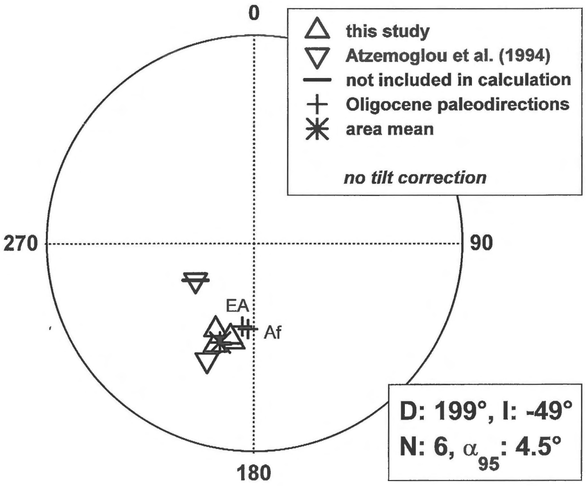

Figure 7. Site-mean magnetization directions, Zagradenia rhyolites. New results from this study were combined with data by Atzemoglou et al. (1994). The data imply clockwise rotation and inclination flattening. EA: Eurasian, Af: African paleodirection. Full symbols: lower hemisphere, open symbols: upper hemisphere.

could be applied, because the paleohorizontal could not be determined.

Granodiorites from Elatia

Unfortunately, approximately a third of the specimens yielded uninterpretable demagnetization patterns or did not reach a final magnetization component. However, the remaining specimens yielded a reverse SSW magnetization direction. Typically, specimens start to unblock at 550°C, but their blocking-temperature spectrum exceeds 600°C (Figures 8, 9). During IRM-acquisition, about a third of the saturation remanence is typically acquired in an ambient field of 0.1 T (Figure 3). Specimens gradually continue to acquire remanence in stronger magnetizing fields and do not reach saturation in the strongest field available (1.45 T). Most likely, NRM is carried by magnetite and/or hematite, but owing to the inconsistent demagnetization behaviour, it was not possible to attribute particular magnetization components to particular magnetic minerals. Again, our present results were combined with site-mean values by Atzemoglou et al. (1994).

Several sites were rejected because they yielded magnetization directions that probably result from incomplete removal of a present-day-field overprint (However, these site-means are depicted in Figure 10.). Moreover, one site merely carries a present-day-field overprint. Nevertheless, the site-means of six sites

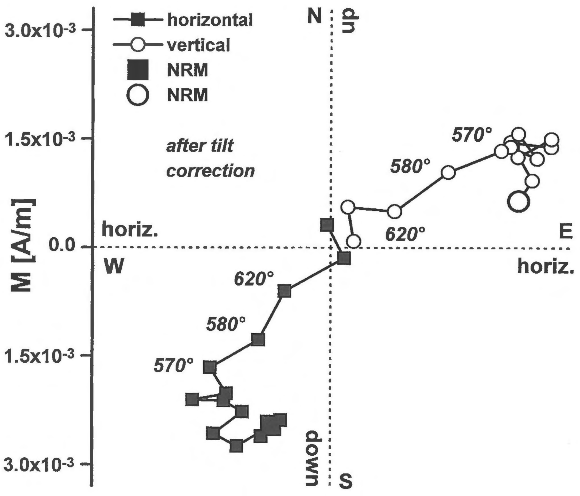

Figure 8. Representative modified Zijderveld diagram, Elatia granodiorite. Samples are weakly magnetized and exhibit a southwesterly magnetization with reverse inclination. Cf. Figure 9.

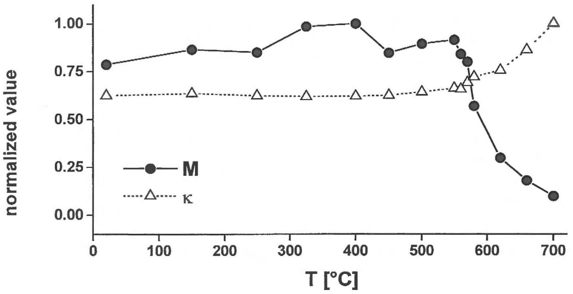

Figure 9. Change of remanent magnetization (M) and bulk susceptibility (κ) during thermal treatment, Elatia granodiorite. The unblocking temperatures of the samples indicate magnetite as the primary carrier of the NRM.

yielded an area-mean of D = 202°, I = −39°, α_{95} = 11.2° (Figure 10, Table 1). Again, these values could not be corrected for tilt.

Andesites from Peplos

Specimens from two out of the four sites contain two directions of NRM, one of which likely is a present-day-field overprint (Figure 11). This low-coercivity and low-unblocking-temperature magnetization typically is removed in an alternating field of less than 25 mT or at less than 400°C during thermal treatment. The second magnetization vector is the final component and is stable up to 120 mT or 550°C, respectively. Many specimens also contain a random magnetization component that is typically removed at less than 2 mT and was probably acquired during sample storage. Another site contains only one well-defined steep northerly magnetization with positive inclination that completely unblocks at 550°C. The fourth site had to be rejected because of the large scatter of specimen magnetization directions. Surprisingly, the high-coercivity component shows a northerly declination but a negative inclination. The average of two sites is D = 354°, I = −27° (Figure 12, Table 1). This higher coercivity magnetization is assumed to be the older component, because, unlike the lower-coercivity component, it is different from the present-day-field direction of the area.

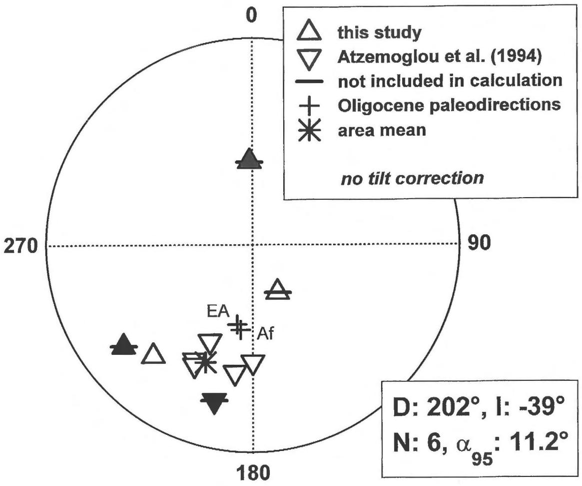

Figure 10. Site-mean magnetization directions, Elatia granodiorites. The mean values of four sites were not included in the calculation of an area-mean direction (see text). The resulting area-mean reflects small clockwise rotation and considerable inclination flattening. EA: Eurasian, Af: African paleodirection. Full symbols: lower hemisphere, open symbols: upper hemisphere.

During IRM-acquisition, specimens rapidly gain remanence at low magnetizing field strengths and entirely saturate at less than 0.2 T (Figure 3). This behaviour implies that the specimens do not contain any significant magnetic phase besides magnetite. This finding and also maximum unblocking temperatures observed during demagnetization suggest that both magnetization components reside in two different phases of magnetite.

Marls from northern Thrace

Specimens from three sites contain magnetization directions that are clearly different from present-day-field overprints when inspected before tilt correction.

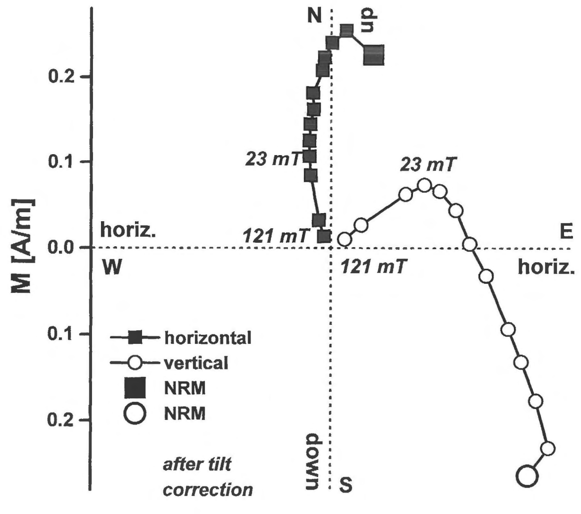

Figure 11. Representative modified Zijderveld diagram, Peplos andesite. The specimen carries a modern magnetization overprint and a northerly component with negative inclination.

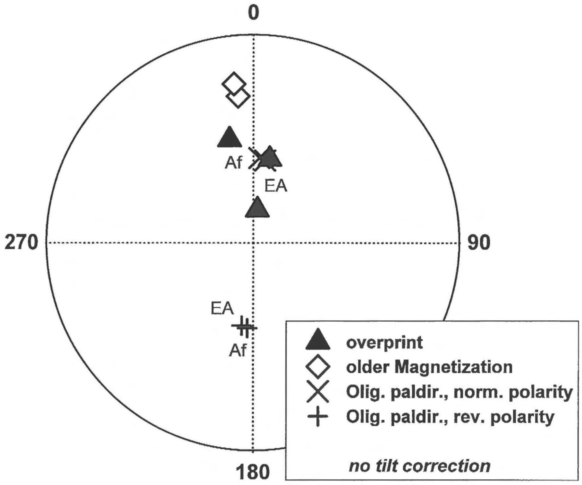

Figure 12. Site-mean magnetization directions, Peplos andesites. Two site-means show an unusual northerly magnetization component with negative inclination. Overprints suggest partial (in one case pervasive) present-day-field remagnetization. EA: Eurasian, Af: African paleodirection. Full symbols: lower hemisphere, open symbols: upper hemisphere.

Three other sites, the specimens of which carry pervasive present-day-field remagnetizations, were rejected. There is considerable variability as to coercivity and unblocking spectra. Most of the specimens lose roughly half of their initial magnetization intensity when heated up to 150°C, suggesting that goethite significantly contributes to the NRM. The remaining NRM completely unblocks at temperatures between 200 and 450°C. These specimens cannot be effectively demagnetized using only the AF method. However, other specimens contain a more significant low-coercivity phase because almost 70% of the initial NRM intensity is removed in an alternating field of 20 mT. Additionally, a magnetically hard phase carries part of the NRM.

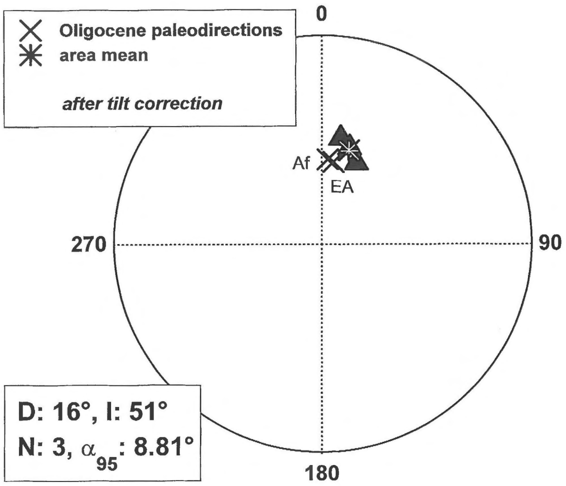

Figure 13. Site-mean magnetization directions, Pithion marls. The area-mean of three sites indicates small clockwise rotation and inclination flattening. However, it lacks statistical significance (Table 1) and is only a preliminary result. EA: Eurasian, Af: African paleodirection.

Accordingly, different kinds of magnetic mineral associations are reflected in various kinds of responses to exposure to magnetizing fields (Figure 3). Some specimens slowly and steadily gain IRM without any significant changes in the slope of the curve. Others acquire half of their saturation IRM at only 0.2 T, but slowly continue to gain remanence at higher field strengths. However, none of the specimens are saturated at the highest field available (1.45 T). NRM demagnetization patterns and IRM-acquisition suggest goethite and variable amounts of magnetite as the predominant carrier minerals.

The observed magnetization vectors show northeasterly directions after tilt correction, regardless of the nature of the carrier mineral. The following mean direction was obtained: D = 16°, I = 51°, α_{95} = 8.8° (Figure 13, Table 1).

Magnetic discordance

Expected magnetization values for the investigated areas are 008/55 to 008/56 (declination/inclination in degrees) with respect to the African paleopole positions and 011/57 to 011/58 with respect to the Eurasian paleopole positions calculated by Besse & Courtillot (1991). These values show differences of up to one degree that reflect the ages of the investigated rocks and/or the coordinates of the areas.

In comparison with the African Oligocene paleopole positions, the mean magnetizations from Medousa, Zagradenia, and Elatia indicate a small clockwise rotation (9°, 12°, 15°, respectively) that is statistically significant at a 95% probability level. Moreover, inclination values are shallower than expected and, again, results are discordant (Table 1).

In comparison with the Eurasian paleopole positions, the rotation angles for these areas are somewhat smaller, whereas flattening slightly increases. Accordingly, only Zagradenia exhibits a clockwise rotation that is significant at 95% probability (8°), whereas Elatia and Medousa yield rotation angles (6°, 11°) that are 1° smaller than their angles of uncertainty. Since these angles are almost equal to their error limits, the data may indeed suggest that the areas underwent some clockwise rotation, even if the Eurasian paleopole position is applied, however, not on a 95% probability level. Nevertheless, inclination flattening is statistically significant in all of these cases.

Obviously, the magnetization of the Peplos area stands out. This direction can either be the result of a large rotation of some 170° (if the average is reversed through the origin) or of tilt of more than 80°. Since only two sites yielded this direction, statistical statements cannot be made.

Rotation and flattening angles calculated from the area-mean of Pithion are not statistically significant regardless which paleopole position is used. The preliminary data indicate a small clockwise rotation. More data are needed to obtain reliable values.

The pole positions by Westphal et al. (1986) were not used, although they are comparable to those by Besse & Courtillot (1991), because their large confidence limits prohibit the calculation of statistically significant rotation and flattening values. However, it should be mentioned that the application of these pole positions would have led to rotation angles that are up to three degrees larger.

Discussion and conclusions

Paleomagnetic characterization of north-eastern Greece

Although the rocks sampled in the Medousa, Zagradenia, and Elatia areas are quite different (ignimbrites, rhyolites, and granodiorites, respectively), the paleomagnetic results are comparable, in each case indicating small clockwise rotation. Unfortunately, it was possible to apply a tilt correction only for the Medousa ignimbrites. Nevertheless, the similarity of the results for the three areas suggests that the Elatia pluton and the Zagradenia rhyolites did not undergo significant tilt after emplacement. This similarity may also be invoked as some evidence that the Medousa ignimbrites did not record a geomagnetic secular variation, although the total number of sites is larger than the amount of pyroclastic flows that were sampled.

These results are in accord with previously published paleomagnetic studies from the region between the Strymon valley and the Kavala-Xanthi-Komotini fault. For instance, the Miocene Kavala pluton and the late Oligocene Xanthi pluton carry characteristic magnetizations of 024/53 *16* (declination/inclination *rotation*) and 208/−55 *17*, respectively (Atzemoglou et al. 1994). Rotation angles (in degrees) reported in this chapter were calculated with the respective Eurasian paleopole positions of Besse & Courtillot (1991). Positive numbers indicate clockwise, negative numbers counterclockwise sense. Other area-means from this region show comparable values (Kondopoulou et al. 1996). The region between the Strymon valley and the Kavala-Xanthi-Komotini fault seems to be a continuous zone of small clockwise rotations of about 10 to 20° on average. Some differences between the area-means can be expected, because in most cases the paleohorizontal could not be determined.

For comparison, paleomagnetic studies of the Vertiskos massif show in four cases larger (~ 30°) clockwise rotations, e.g. Eocene volcanics of the Metalliko area: 039/33 *29* (Westphal et al. 1991), or lower Miocene volcanics from Gavra: 225/−44 *37* (Atzemoglou et al. 1994). Only one area within the Vertiskos massif, the upper Oligocene to lower Miocene volcanics of Kilkis, exhibits counterclockwise rotation: 329/48 *−41* (Pavlides et al. 1988). Importantly, from the Vardar basin, west of the Vertiskos massif, again, area-means from Miocene formations indicating smaller clockwise rotation angles were documented (e.g. Kondopoulou 1994): 020/46 *09*.

Oligocene formations of southern Thrace have been investigated thoroughly by Kissel et al. (1986). Site-means reported in that study show various amounts of both clockwise and counterclockwise rotations. The authors report an area-mean of 007/47 −*04* (rotation statistically insignificant) and conclude that southern Thrace did not undergo tectonic rotations. However, the practice of calculating only one average value from as many as fifteen sites for the large Feres-Essimi-Leptokarya-Maronia area may be somewhat questionable, particularly since site-means are quite different. More likely, these variations reflect complex local structural kinematics. Also Spais (1987) reported two different area-mean values for the Oligocene Essimi volcanics and the upper Oligocene Leptokarya pluton of 002/52 −*09* and 023/46 *12*, respectively.

The result obtained in our study from the Peplos andesites in southern Thrace could reflect either magnetization on the southern hemisphere, or large rotation and/or tilt. Since the former can be ruled out, we attribute this somewhat perplexing result to local tectonism.

Apparently, the area east of the Kavala-Xanthi-Komotini fault is characterized by local structural deformations and did not undergo any tectonic rotation as an entity; in this regard we agree with Kissel et al. (1986). Owing to the sedimentary cover of northern Thrace, the continuation of the fault could not be elucidated. Most probably, Pithion is situated on the eastern side of the fault and the result should, therefore, be discussed in the context of the data from southern Thrace. Our result from the Pithion area tentatively reflects small clockwise rotation. This tentative result neither confirms nor contradicts the statements made before.

All of the data reported in this paper show inclination angles that are shallower than expected. Such inclinations were obtained by several authors in the entire Aegean area (Van der Voo 1993); however, the origin of this systematical inclination flattening remains unanswered. Although there is no evidence for any explanation other than northward relative transport of the area with respect to both Eurasia and Africa (Beck & Schermer 1994), no tectonic model can possibly accommodate this substantial translation. Westphal (1993) suggests an alternative early Tertiary magnetic pole position for Eurasia, i.e. during this period the poles of the Earth's magnetic field were different from the poles of the rotational axis. However, this model is not convincing because early Tertiary rocks should have recorded such an excursion worldwide, and Miocene rocks from the Aegean also show a flattened inclination (Beck & Schermer 1994).

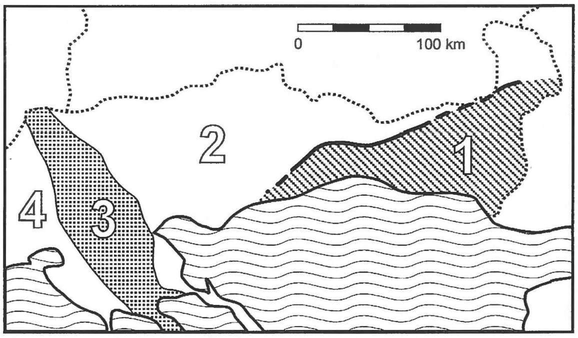

Figure 14. Map of proposed zones of different Neogene rotational characteristics. Zones are: 1) various rotational patterns (clockwise: cw and counterclockwise: ccw) but no overall trend; 2) ∼ 10° cw; 3) the Vertiskos massif, ∼ 30° cw; 4) an area west of the Vertiskos massif that also shows ∼ 10° cw.

Structural implications

Based on the rotational patterns inferred from our findings and from previous work, we propose to subdivide north-eastern Greece into four zones (Figure 14).

1) the area east of the Kavala-Xanthi-Komotini fault (various rotational patterns, no overall trend),
2) the area between this fault and the Strymon valley (∼ 10° clockwise rotation),
3) the Vertiskos massif (∼ 30° clockwise rotation, assuming the counterclockwise rotation of the Kilkis area is a local phenomenon),
4) an area west of the Vertiskos massif (again ∼ 10° clockwise rotation).

The Kavala-Xanthi-Komotini fault separates two zones of different rotational character. Therefore, as suggested by Kondopoulou et al. (1996), it appears to be an important lineament. Zone 1 is part of a strip between this fault and the north-Anatolian fault zone. Thus, it seems plausible that this area between two shear zones suffered intense disruption. Complex kinematics, owing to the interaction of two major dextral faults or fault zones, resulted in comparatively small individual structural units with a seemingly irregular pattern of different rotation angles and senses.

The structural or erosional mechanism of unroofing of the Rhodope metamorphic core complex is currently debated (see 'Geological setting'). Notwithstanding the question whether the low-angle fault mapped in the Strymon valley is compressional (overthrust) or extensional (detachment), the Strymon valley separates two zones, i.e. zones 2 and 3, of distinctive rotational attributes. Possibly, both structural interpretations are equally reasonable, because cases of extensional reactivation of older thrust surfaces have been observed before (e.g. Henk 1993). It is generally accepted that in the North American Basin and Range province, gravity-driven detachment faulting followed compressional tectonics. As soon as the upper (younger) sheets became gravitationally unstable, they began to slide laterally. If the same process caused the south-westward translation of the Vertiskos massif, its paleomagnetic signature, our zone 3, reflects a rotation of this nappe, relative to the underlying units, during the sliding process.

This hypothesis is supported by the similarity of the rotational properties of zones 2 and 4. Indeed, these two zones may be part of the same structural unit, i.e. the lower (older) sheets underneath the sliding nappe. We want to emphasize that at this time the two zones cannot be given equal weight, because the rotation of rock units within the Vardar basin is not as well documented as is the case in zone 3. Obviously, more work is needed in this area, and also in the vicinity of the important lineaments, i.e. the Kavala-Xanthi-Komotini fault, the Strymon valley, and the Vardar fault zone west of the Vertiskos massif.

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