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# PALEOMAGNETISM OF LATE TERTIARY AND PLIO–PLEISTOCENE FORMATIONS FROM NORTHERN GREECE

**M. Westphal[1], D. Kondopoulou[2], J. B. Edel[1] and S. Pavlides[3]**

## Abstract

Previous paleomagnetic measurements in the Ionian zone have shown strong clockwise rotations. The last one, of about 25°, begun 5 My ago. Measurements in Chalkidiki, on Oligocene volcanics, have also shown a recent clockwise rotation of about the same magnitude. In order to constraint the age and the amplitude of this rotation, paleomagnetic sampling was done in Chalkidiki (Pliocene sediments), in Tertiary volcanics north of Thessaloniki and in the Pelagonian zone (Ptolemais basin).

The marls from the Ptolemais basin do not show any significant rotation although some less precise results may indicate a clockwise one. Older rocks, of lower Miocene age, north of Thessaloniki and in Chalkidiki show a clear clockwise rotation. Thus all these paleomagnetic results demonstrate that:

-- The internal parts of the Aegan had the same rotational behaviour than the external parts.

-- The rotation of the Ionian zone is not just due to cover thrusting, but seems to follow the general rotation of the whole Aegean.

We discuss several models for the rotation of Greece.

## ΠΕΡΙΛΗΨΗ

Προηγούμενες παλαιομαγνητικές μετρήσεις στην Ιόνιο ζώνη έδειξαν μεγάλες δεξιόστροφες περιστροφές. Η τελευταία, περίπου 25°, άρχισε πριν 5Μα. Μετρήσεις στη Χαλκιδική, σε ολιγοκαινικά πλουτώνια πετρώματα, έδειξαν επίσης μιά πρόσφατη δεξιόστροφη περιστροφή του ίδιου περίπου μεγέθους. Για να οριοθετήσουμε την ηλικία και το εύρος αυτής της περιστροφής έγινε δειγματοληψία στη Χαλκιδική(ιζήματα Πλειοκαίνου) σε τριτογενή ηφαιστειακά βόρεια της Θεσσαλονίκης και στη λεκάνη της Πτολεμαίδας (Πελαγονική).
Οι μάργες της Πτολεμαίδας δεν δείχνουν αξιόλογη περιστροφή. Παλαιότερα πετρώματα Μειοκαινικής ηλικίας, στη Χαλκιδική και βόρεια της Θεσσαλονίκης δείχνουν μία σαφή δεξιόστροφη περιστροφή.
Όλα αυτά τα παλαιομαγνητικά αποτελέσματα δείχνουν ότι:
- Τα εσωτερικά τμήματα του Αιγαίου έχουν την ίδια περιστροφική συμπεριφορά με τα εξωτερικά.
- Η περιστροφή της Ιονίου ζώνης δεν οφείλεται απλά σε επώθηση αλλά μοιάζει να ακολουθεί τη γενική περιστροφή όλου του Αιγαίου.
Συζητάμε επίσης αρκετά μοντέλα για την περιστροφή της Ελλάδας.

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[1] University of Strasbourg, Institut de Physique du Globe, 5 rue Descartes, F 67084 Strasbourg, France.

[2] Aristotle University of Thessaloniki, Department of Geophysics, 54006 Thessaloniki, Greece

[3] Aristotle University of Thessaloniki, Department of Geology, 54006 Thessaloniki, Greece

## Introduction.

Paleomagnetic results obtained in the last ten years have shown that Greece had a quite different behaviour in the Tertiary than more western parts of the Alpine-Tethyan belt, namely Iberia, Corsica, Sardinia, Apulia, Istria, Western and Central Alps. All these last regions were anticlockwise rotated like Africa. Two main phases of rotations are recognized : a late Cretaceous one, coupled with the main rotation phase of Africa, and an early Miocene one, less documented, but visible in Sardinia and Apulia. In the Greece, at least for the Tertiary, the things are quite different. Results from the most external zones show a clockwise rotation in Epirus, in the Ionian islands and in the southern Peloponesus (Kissel et al., 1985, 1986; Horner and Freeman, 1983; Laj et al., 1982), (Fig. 1). The maximum rotation amounts to 65° since Paleocene-Eocene (Horner and Freeman, 1983). Kissel et al. (1985) think that there were two phases of rotation. The first one about 20 Ma during Miocene and the second one since 5 Ma, both of about 25°.

Therefore adjacent units show two very different tectonic styles: Apulia and northern Yugoslavia are anticlockwise rotated, and the external Hellenides, clockwise rotated. This clockwise rotation is not limited to the external parts, we have similar results in internal parts : Chalkidiki (Kondopoulou and Westphal, 1986; Pavlides et al. 1988), Evia, Skyros (Kissel et al., 1986), Lemnos, less well established in Almopias and Lesbos (Kondopoulou, 1982; Kissel et al., 1986). We have also found several secondary magnetizations with NE-SW directions in Cretaceous, Permian or Carboniferous rocks from Northern Greece (Edel et al., 1990). We have looked in recent rocks if we could better constrain this rotation.

## Geology and sampling.

We sampled first recent sediments in Northern Greece from Late Miocene, Pliocene and Pleistocene age (Pavlides, 1985; Syrides, 1989). These are not very easy to sample as they are often very coarse sandstones and conglomerates. We could nevertheless take some lacustrine limestones and redbeds in Chalkidiki and marly beds in the Ptolemais basin. We have also sampled two Miocene volcanic units north of Thessaloniki : a rhyolitic flow near Kilkis and a rhyodacitic dome near Strymonikon ( see Table 1 and Fig. 1 for location).

**Table 1**
**Paleomagnetic sampling sites.**

| name | age | number of sites | samples | dip | lat (°N) | long (°E) |
|---|---|---|---|---|---|---|
| **Chalkidiki** | | | | | | |
| Riza | Villafranchian | 2 | 11 | 0/0 | 40.50 | 23.45 |
| Ierissos | Upper Pliocene | 1 | 6 | 0/0 | 40.40 | 23.90 |
| Nea Gonia | Ruscinian | 2 | 16 | 0/0 | 40.35 | 23.10 |
| **Pelagonian zone** | | | | | | |
| Neapolis | Pleisto/Plioc. | 4 | 21 | 245/15 | 40.65 | 21.70 |
| Kariochori | U. Pliocene | 1 | 11 | 0/0 | 40.55 | 21.75 |
| Vevi | U. Mioc. L.Plio | 2 | 32 | 340/15 | 40.80 | 21.60 |
| Vegora | U. Mioc. L.Plio | 3 | 39 | 225/10 | 40.70 | 21.70 |
| **N. Thessaloniki**, volcanics | | | | | | |
| Kilkis | Olig-Mioc. | 1 | 7 | 15/15 | 41.05 | 22.85 |
| Strymonikon | Olig-Mioc. | 2 | 19 | 90/25? | 41.00 | 23.30 |

The samples were usually cored directly in the field with a portable drill. A site covers a distance of several meters or tens of meters in order to detect and eliminate local disturbances such as lightnings strokes or tilted blocks. The samples were cut in standard cylinders 25 mm in diameter and 22 mm high.

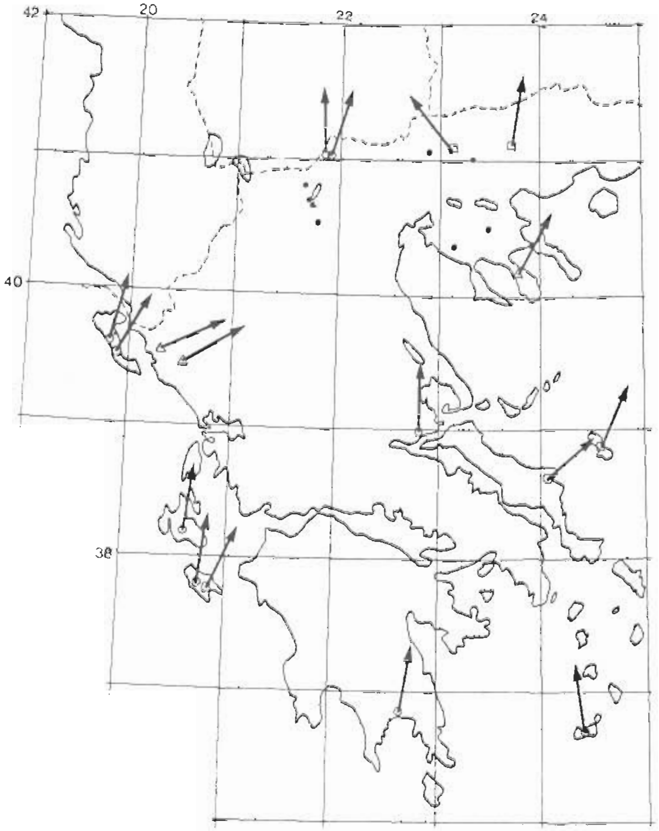

**Fig. 1.** Previous paleomagnetic results obtained in continental Greece for the Tertiary. Triangles: Eocene and Oligocene results; squares: Miocene; circles: Pliocene and Pleistocene. The arrows show the ancient field directions. The black circles give the present study sampling locations.

**Measurements.**

The remanent magnetization was measured in Strasbourg and in Thessaloniki either with a recomputerized Digico spinner magnetometer or with a Molsin spinner. The samples were demagnetized by step heatings for most of them. Some specimens were submitted to IRM experiments.

**Rockmagnetic properties.**

The NRM of sediments range from 10 mA/m to less than 0.03 mA/m, noise level of our Digico. IRM acquisition curves saturates quickly with fields of 0.1 to 0.2 Tesla (Fig. 2A). Samples with the lower NRM are also usually those with the lower IRM showing that the low NRM values are due to low magnetic content. Thermal demagnetization of the IRM indicate unblocking temperatures of 400 to 500°C (Fig. 2B). Goethite and hematite are not present in these rocks. The color of the samples changes often during heating above 300°C and spurious magnetizations appear above 400°C. This is especially the case for samples coming from the Vevi and Vegora xylite mines, where sulfides are suspected to be the carriers of the magnetization.

**Results.**

- Sediments.

Normal and reversed magnetizations are found in these sediments. The demagnetization curves by step heatings were analyzed by a least square method and they show one, two or sometimes three different magnetic components (Fig. 3). The first component is eliminated at temperatures less than 150°C. It is always a normal one, usually scattered except in a few sites where a mean direction could be calculated. It has always a strong inclination and contains at least a large part of recent viscous magnetization. The second component is destroyed at 400°C or above, it is either a normal or a reversed magnetization. The best results were obtained in quarries and fresh road cuts (Riza, Vevi, Vegora). In degraded or weathered outcrops the directions are more scattered, although the unblocking temperature may be higher. The normal and reversed directions are nearly antiparallel, but bedding corrections do not improve the grouping of the results ( $k_1/k_2=1.9$) (Fig. 5). The scatter is even larger but not in a significant way. It would mean that the magnetization is younger than the tilting, but we cannot conclude now. The third component in only found in one section, in Vegora quarry, it has unblocking temperatures of 400 to 580°C, it is reversed whereas the main component of the same section is normal.

Other sites have a larger scatter (Ierissos, Nea Gonia, Kariochori). The trend of the results and the low inclinations for two of them suggest that we have not completely eliminated a normal viscous component. These sites are also the less fresh ones.

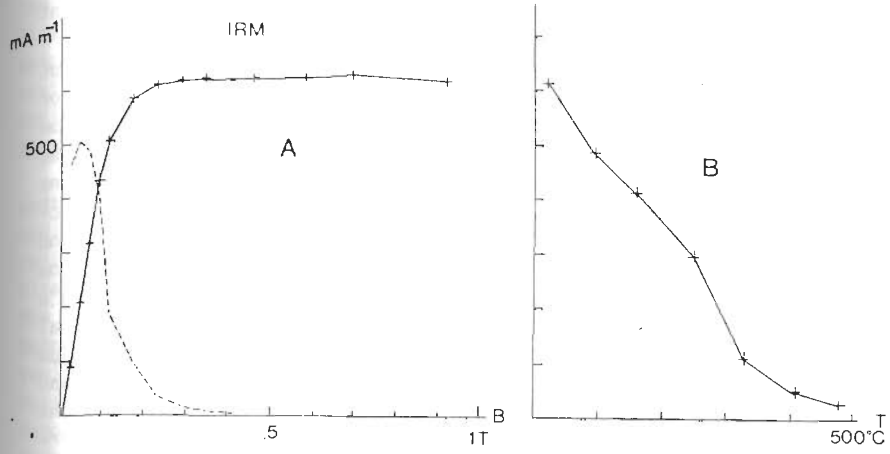

**Fig. 2.** A: Solid line: IRM acquisition curve for a sample from Vegora. Dotted line: first derivative of this curve showing that most of the magnetization is acquired between 0.1 and 0.2 Tesla.
B: Thermal demagnetization of this IRM.

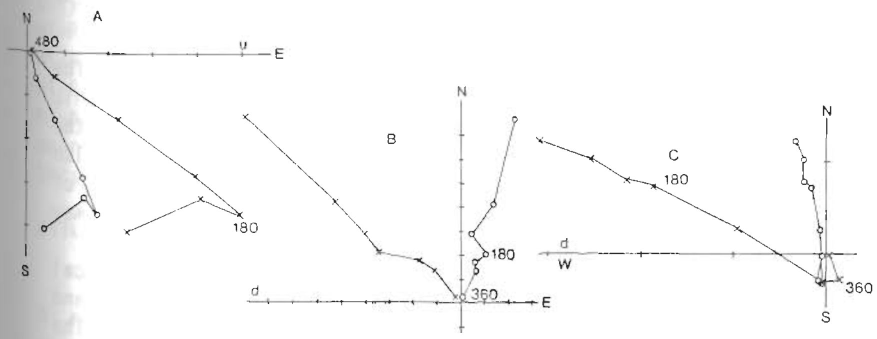

**Fig. 3.** Thermal demagnetization of three sedimentary samples from Vevi and Vegora. Circles: horizontal plane, crosses: vertical N-S plane (u: up, d: down). Characteristic temperatures are indicated.
A: reversed sample from Vevi. B: normal sample from Vegora. C: normal sample from Vegora with a reversed residual magnetization.

- Volcanics.

The rhyolitic flow near Kilkis Metalikon has a normal NRM ranging from 2 to 9 mA/m. The thermal demagnetization shows unblocking temperature of about 660°C characteristic of hematite. The characteristic component is normal with a rather low inclination.

The dome near Strymonikon was sampled along a section of about 200 m. It has a very complex magnetization. Step heatings show 2, 3 or even 4 different magnetizations (Fig. 4). After elimination of a soft low temperature component (T< 150°C) the demagnetization curves show for the lower part of the section a normal component ( 150-300°C), a reversed one (350-580°C) and a normal one again above 580°C. The upper part of the section shows only two reversed components, the first between 200-500°C and the second above 500°C. We have calculated 5 different means: a normal low temperature one (T< 150°C), probably of viscous origin, a normal and a reversed medium temperature components noted mT-N and mT-R and a normal and a high temperature components noted hT-N and hT-R. The reversed medium temperature component is present in almost all the samples. The medium and high temperature normal components are present in the same area and the reversed high temperature component in a separate area. Normal and reversed components are antiparallel, but for the medium temperature reversed component which is slightly different.

This dome was magnetized during at least two polarity intervals and at least one, if not all, the magnetizations are overprints. A layering, which is not necessarily a bedding plane, can be seen in the rock and a tilt correction was made according to it. This correction gives high inclinations above 75° which are clearly unrealistic for late Tertiary rocks in this part of the world. We do not use these corrected values. As the medium temperature reversed component is present everywhere we think that it is the oldest and that the other components are overprints. (Table 2 and Fig. 5).

## Tectonic interpretation.

All the directions obtained do not show a clear rotation. The mean declination for the best sedimentary sites is 1° without tectonic corrections and 4° after tectonic corrections. The mean direction for the 3 directions of the Strymonikon dome considered as overprints is also North-South (D= 358°). The direction of Kilkis, the main component of Strymonikon and some less reliable directions Ierissos, Nea Gonia, may show a clockwise rotation (D= 26°) (see figure 6).

When the first clockwise rotations were found in Epirus, local and superficial tectonic movements could be thought about. But as more and more results are obtained, such an explanation must be discarded. The rotation is not only found in the sedimentary cover, but also in plutonic units like Sithonia. The main tectonic phases in the Hellenides are older, Cretaceous and early Tertiary. A large rotation of a broad part of the cover would have left uncovered the lower crust in the same extent.

**Table 2**
**Paleomagnetic results**

| site | N | D | I | k | $a_{95}$ | D' | I' | |
|---|---|---|---|---|---|---|---|---|
| low temperature components | | | | | | | | |
| Riza | 9 | 18 | 64 | 11 | 15 | | | |
| Neapolis | 12 | 295 | 87 | 14 | 12 | | | |
| Vevi 21 | 7 | 261 | 72 | 23 | 13 | | | |
| Kariochori | 5 | 14 | 65 | 151 | 6 | | | |
| Strymonikon | 12 | 14 | 61 | 14 | 11 | | | |
| **sediments** | | | | | | | | |
| medium and high temperature components | | | | | | | | |
| Ierissos | 5 | 212 | -17 | 5.5 | 38 | 212 | -17 | |
| Riza | 7 | 195 | -45 | 61 | 8 | 195 | -45 | * |
| Nea Gonia | 4 | 217 | 18 | 8.6 | 32 | 217 | 18 | |
| Neapolis | 12 | 178 | -55 | 3.2 | 25 | 172 | -41 | |
| Vevi 21 | 7 | 176 | -51 | 13 | 17 | 195 | -42 | * |
| Vevi 55 | 11 | 172 | -70 | 70 | 5 | 217 | -73 | * |
| Vegora 26 | 13 | 20 | 49 | 25 | 8 | 12 | 46 | * |
| Vegora 27 | 6 | 353 | 58 | 122 | 6 | 345 | 50 | * |
| Vegora 54 | 5 | 346 | 48 | 39 | 12 | 341 | 37 | * |
| Kariochori | 5 | 269 | -58 | 5.6 | 33 | 269 | -58 | |
| high temperature residual | | | | | | | | |
| Vegora 27 | 5 | 206 | -52 | 5.8 | 32 | 195 | -48 | |
| means: | | | | | | | | |
| sediments with k>10 | | | | | | | | |
| | **6** | **1** | **54** | **42** | **10** | | | |
| | **6** | | | **21** | **15** | **4** | **50** | |
| **Volcanics** | | | | | | | | |
| Kilkis | 5 | 29 | 38 | 16 | 19 | 39 | 33 | * |
| Strymonikon | | | | | | | | |
| mT-R comp. | 18 | 201 | -56 | 51 | 5 | 239 | -76 | * |
| mT-N comp. | 5 | 356 | 53 | 375 | 4 | 349 | 78 | |
| hT-R comp. | 9 | 180 | -61 | 342 | 3 | 180 | -80 | |
| hT-N comp. | 8 | 358 | 59 | 54 | 5 | 350 | 84 | |
| means: | | | | | | | | |
| Strymonikon (overprints) | | | | | | | | |
| | 3 | 358 | 58 | 355 | 7 | | | |
| Kilkis +Strymonikon mT-R | | | | | | | | |
| | **2** | **26** | **47** | | | | | * |

N: number of samples used, D,I : declination and inclination before tilt correction, k, $a_{95}$ : Fisher statistical parameters, D', I' : declination and inclination tilt corrected. Reliable results are starred.

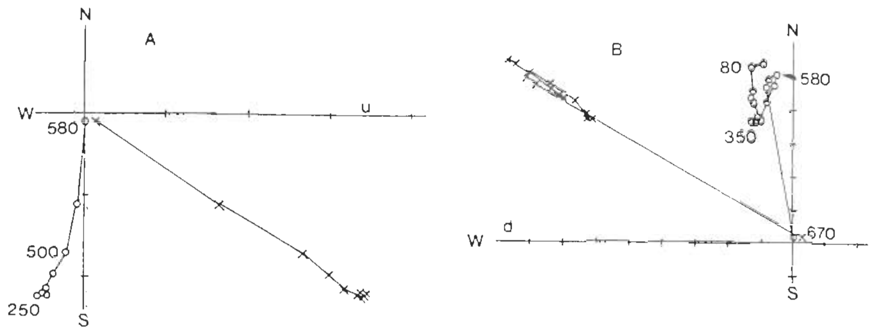

**Fig. 4.** Thermal demagnetization of two samples from Strymonikon. same conventions as in figure 3.
A: sample with two reversed magnetizations, the first between 250 and 500°C and the second above 500°C.
B: sample with two normal (80-350°C) and (580-670°C) and one reversed magnetization (450-580°C).

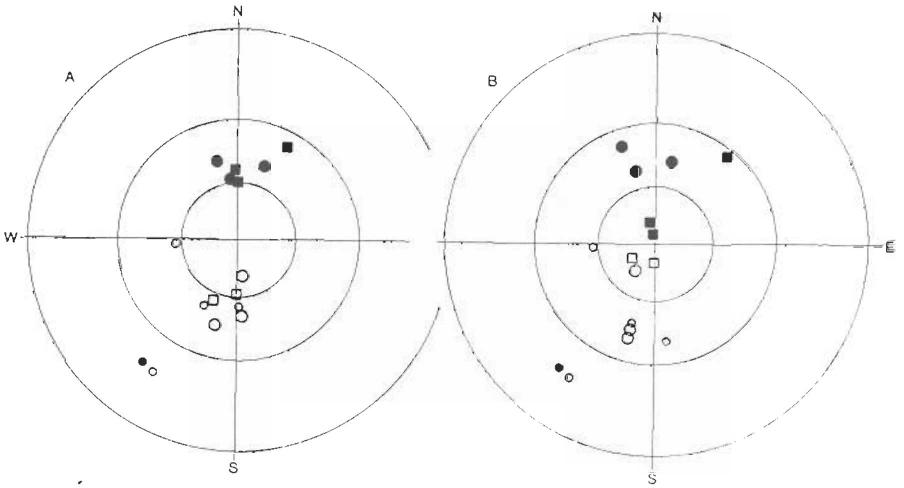

**Fig. 5.** Stereograms of the different magnetizations before (A) and after (B) tilt corrections. Large circles: sediments with k>10, small circles: sediments with k< 10, squares: volcanics. Open symbols: negative inclinations, closed symbols: positive inclinations.

We must consider a more rigid plate tectonic involving the whole thickness of the lithosphere of a domain of the size of Greece, that is to say at least 500*500 $km^2$. The rotation of Greece is rather large : 25° since 5 Ma which gives a speed of about 5°/Ma. The first problem is to find where the finite rotation pole should lie. A rotation pole too close to Greece would give mainly shearings with the neighbour plates and we have no proofs of that. If we admit a clockwise rotation of 25° with a more distant pole, we must have compression and shortening at the leading edge and extension at the trailing edge :
a pole to the North gives shortening West and extension East,
a pole to the East gives shortening North and extension South,
a pole to the South gives shortening East and extension West,
a pole to the West gives shortening South and extension North.
The best choice would be a pole to the North or the West. This will explain shortening in the Hellenic Trench, extension in the Aegean Sea and leave place for Moesia in the North.

The distance of this rotation pole is a second problem. A pole too far away would give very large displacements without substantial rotations. A distance of 1000 km will give a displacement of about 440 km for a rotation of 25° and a speed of 9 cm/y. This is quite reasonable values. A pole to the North-West, in Italy, is also approximately perpendicular to the Scutari-Pec line and the offset, dextral, compatible with this position (Fig. 7).

This model of a rigid plate explains the rotation of Greece, but ignores the complicated rotations which occur inside the plate. In the north Aegean region, neotectonic and active faulting bound rotated blocks in upper crust brittle conditions. This brittle deformation does not follow very well the general motion of the plate. We have the example of northern serbomacedonian results where clockwise and anticlockwise rotations coexist in very close areas. A similar situation was also observed in northeastern Aegea and in western Anatolia (Lauer and Kondopoulou, 1984; Kissel et al., 1987).

On an other hand, a model with a continous deformation of the Aegean plate was proposed by Le Pichon and Angelier (1981). This model shows well the rotations observed in the outer Aegean ( in the Ionian islands), but less well the rotation in the northern Aegea.

Jackson and McKenzie (1988) model of small blocks rotating and sliding close to each other is very interesting and can explain the brittle deformation observed. They proposed that a difference may exist between central and northern Aegea, divided by the north aegean trough, extension of the northern anatolian fault. It may explain why only a limited rotation, if no rotation at all, was seen in the most recent formation from the Ptolemais basin and in Chalkidiki.

The truth is as usual probably something in between a large scale movement, leaving place for Moesia for instance, a continuous expansion and deformation of the Aegean sea itself and brittle deformation with rotations on the older crust.

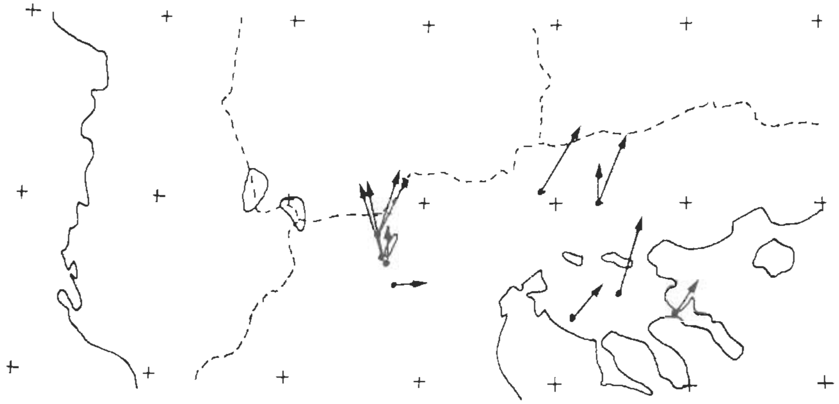

**Fig. 6.** Directions obtained in this study in northern Greece. Shorter arrows correspond to less reliable sites. Reversed directions changed to normal.

**Fig. 7.** Map of Apulia and the Dinaric-hellenic chain and inferred clockwise rotation of continental Greece.

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