Δελτίο της Ελληνικής Γεωλογικής Εταιρίας, Τομ. XXXIV/1, 61-68, 2001
Πρακτικά 9ου Διεθνούς Συνεδρίου, Αθήνα, Σεπτέμβριος 2001

Bulletin of the Geological Society of Greece, Vol. XXXIV/1, 61-68, 2001
Proceedings of the 9th International Congress, Athens, September 2001

PALAEOMAGNETISM AND MAGNETIC FABRICS OF THE ALMOPIAS, THESSALY AND MILOS VOLCANICS. IMPLICATIONS FOR THE REGIONAL DEFORMATION*

A. ATZEMOGLOU[1], D. KONDOPOULOU[2] AND I. ZANANIRI[2]

ABSTRACT

New palaeomagnetic and rock magnetic data obtained from the plio-quaternary volcanics in Almopias (NW Greece) are presented, together with existing ones from two other localities (Thessaly and Milos) in the Aegean extensional area. In most cases a stable component, slightly deviated from the expected direction, has been identified. Rock magnetic analysis reveals the presence of either magnetite (Thessaly), hematite (Milos) or both (Almopias) The anisotropy of magnetic susceptibility reaches significant levels for only part of the samples whereas the anisotropy ellipsoid could be defined in only one case (Almopias).

The existing structural data for the three areas, together with fault plane solutions provide a representative deformation pattern. Comparison of -small- rotation angles and possible rotation of the stress field has been possible in the case of Almopias.

KEY WORDS: palaeomagnetism, volcanics, magnetic fabric, rotation, Almopias, Thessaly, Milos, Aegean tectonics.

ΠΕΡΙΛΗΨΗ

Νέα παλαιομαγνητικά αποτελέσματα από τα πλειοτεταρτογενή ηφαιστειακά πετρώματα της Αλμωπίας παρουσιάζονται, μαζί με ήδη υπάρχοντα από δυο άλλες περιοχές της εφελκυστικής περιοχής του Αιγαίου. Στις περισσότερες περιπτώσεις προσδιορίσθηκε μια σταθερή συνιστώσα η οποία αποκλίνει ελαφρά από την αναμενόμενη διεύθυνση. Η ανάλυση των μαγνητικών ιδιοτήτων αποκαλύπτει την παρουσία μαγνητίτη (Θεσσαλία), αιματίτη (Μήλος) ή αμφοτέρων (Αλμωπία). Η ανισοτροπία της μαγνητικής επιδεκτικότητας πλησιάζει σε σημαντικές τιμές για τμήμα των δειγμάτων, ενώ το ελλειψοειδές της ανισοτροπίας ορίσθηκε με ακρίβεια μόνο σε μια περίπτωση (Αλμωπία).

Τα υπάρχοντα τεκτονικά δεδομένα για τις τρεις περιοχές, σε συνδυασμό με τους μηχανισμούς γένεσης των σεισμών παρέχουν ένα αντιπροσωπευτικό μοντέλο παραμόρφωσης. Σύγκριση των -μικρών- γωνιών περιστροφής των σχηματισμών και πιθανής περιστροφής του πεδίου τάσεων πραγματοποιήθηκε στην περίπτωση της Αλμωπίας.

1. INTRODUCTION

Plio-quaternary volcanics outcrop at several places in the broader Aegean province. They are related either to the South Aegean active volcanic arc or to the back-arc extensional area. In all cases, radiometric data and detailed mineralogical studies are available.

The present study focuses at three areas one of which belongs to the Aegean volcanic arc (Milos) whereas the other two are situated further to the North (Thessaly, Almopias). The aim of the study was the careful investigation of the palaeomagnetic and rock magnetic properties of these recent volcanics in order to define stable, reliable directions and eventual rotations. At a second step, an examination of the existing numerous neotectonic and seismological data would allow comparison between these rotations and stress field.

2. GEOLOGY AND SAMPLING

The studied formations are spread over a wide area of Greece, in three different geotectonic units: The

* ΠΑΛΑΙΟΜΑΓΝΗΤΙΣΜΟΣ ΚΑΙ ΜΑΓΝΗΤΙΚΕΣ ΥΦΕΣ ΗΦΑΙΣΤΕΙΑΚΩΝ ΠΕΤΡΩΜΑΤΩΝ ΑΠΟ ΤΗΝ ΑΛΜΩΠΙΑ, ΤΗ ΘΕΣΣΑΛΙΑ ΚΑΙ ΤΗ ΜΗΛΟ. ΣΥΝΕΠΕΙΕΣ ΓΙΑ ΤΗΝ ΤΟΠΙΚΗ ΠΑΡΑΜΟΡΦΩΣΗ.

1. IGME, Frangon 1, 54626 THESSALONIKI
2. Aristotle University of Thessaloniki, P.O. Box 352-1, 54006 THESSALONIKI
e-mail: despi@geo.auth.gr

Vardar zone (Almopias area), the Pelagonian zone (Thessaly) and the Attico-cycladic zone (Milos) (Fig. 1).

Almopias is situated about 130 Km north-west of Thessaloniki, near to Greek-FYROM frontiers and belongs to the Vardar zone. The volcanism was active in the mountainous area during the whole Pliocene. Volcanic centres are lava domes, dome complexes, lava flows and some dykes. In the surrounding area outcrops are volcaniclastics confirming that explosive activity was intense. Volcanic centre alignment and dykes are oriented in N-S to NE-SW directions. The magmatic products belong to calc-alcaline series with the most alkaline being the youngest volcanic products. Ages vary between 1.8 to 4.5 Ma (Kolios et al, 1980). Sites AL (Alexandros), KOU (Koukourou), PA (Papadhia) and SF (Sfines) belong to the SW part of the complex (Upper Pliocene). Sites KFA, BA (Baltatsouko) are in the northen part (Lower Pliocene, Vougioukalakis, 1994)

Table 1: General information and paleomagnetic results from the studied sites.

Site	N	Age (Ma)	D	I	k	a95	Location	Reference
I	7	2.0	182.2	-56.4	49.6	10.9	Milos	1
III	8	2.3	167.7	-54.7	31.4	12	Milos	1
IV	6	2.3	156.7	-62.8	198	6.5	Milos	1
V	6	1.8	357.6	53	20	17.7	Milos	1
VI	5	0.95	176.1	-32	73.5	10.7	Milos	1
VII	5	0.95	163.9	-42.9	58.6	12.1	Milos	1
VIII	5	1.8	158.7	-42	78	14	Milos	1
MTHB1	7	1.4	196	-55	125	4.7	Thessaly	2
MTHB2	6	1.4	152	-66	14	16.2	Thessaly	2
MTHB3	5	1.4	181	-38	17	15	Thessaly	2
AGH	7	1.4	190	-62	374	2.7	Thessaly	2
AL	7	1.8-1.9	193.2	-59.6	27	11	Almopias	3
KOU	12	4.3-4.4	6.4	62	26	8.3	Almopias	3
KFA	4	4.6	11.7	51	111	6.6	Almopias	3
SF	8	1.8-1.9	353.1	58.8	50	6.6	Almopias	3
PA	6	2.5	5.5	49	26	11.1	Almopias	3
BA	9	4.6	348.5	54	63	5.9	Almopias	3
ALM-ALL	**6**	**1.8-4.6**	**3.1**	**56.1**	**112**	**5.4**	**Almopias**	**3**

1. *Kondopoulou and Pavlides (1990)*
2. *Kondopoulou and Caputo, (1997)*
3. *Present study*

The broader area of Thessaly-Pilion-Pagasitikos Gulf has been affected, during Early Pliocene to present, by two main normal fault systems (Galanakis et al, 1998). At **Thessaly**, the NAFS (Nea Anchialos Fault System) is the major tectonic structure, which lies along the prolongation of the North Aegean Trough (NAT) along which oblique-slip and strike-slip motions are recorded from the focal mechanisms. Both structural and seismological data indicate that the NAFS has a pure dip-slip normal structure (Caputo, 1996). According to available data, NAFS had been active throughout quaternary and is still active up to present. The volcanics (basaltic lava flows), sampled for this study, were dated at 1.4±0.1 Ma (Innocenti et al, 1979).

Milos Island is situated in the central-western part of the Hellenic volcanic arc, which extends from East (Nisyros, Kos) through Santorini and Milos, to west (Methana, Aegina, Krommyonia). According to Fytikas et al (1986), the calcaline volcanism began during the early Pliocene (5 Ma), while the submarine volcanic activity of Milos began during the middle Pliocene (3.5-2 Ma). The oldest volcanic products consist of tuffs, pumice, ignimbrites, andesitic and rhyolitic lava domes and flows, pyroclastics and lahars. The most recent eruptional products are mainly rhyolites. The main faults are E-W in strike and secondly NW-SE. The oldest formations are metamorphic rocks of the crystalline basement.

Drilled cores and oriented samples have been collected from the three areas on the basis of access facility and freshness of materials. A total of 150 cores have been measured and 113 have been demagnetised (stepwise thermally and by AF techniques). Measurements have been done in the laboratories of Thessaloniki, Strasbourg, Utrecht and Paris.

3. RESULTS

Almopias: 6 sites have been sampled in the Almopias volcanic formations. A total of 80 cylindrical specimens have been measured with a Molspin magnetometer among which 46 have been demagnetized by stepwise heating as well as AF demagnetization. Thermal process was done in ENS (Paris) and in the laboratory of the university of Strasbourg (EOST) and AF in Thessaloniki. In almost all cases, the demagnetization with an AF shielded demagnetizer was not successful because an important amount of NRM remained after the highest capacity was reached by the instrument (about 95 mT). Demagnetization procedure by stepwise heating up to temperature ranges of 500° to 630C° was more satisfactory because a stable component could be defined and destroyed.

Thessaly: The NRM values are sufficiently high ranging from 15 to 800 mA/m. The AF demagnetization procedure was efficient in about 50% of the cases. During thermal demagnetization (heating up to temperature ranges of 450-685°C), a stable component, directed to the origin, could be defined. Thermomagnetic curves were obtained displaying Curie temperatures below 600°C. This, combined to the maximum unblocking temperatures observed during thermal demagnetization (about 600°C), leads to the conclusion that the main magnetic carrier is magnetite. The factor of anisotropy of magnetic susceptibility varies from 0.6% - 5.4%. (Kondopoulou & Caputo, 1997).

Milos: All samples are strongly magnetized with NRM intensities ranging between 50 and 4500 mA/m. AF demagnetization on pilot samples was inefficient as half of the initial magnetization remain after applying a field of 95 mT. Well-defined directions were obtained when the samples were stepwise heated between 25° and 550°°C. Details on these results can be found in Kondopoulou and Pavlides (1990).

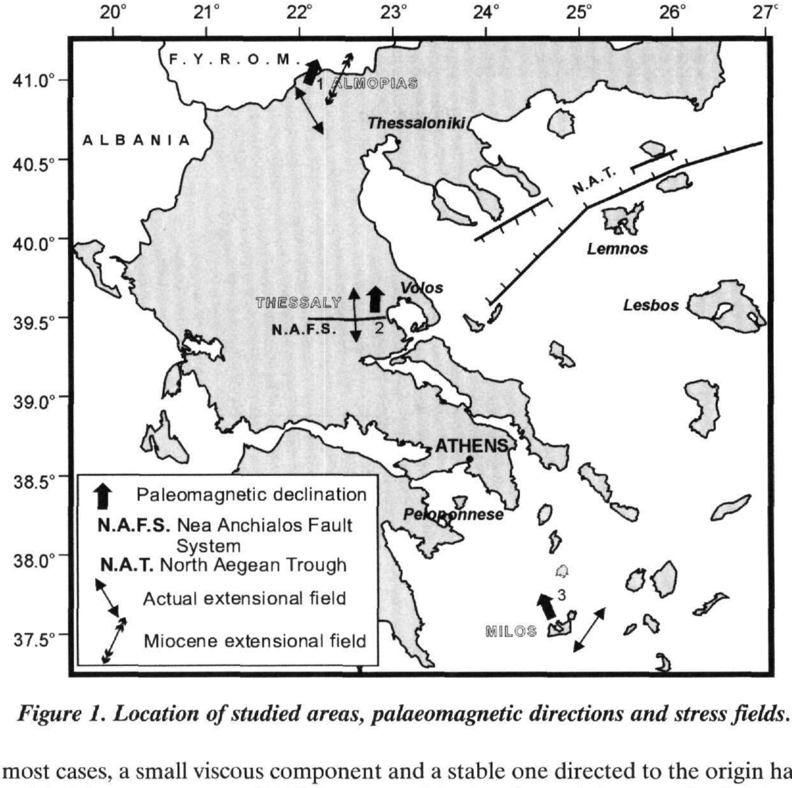

Figure 1. Location of studied areas, palaeomagnetic directions and stress fields.

Site SF. In most cases, a small viscous component and a stable one directed to the origin have been defined. The maximum unblocking temperature (630°C) observed during thermal demagnetization leads to the conclusion that the rocks of this site contain mainly hematite.

Site BA. We generally observe a stable component directed to the origin and rarely a small viscous one. The samples are demagnetized at temperatures up to 585°C and alternating fields up to 60 mT, therefore magnetite is the main magnetic carrier.

Site PA. Some samples are quickly demagnetized in fields up to 30 mT while others are not fully demagnetized in higher fields (80 mT). In all cases, a viscous and a primary component are well defined. The dominant

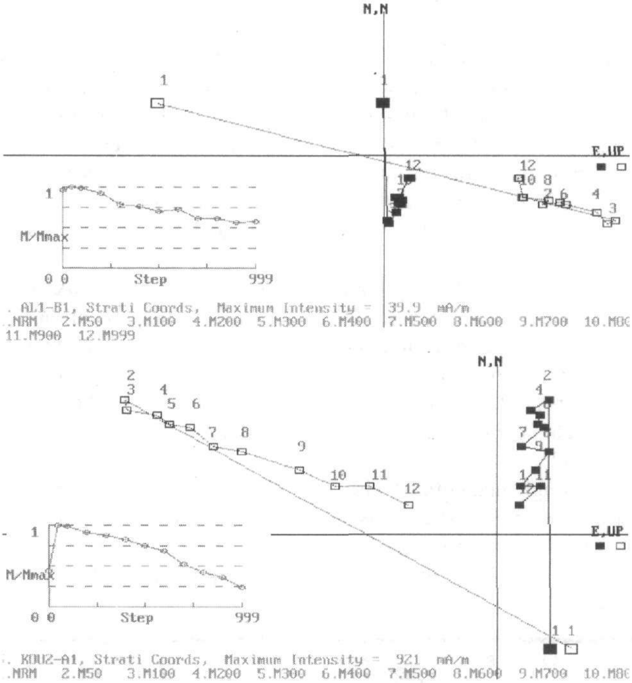

Figure 2a.

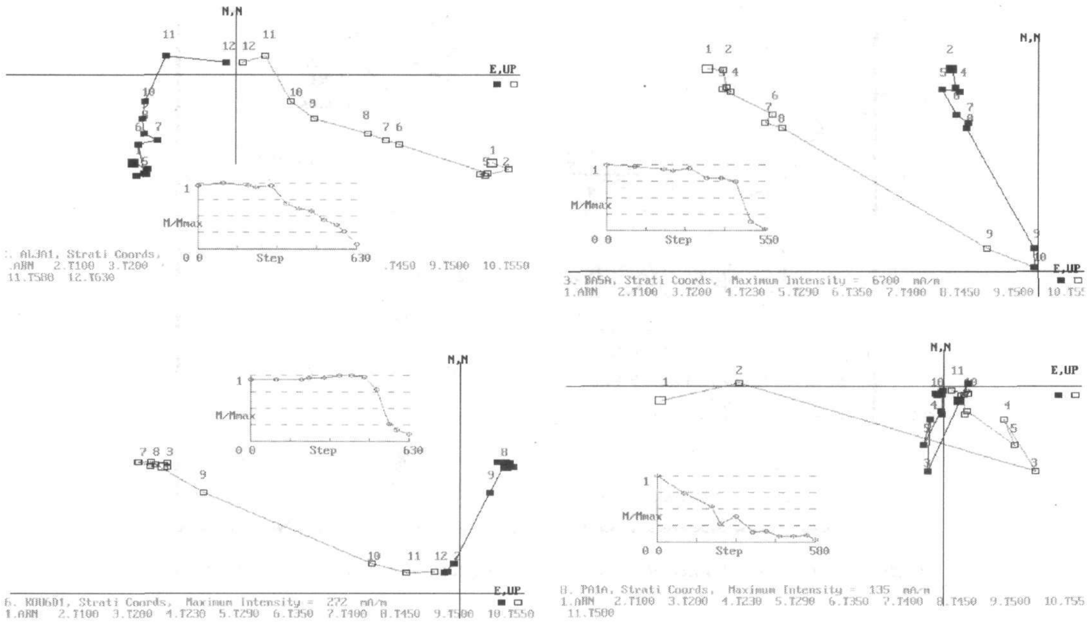

Figure 2b.

Figure 2(a,b): Typical analysis of palaeomagnetic directions and decay curves for representative samples.

magnetic mineral is magnetite.

Site AL. Using both AF and thermal techniques, two components are isolated, a strong viscous with stable direction and a primary one. Magnetite is the main magnetic carrier.

Site KOU. Same as site AL. Two components have been registered: a viscous and a primary one directed to

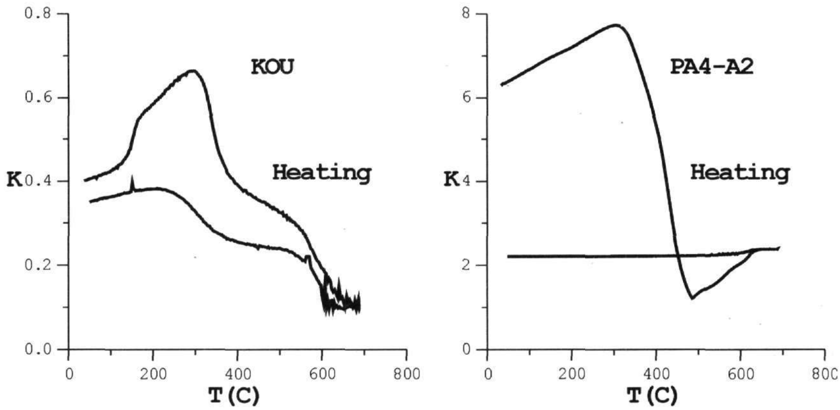

Figure 3: Representative thermomagnetic curves of Almopias volcanic samples, showing the magnetic susceptibility, K, changes with temperature.

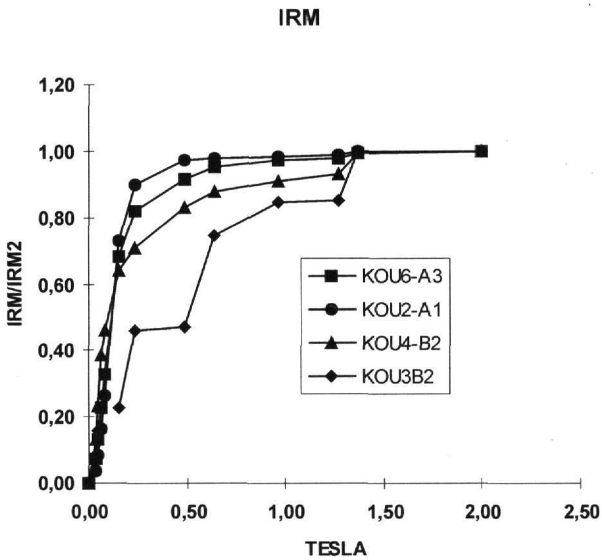

Figure 4: Isothermal remanent magnetization curves for site KOU.

the origin. In four cases magnetite and in most other cases hematite are the carriers of magnetization.

4. ANISOTROPY OF MAGNETIC SUSCEPTIBILITY.

By applying the method of anisotropy of magnetic susceptibility (AMS) on rock samples several parameters -scalar and directional- arise (Zananiri, 2001 and references therein). The AMS measurements were performed using the KLY-2 Kappabridge (Geofysica, Brno) equipment at the University Paul-Sabatier, of Toulouse (France). The most important ones are examined.

The bulk magnetic susceptibility magnitude, $K_m = 1/3\ (K_1+K_2+K_3)$, varies from 196.49×10^{-6} SI to 26795.95×10^{-6} SI, with a mean value of 14161.00×10^{-6} SI. This, generally, high susceptibility can be attributed to the presence of magnetite, which is confirmed by thermomagnetic analysis (figures 3a &3b) and microscopic examination of thin sections.

The anisotropy degree, $P=K_1/K_3$, ranges, in the studied samples, from 1.001 to 1.065 - average of 1.028, that is 2.8%. Those values are quite low, however they are expected for the case of volcanic rocks.

The variation plot of Jelinek (1981) of AMS anisotropy degree versus bulk magnetic susceptibility (Fig.5a) shows that the anisotropy degree remains quite constant and there is no obvious correlation with the magnetic susceptibility magnitude.

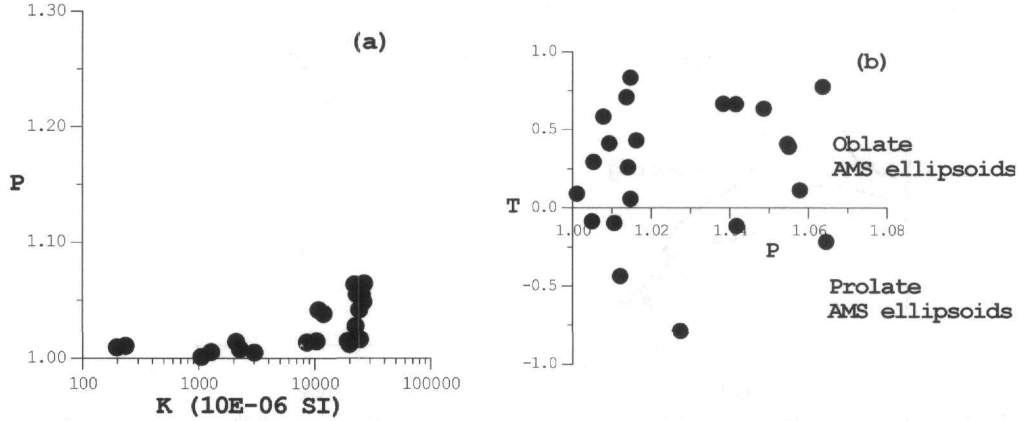

Figure 5: (a) Anisotropy degree (P) versus magnetic susceptibility (K) plot; (b) Variation plot of Jelinek (1981) AMS anisotropy parameter (T) and anisotropy degree (P).

Finally (fig.5b), the shape parameter $T = \frac{2(\ln K_2 - \ln K_3)}{\ln K_1 - \ln K_3} - 1$, exhibits great variation, but changes irrespective of the anisotropy degree. The majority of the samples lie in the T>0 domain, implying an oblate shape of the AMS ellipsoid.

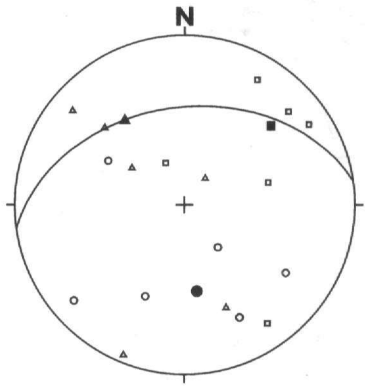

Figure 6: Lower-hemisphere stereoplot of AMS fabrics (squares = K_1 axes, triangles = K_2 axes, circles = K_3 axes).

Considering the orientation of the principal axes of the magnetic susceptibility ellipsoid, in most of the sites they are quite well-clustered. Their mean values for the Almopias region are K_1=47/31, K_2=325/38, K_3=172/48 (Fig.6).

5. DISCUSSION AND CONCLUSIONS

The majority of the studied samples have displayed a coherent behavior during palaeomagnetic processes. Stable components have been isolated and their primary character confirmed by the existence of both normal and reverse polarities. These directions are directed either N-S (Thessaly) or are slightly deviated (Milos, Almopias). Inclinations significantly lower than the expected have been observed only in few sites of Milos that are situated in the main depression (graben) of the island. In all other cases, I values are averaged around the expected ones. The slight counterclockwise rotation of Milos (~11°) is in good agreement with palaeomagnetic results obtained in Naxos, Rhodes, Kassos and Crete (Duermeijer et al., 2000) and suggests a possible connection of the island with the central-eastern Aegean "bloc" which is probably coupled to the westward moving Anatolia. Nevertheless, this small rotation is not supported by the rotation of the stress field which id directed NE-SW as inferred by earthquake focal mechanisms (Louvari, 2000) and appears as constant at least since Pliocene (Kondopoulou and Pavlides, 1990 and references therein).

The absence of rotation in the Thessaly volcanics (Kissel et al, 1986; Kondopoulou and Caputo, 1997) confirms that no strike-slip motion could be in the origin of the deformation which is taken up by dip-slip normal faulting. Therefore the movement of the older E-W dextral fault, formed in Miocene times (Mountrakis et al, 1993) seems to be totally replaced by the two normal re-activations suggested by the previous authors.

The new results from Almopias do not indicate a rotation for these volcanics (D=3°). Nevertheless previously obtained data from different parts of the complex had shown an about 15 to 17° clockwise rotation (Bobier, 1968; Kondopoulou and Lauer, 1984). When combined, the three sets of data yield a mean value of D=10.7° and I=58.8°, indicating a small clockwise rotation which is supported by the counterclockwise rotation of the stress field between Miocene and Quaternary (Pavlides, 1998, fig.1).

The existence of important geothermal fields in two of the studied areas (Milos and Almopias) could be partly connected to the absence of important rotations. A similar case has been observed in Italy (Baldi et al, 1995), where in an extensional geothermal province (Tuscan, Latium) the inferred continuity between the crustal and lithospheric parts, as this is suggested by the weak rotations, allows the persistence of the thermal processes.

ACKNOWLEDGEMENTS

We wish to thank V. Spatharas for his help in obtaining the magnetic mineralogy data. Part of the Almopias measurements has been performed in the Paleomagnetism Laboratory of the E.N.S. (Paris) through a bilateral cooperation project (Platon).

REFERENCES

BALDI, P., BUONASORTE, G., MATTEI, M., FUNICIELLO, R. & KISSEL, C., 1995. Paleomagnetic evidence of non rotational tectonism in the Tuscan-Latium geothermal province (Italy). Proccedings of the World Geothermal Congress, Florence, Italy, 939-943. Intern. Geoth. Ass., Stanford, USA.

BOBIER, C., 1968. Etude paleomagnetique de quelques formations du complexe volcanique d' Almopias C.R.A.S. (267), 1091-1094.

CAPUTO, R., 1996. The active Nea Anchialos Fault System (Central Greece) : comparison of geological, morphotectonic, archaeological and seismological data. Ann. Geofis., 39, 557-574.

DUERMEIJER, C.E., NYST, M., MEIJER, P.TH., LANGEREIS, C.G., SPAKMAN, W., 2000. Neogene evolution of the Aegean arc : paleomagnetic and geodetic evidence for a rapid and young rotation phase. Earth and Planet. Sci. Let., 176, 509-525.

FYTIKAS, M., INNOCENTI, F., KOLIOS, N., MANETTI, P., MAZZUOLI, R., POLI, G., RITA, F., VILLARI, L., 1986. Volcanology and Petrology of volcanic products from the Island of Milos and neighbouring islets. J. Volcan. Geoth. Res. 28, 297-317.

GALANAKIS, D., PAVLIDES, S., MOUNDRAKIS, D. 1998. Recent brittle tectonic in Almyros-Pagasitikos, Maliakos, N. Euboea & Pilio. Bulletin of the Geological Society of Greece, vol.XXXII/1, 263-273.

INNOCENTI, F., MANETTI, P., PECCERILLO, A., POLI, G., 1979. Inner arc volcanism in NW Aegean arc: geochemical and geochronological data. N. Jb. Miner. Mh., 4, 145-158.

JELINEK, V., 1981. Characterization of the magnetic fabric of rocks. Tectonophysics 79, T63-T67.

KISSEL, C., LAJ, C., MAZAUD, A., 1986. Paleomagnetic results from Neogene formations in Evia, Skyros and the Volos region and the deformation of Central Aegea. Geophys. Res. Lett., 13: 1446-1449.

KOLIOS, N., INNOCENTI, F., MANETTI, P., PECCERILLO, A., GUILIANI, O., 1980. The Pliocene volcanism of the Voras Mts (Central Macedonia, Greece). Bull. Volcanol., Vol.43-3, 553-568.

KONDOPOULOU, D., LAUER, J.P., 1984. Paleomagnetic data from tertiary units of the North Aegean zone. In J.E.Dixon and A.H.F. Robertson (Editors). The geological evolution of the Eastern Mediterranean. Spec. Publ. Geol. Soc., London, 17, 681-686.

KONDOPOULOU, D., PAVLIDES, S., 1990. Paleomagnetic and neotectonic evidence for different deformation patterns in the South Aegean volcanic arc: the case of Milos island. Proceedings of IESCA, Izmir, 210-223.

KONDOPOULOU, D., CAPUTO, R., 1997. Palaeomagnetic evidence for non-rotational deformation along the Nea Anchialos Fault System, Central Greece. Annali di Geofisica, Vol.XL, N.4.

LOUVARI, E., 2000. A detailed seismotectonic study of the Aegean and surrounding regions, based on focal mechanisms of small earthquakes. PhD Thesis, Univ. of Thessaloniki, 373 p.

MOUNDRAKIS, D., KILIAS, A., PAVLIDES, S., ZOUROS, N., SPYROPOULOS, N., TRANOS, M. AND SOULAKELLIS, N., 1993. Field study of the southern Thessaly highly active fault zone. 2nd Congress Hellenic Geolophysical Union, Florina, 5-7 May 1993, Macedonia, Greece, 603-615.

PAVLIDES, S., 1998. Dating the neotectonisms in South Almopias (Central Macedonia, N.Greece). Bulletin of the Geological Society of Greece, vol.XXXII/1, 189-197.
VOUGIOUKALAKIS, G. 1994. The Pliocene volcanics of mountain Voras, Central Macedonia, Greece. Bulletin of the Geological Society of Greece, vol. XXX/1, 223-240 (In Greek, abstract in English).
ZANANIRI, I., 2001. The method of anisotropy of magnetic susceptibility: theory and applications. A case study from the Rhodope Massif. 9th Congress of the Hellenic Geological Society (accepted for publication).