

**POLIPHASED PALEOMAGNETIC EVOLUTION  
OF GRANITOIDS FROM MACEDONIA (N.GREECE)**

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**A B S T R A C T**

The present study aims to unravel the geotectonic evolution of N.Greece prior to the already established Tertiary clockwise rotation. Therefore, Mesozoic sediments and Carboniferous granites were sampled in the North Pelagonian zone, but only the granites have yielded coherent results. The demagnetizing process has evidenced a polyphased magnetic evolution. The oldest magnetization  $M$  ( $D=321^\circ$   $I=26^\circ$   $a=11^\circ$ ) is interpreted as an overprint acquired in Late Jurassic Early Cretaceous. The younger one  $C_2$  ( $D=64^\circ$   $I=2^\circ$   $a=11^\circ$ ) is a Tertiary overprint. The presence of northeasterly directions with negative inclinations  $c'$  suggests that the N.Pelagonian granitic belt has undergone backthrusting during the Early-Middle Tertiary convergence phase. When these results are compiled with already published ones for Mesozoic formations they suggest a late Cretaceous counterclockwise rotation for the Hellenides followed by a clockwise Tertiary one which probably occurred in several phases.

**ΠΟΛΥΦΑΣΙΚΗ ΠΑΛΑΙΟΜΑΓΝΗΤΙΚΗ ΕΞΕΛΙΞΗ ΓΡΑΝΙΤΟΕΙΔΩΝ ΤΗΣ ΜΑΚΕΔΟΝΙΑΣ**

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**Π Ε Ρ Ι Λ Η Ψ Η**

Η παρούσα μελέτη στοχεύει στην διερεύνηση της γεωτεκτονικής εξέλιξης της Β.Ελλάδας η οποία προηγήθηκε από την ήδη γνωστή, δεξιόστροφη περιστροφή, στην διάρκεια του Τριτογενούς. Για το σκοπό αυτό μελετήθηκαν Μεσοζωϊκά ιζήματα και γρανίτες του Λιθάνθρακοφόρου στη Βόρεια Πελαγονική ζώνη, αλλά μόνο οι γρανίτες έδωσαν αξιόπιστα αποτελέσματα. Η διαδικασία απομαγνήτισης έδειξε μια πολυφασική μαγνητική εξέλιξη. Η παλαιότερη μαγνήτιση  $M$  ( $D=321^\circ$   $I=26^\circ$   $a=11^\circ$ ) ερμηνεύεται σαν διεύθυνση που αποκτήθηκε κατά το Ανώτερο Ιουρασιό - Κατώτερο Κρητιδικό. Η νεώτερη  $C_2$  ( $D=64^\circ$   $I=2^\circ$   $a=11^\circ$ ) είναι Τριτογενής. Η παρουσία ΒΑ διευθύνσεων με αρνητικές εγκλίσεις  $c'$  υποδηλώνει ότι η γρανιτική ζώνη της Βόρειας Πελαγονικής υπέστη επώθηση κατά τη φάση σύγκλισης του Κάτω-Μέσου Τριτογενούς. Όταν τα αποτελέσματα αυτά συνδυαστούν με ήδη δημοσιευμένα για Μεσοζωϊκούς σχηματισμούς, μπορεί να προταθεί μια αριστερόστροφη περιστροφή ηλικίας Ανω Κρητιδικού η οποία ακολουθείται από μία δεξιόστροφη Τριτογενή που έλαβε χώρα σε

## INTRODUCTION

Greece belongs to a set of blocks and microblocks caught between the Eurasian and African plates. As a consequence of this geographic position, the geotectonic evolution of the Hellenides results from the relative motions of the two plates. To the Mesozoic sinistral strike-slip motion succeeded first the Late Cretaceous counterclockwise rotation of Africa relative to Europe, then the Tertiary S-N convergence. During this convergence, the Ionian zone in Epirus (Horner and Freeman, 1983; Kissel et al., 1985), and Albania (Speranza et al. 1992) and the Circum Rhodope (Kondopoulou and Westphal, 1986) have undergone a post-Oligocene clockwise rotation. Investigation of earlier block motions is hampered by the lack of rocks suitable for paleomagnetism with exception of a few sedimentary layers as the Ammonitico Rosso and Permo-Triassic volcanics, which have yielded reliable results in the Pelagonian zone (Lauer and Kondopoulou, 1987; Turnell, 1988; Surmont, 1989). A poorly documented north-western direction, consistent with directions measured in layered Permo-Triassic volcanics from the Pelagonian (Lauer and Kondopoulou, 1987; Turnell, 1988) was obtained in gabbros from the Pindus (Pucher et al., 1974). These NW directions are in favour of an earlier rotation in opposite direction, which is still debated.

During a first field trip in 1988, different rock types of different ages were sampled along an E-W section from Chalkidiki to the Albanian border, in order to check which rocks are the most suitable for paleomagnetism. The Mesozoic sediments had to be rejected because of too weak magnetizations. The Mio-Pliocene sediments demonstrated that N.Greece has not undergone recent rotations (Westphal et al., 1991). Surprisingly, the granitic sites provided the best results. The following year, sampling was extended in these rocks despite of the uncertainty concerning the bedding of the units.

## THE N. PELAGONIAN GRANITOIDS

The north Pelagonian zone (Internal Hellenides) consists of: a) the pre-Alpine crystalline basement, b) Mesozoic "sediments" consisting mainly of crystalline limestones and known as the Mesozoic cover, c) ophiolites and d) the post-Alpine, mostly recent sediments. The crystalline rocks are orthogneisses, augengneisses, two mica schists, amphibolite schists and amphibolites. The plutonic massif of mount Varnous lies close to the Greek-Yougoslavia border and extends northward to Yougoslavia. The granite corresponds to the lower part of the crystalline basement. From the petrographic point of view it consists of granites, granodiorites, porphyroid granites and granodiorites, and quartz monzonites with the I-type, calc-alkaline character.

The radiometric ages are very scattered and range from 465 to 50 Ma (Marakis, 1969; Kiliass, 1980). The Cambrian-Ordovician ages have been rejected after geological observations. Two

intrusive phases have been proposed by Kiliias (1980) according to tectonic correlations, one in the Late Jurassic, the other in the Early Cretaceous. But recent U-Pb dating of the Kastoria granite (Mountrakis, 1984) (fig. 1) and Rb-Sr wholerock processing on the Varnous granite (Koroneos et al., unpublished) are in favour of a Late Carboniferous age around 300 Ma. Biotite is affected by an Early Tertiary event and gives an age of 55 Ma (Koroneos et al., unpublished).

The eastern Varnous has undergone four main tectonic phases (Kiliias, 1980), which are: the P1 phase in the Late Jurassic, the Early Cretaceous P2, the Late Crataceous P3 and the Priabonian-Oligocene P4 phases. A post-Oligocene brittle deformation led to normal faulting.

90 cores were drilled in 12 sites; 7 sites are located in the granitoids of the Varnous massif, west of Florina, 3 sites in the Kastoria massif, and one site (Gr 56) on a smaller granitic body located near Aetos (fig. 1).

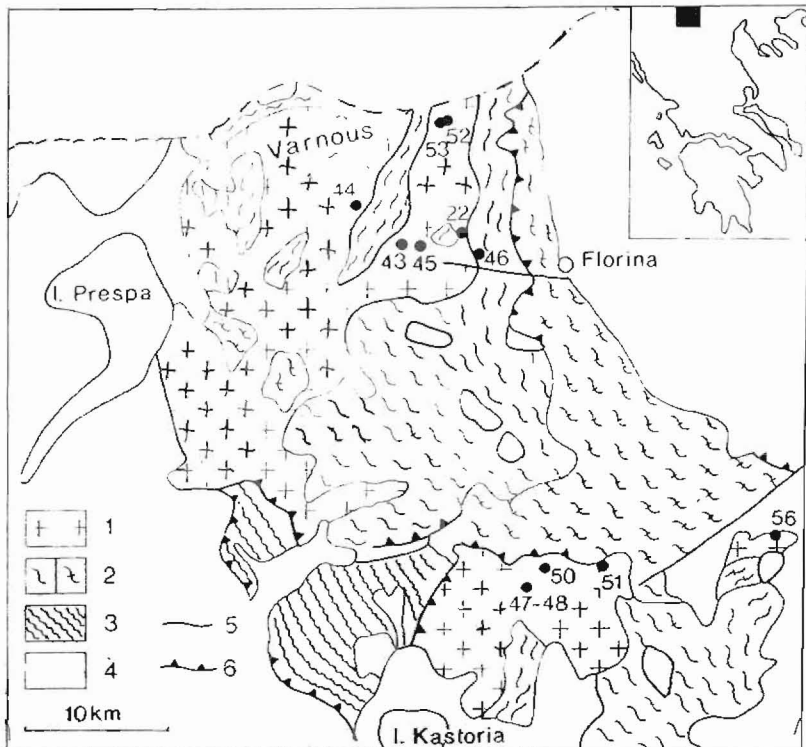


Fig.1. Geological sketch map of the N. Pelagonian Paleozoic units (after Kiliias and Mountrakis, 1989) and location of the paleomagnetic sites. 1) granitoids, 2) metamorphics, 3) Permo-Triassic series, 4) post-Triassic, 5) faults, 6) thrusts.

## PALEOMAGNETIC PROCESSING AND RESULTS

The cored samples were cut into 22mm long specimens with a diameter of 25mm. The remanent magnetizations were measured with a modified Digico magnetometer, with a noise level of  $3 \cdot 10^{-5} \text{ A.m}^{-1}$ . To separate the different components of the Natural Remanent Magnetization, an average of 2 specimens per sample were demagnetized by stepwise heating (11 steps up to  $600^{\circ}\text{C}$ ) (Fig. 2a). In a few sites, Alternating Field process was also efficient. Systematic measurements of Anisotropy of Magnetic Susceptibility were carried out with a Digico apparatus in order to get more indications on the layering and to detect eventual deviations of the remanent direction by anisotropy of tectonic origin. With few exceptions, the AMS foliation is consistent with the macroscopic observation.

With a few mean directions interpreted as Late Tertiary-Present directions (C,P, fig.2; tab.2), the demagnetizing process has yielded two main groups of directions. Most are directed to the NE with shallow inclinations and scattered declinations (Gr 48-48, 43, 44, 45, 46). Site Gr 56 and some specimens from Gr 50 can be considered as reversed. In the case of sites Gr 43, 45, 22, 46 (fig.1), the macroscopic foliation and the AMS foliation and/or lineation exclude a local rotation as responsible for the difference in declination between Gr 22 and Gr 43, 45, 46. The deviation seems rather to be due to emplacement of the magnetization at different stages of the geotectonic evolution. That is the reason why we consider two separate clusters, the  $C_2$  with sites Gr 22, 52, and 56, the mean of which is:

$$D=64^{\circ}, I=2^{\circ}, k=133, a_{95}=11^{\circ}, (20^{\circ}\text{N}, 276^{\circ}\text{E}),$$

and the C' consisting of Ka of few stable directions from Gr43, Gr50.

$$D=38^{\circ}, I=-16.5^{\circ}, k=38, a_{95}=11^{\circ}. (29.6^{\circ}\text{N}, 157^{\circ}\text{E})$$

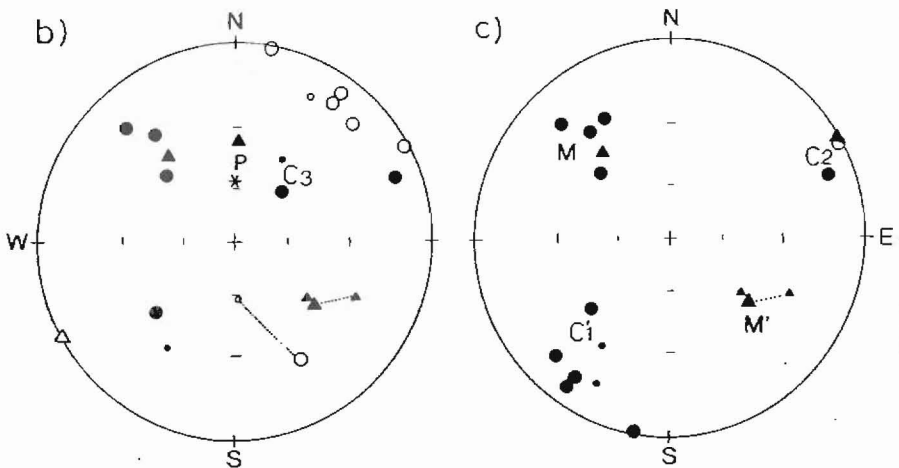
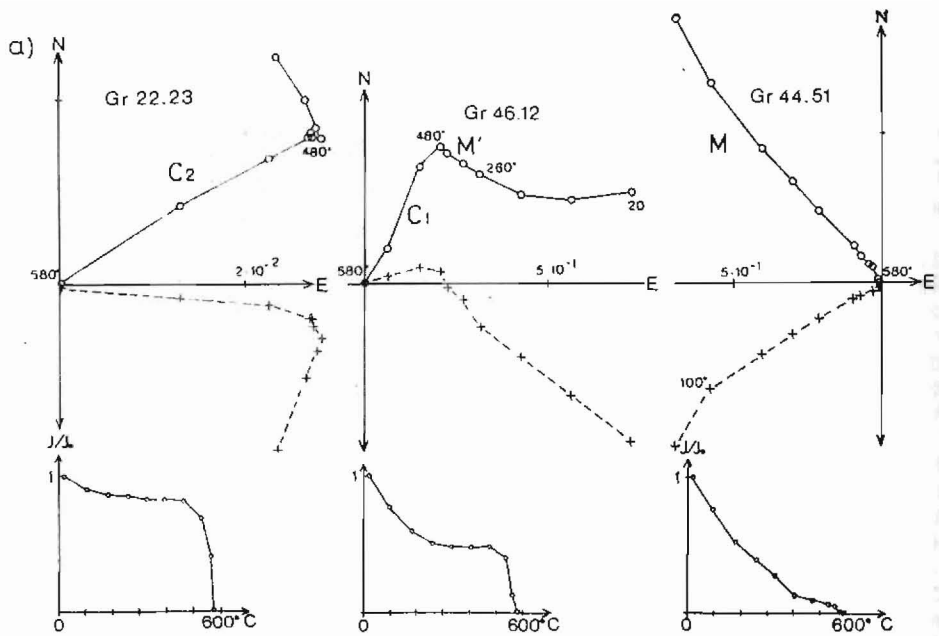
The other main group of directions has NW declinations and positive inclinations. They are labelled M. Their mean direction is:

$$D=320.5^{\circ}, I=26^{\circ}, k=45, a_{95}=11^{\circ}, (46^{\circ}\text{N}, 264.5^{\circ}\text{E}),$$

The maximum unblocking temperatures vary, from  $300^{\circ}$ - $350^{\circ}$  in Gr 22, 47-48 and 43 to  $580^{\circ}$  in Gr 43, 44, 47-48, 50. The unblocking temperature is not characteristic of a specific group of directions. Two sites (Gr 22, 46) display also low temperature M' magnetizations with SE declinations and positive inclinations.

## DISCUSSION

Unexpectedly, the studied granites show rather coherent directions of magnetizations. The occurrence all along a belt of  $C_1$ ,  $C_2$  or M directions excludes important relative movements from one site to the other and this granitic belt can be considered as cylindrical. Also unexpected is the similarity of the results of the Pelagonian and of the Circum-Rhodope where an ophiolitic sequence has been studied (Edel et al., 1991). Although considered as zones with a different history, C and M directions are present in both of them, the only difference is the inclination of the  $C_2$  directions which is shallower in the granites than in the ophiolites.



**Fig.2.** Typical orthogonal projections and thermal demagnetizing  $J/J_0$  curves of  $C_1$ ,  $C_2$ ,  $M$  and  $M'$  components in Pelagonian granites. 2b,2c: Mean in situ site directions in the granites. Symbols represent maximum unblocking temperatures: 300-400°: triangles; 500-560°: losanges; 570-585°: dots; 590-610° squares. Small symbols represent directions obtained in specimens from only one or two samples. Dotted lines join the two poles of the trend, when inclinations are dispersed.

Both zones are striking NW-SE. The field measurements and the AMS give directions of N130° to N150° for the Paleozoic series of the Pelagonian. In our case, unclear bedding has no significant effect on the declinations of the C<sub>1</sub> and C<sub>2</sub> directions, but it has one on the inclinations. Concerning the M directions, tilting the massif by less than 90° around a NW-SE axis keeps the direction in the north-easterly positive quadrant. Consequently, conclusions using the declinations can be drawn for both zones. But the inclinations also give some informations on the geotectonic evolution. Interpretation of the paleomagnetic directions requires that the corresponding magnetizations are dated. As most magnetizations encountered are overprints, attempt is made to date them indirectly by comparing with results obtained on dated units.

**Table 1.** Mean in situ directions computed for the different components. bt: maximum unblocking temperatures; L: component label; N/N<sub>0</sub>: number of samples containing the considered component/total number of samples; n: number of specimens containing the considered component; D°, I°: declination, inclination; k, a<sub>95</sub>: Fisher statistic parameters. Mean directions of mean site directions.

Site	Rock Type	Lab	bt	N/No	n	Do	lo	k	a <sub>95</sub>
Gr 22	granite (foliated)	M	350	4/9	5	321	33	43	10
		M'	400+450	5/9	5	127.5	41	42	11
		C2	580	8/9	14	62	-1	40.5	5
Gr 43	gneiss	M	350-580	7/10	8	312	39	177	4
		C'1	580	1/10	2	29	-12	41	
		C3	350>500	5/10	5	45	53	101	8
Gr 44	granite (biotite + amphibole)	M	580	4/10	7	322	23	50.5	8.5
		C'1	580	4/10	7	46	-11	99	6
		C3	580	3/10	3	30	40	21	21
Gr 45	granite	C'1	580	7/7	9	35	-10	53	7
Gr 46	dolerite	M'	350	3/5	3	115	22	51	17
		M'	480	5/5	7	128	35.5	25	12
		C'1	580	5/5	7	36	-6	42	9
Gr 47-48	granite (foliated)	M	350-580	4/14	7	316	12.5	23	19
		C'1	450-580	5/14	7	229	34	32	11
			580	6/14	9	11	-1	46	7.5
Gr 50	granite (foliated)	C'1	580	3/8	3	213	25	214	8
		C3	480-580	2/8	2	177	-57	248	
		M	580	4/8	6	150.5	-21	33	12
Gr 52	granite	C2	350>600	5/8	6	69	9	70	8
Gr 55	granite (foliate)	C2	350-400	9/9	9	242	-1	274	3

## THE C DIRECTIONS

Comparison of the mean directions of this study with those published for different zones of Northern and Central Greece (fig.3) establishes some agreement.  $C_2$  directions considered as primary, indicating clockwise rotations (with respect to the present day position), were found in Eocene-Oligocene sediments of the Ionian and Pindus zones (Horner and Freeman, 1983; Kissel et al., 1985; Marton et al., 1990) (fig. 3a) Such directions exist also in Permo-Triassic lavas and Jurassic limestones of the Pelagonian and Sub-Pelagonian zones (Pucher et al., 1974; Turnell, 1984, 1988; Surmont, 1989) (fig 3b), but with shallower inclinations. Triassic Mid-Jurassic and Upper Cretaceous Carbonates from Argolis, NW Peloponnese and central Greece indicate also rotations of about  $70^\circ$ , that is  $C_2$  directions (Morris, 1992).

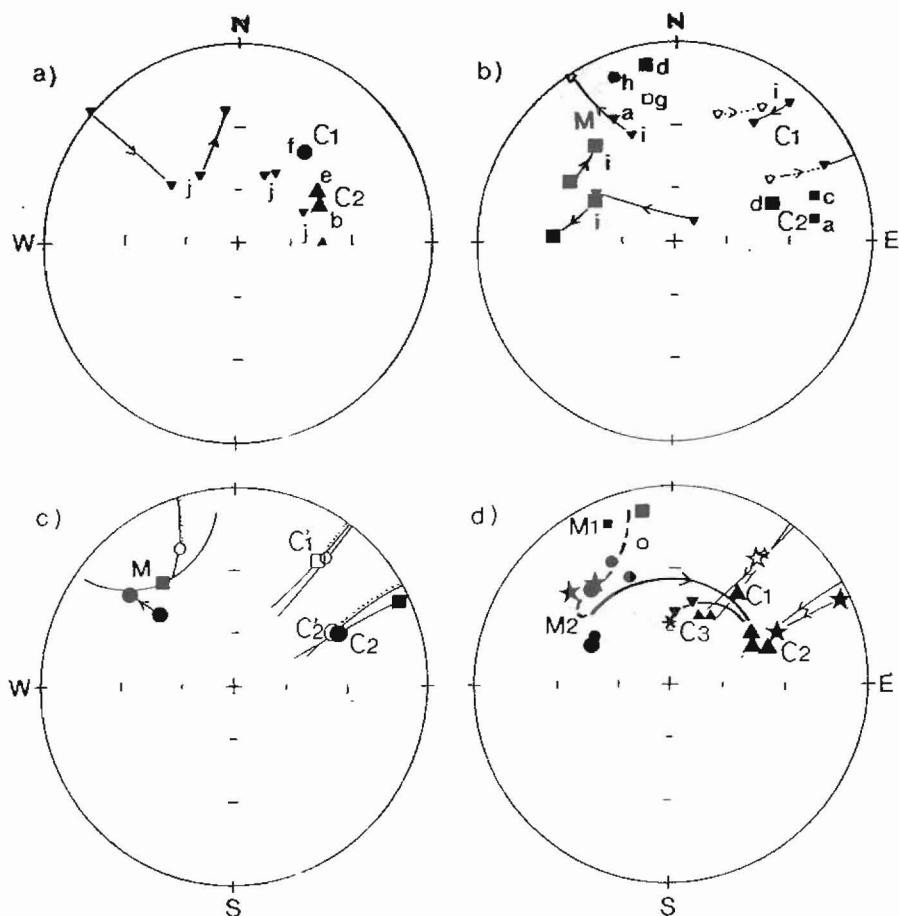
In the Chalkidiki ophiolites, the  $C_2$  group magnetizations are clearly overprints, likely emplaced in the Early Tertiary, during or after the SW thrusting phase (Edel et al. 1991). The inclinations for Mesozoic units obtained by different authors and by us in the Pelagonian and sub-Pelagonian zones are lower than the ones found in the Early Tertiary sediments from the Ionian and Pindos zones. This could be interpreted as due to a slight back-tilting of the belt. In the granites of the present study the inclination of the  $C_2$  being nearly flat, a  $40^\circ$  back-tilting relative to the NW-SE axis of the belt brings to the awaited Paleocene-Oligocene inclination. It is clear that the small circles corresponding to tilting of the Pelagonian granites pass through the Early Tertiary directions of the Ionian and Pindus zones (fig. 3a,c,d).

This interpretation in terms of overprints acquired prior to Middle-Late Tertiary tilting of the belt may also be available for the  $C'_1$  directions evidenced in the granites but also ophiolites in Chalkidiki. The most likely way to explain them is to rotate the belt relative to its horizontal axis. The same interpretation may be proposed for the  $C'$  directions obtained by Surmont (1989) in the Mesozoic series of Pende Oria in the Parnassos zone (fig.3b).

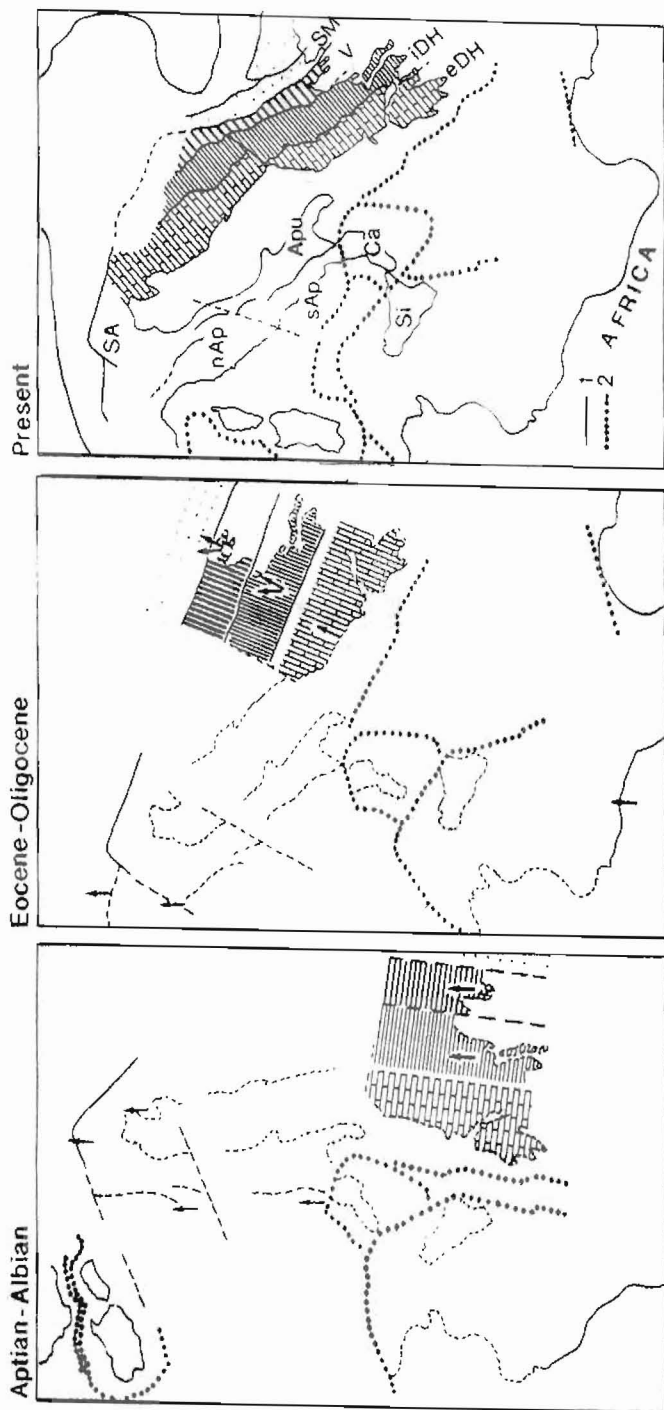
Summing up, the  $C'_1$  magnetizations were emplaced in series tilted toward south. Back-tilting probably occurred during the major shortening phase in the Early Tertiary. The  $C_2$  overprints were acquired in the latest stage or posteriorly to back-thrusting, likely in Eocene-Oligocene times.

## THE M DIRECTIONS

North-north-westerly directions with shallow inclinations labelled  $M_2$  were found in Permo-Triassic volcanics (Atalandi: Turnell, 1988; Eratyra: Lauer and Kondopoulou, 1987) from the Pelagonian zone, in ophiolites from the Pindus (Pucher et al., 1973) Jurassic-Cretaceous sediments of the Ionian zone (Horner, 1983) and in Permo-Triassic volcanics from the Serbo-Macedonian zone (Nea Santa: Lauer and Kondopoulou, 1991) (fig. 3b). Slightly higher inclinations were exhibited in Jurassic-Early Cretaceous sedimentary units from the Pelagonian zone (Theopetra and Bafi: Surmont, 1989) and the Parnassos zone (Pende Oria: Surmont, 1989).



**Fig.3.** a: Mean directions published for Early Tertiary units, b: for Mesozoic units, from the Ionian (upright triangles), Pindus and Parnasse (reversed triangles), Sub-Pelagonian and Pelagonian (squares), and Circum-Rhodope (dots) (after Pucher et al., 1973; Horner and Freeman, 1983; Turnell, 1984, 1988; Kissel et al., 1985; Kondopoulou and Westphal, 1986; Lauer and Kondopoulou, 1987, 1990; Surmont, 1989). The small circles join the directions before and after tilt correction. c: Mean directions obtained in Pelagonian granites (squares) (this work) and in Chalkidiki ophiolites (dots) (Edel et al., 1991) with the corresponding small circles. d: All results obtained in Permo-Triassic (squares), Jurassic-Cretaceous (dots), Early Tertiary (upright triangles) and Late Tertiary units (reversed triangles). Stars represent the results obtained in Pelagonian granites and the Chalkidiki ophiolites. The thick line shows the evolution with time of the paleomagnetic directions.



**Fig. 4.** Possible reconstruction of Central Mediterranean drawn from paleomagnetic directions (after Edel, 1980), and the directions listed in Westphal et al., 1986) and the relative positions of Africa and Europe (Olibet, 1978). The lateral extension of the external (eDH), internal (DH) Dinarides-Hellenides, the Vardar (V) and Serbo-Macedonian (SM) zones (after Sandulescu, 1984) is arbitrary. The reconstruction for the Eocene-Oligocene is based on the  $C_1$  directions; at time of emplacement of the  $C_2$  magnetizations (probably Oligocene), the Hellenides were striking E-W. 1: faults and thrusts; 2: present block boundary; SA: southern Apennine; nAp: northern Apennine; Apu: Apulia; Ca: Calabria; Si: Sicily.

M in situ directions have been also obtained in Chalkidiki ophiolites and together with the ones from the Pelagonian granites lie very close to the direction from Theopetra.

In the granites, by reason of the unknown bedding, the original M direction lies on a small circle (fig.3c), but stays in the M area defined by the Permo-Mesozoic directions (fig. 3b).

In order to assess the age of the M magnetizations the following reasoning is used: in the Pelagonian zone, the sedimentary series of Theopetra are Kimmeridgian to Berriasian, probably postdate the obduction of the ophiolites. The consistency of our  $M_2$  directions with that of Theopetra leads to an Early Cretaceous age of the overprinting phase. The older  $M_1$  directions obtained in Permo-Triassic units show slightly deviated NNW declinations and shallower inclinations (fig.3d).

### CONCLUSION: GEOTECTONIC EVOLUTION OF THE PELAGONIAN

$C_2$  directions were found as primary Eocene-Oligocene magnetization in the Ionian zone (Horner and Freeman, 1983; Kissel et al., 1985), and as overprints in granites (this work) and Permo-Triassic (Turnell, 1984) from the Pelagonian zone, in Jurassic Limestones from the Argolis peninsula (Turnell, 1988; Morris 1992) and in Jurassic ophiolites from Chalkidiki (Edel et al., 1991). Primary  $C_1$  directions characterize Tertiary granodiorites from Chalkidiki dated between 40 Ma, i.e. Late Eocene (Kondopoulou and Westphal, 1986) and 50,4Ma (Christofides et al., 1990).

M directions are considered as primary in Permo-Triassic flows from the Pelagonian (Lauer and Kondopoulou, 1987; Turnell, 1988), the Serbo-Macedonian (Lauer and Kondopoulou, 1991), and in Late Jurassic-Early Cretaceous limestones from the Pelagonian (Surmont, 1989). We have found them, mainly as overprints in granites from the Pelagonian and in ophiolites from the Circum-Phodope (Edel et al., 1990). They exist also in ophiolites from Pindus (Pucher et al., 1974).

A first conclusion can be drawn: The paleomagnetic evolution of the Pelagonian seems to be similar to that of the Serbomacedonian in the east and Pindus and Ionian in the west.

#### - Jurassic-Early Cretaceous

The  $M_2$  overprints in granites and ophiolites have likely taken place subsequently to the Late Jurassic-Early Cretaceous obduction and thrusting phase. In Early and Middle Cretaceous times the Pelagonian was oriented N-S (fig.4a).

#### - Late Cretaceous-Early Tertiary:

The change in declination from  $M_2$  to  $C_2$  implies a large rotation by about  $80^\circ$ , and from  $M_2$  to  $C_1$  a  $100^\circ$  rotation. In both cases, the Hellenides have undergone the most important counterclockwise rotation of all the Mediterranean blocks.

During the Early Tertiary shortening phases the Pelagonian was strongly tilted. To restore the  $C_1$  directions to the expected Early Tertiary inclination a rotation of about  $60^\circ$  around a NW-SE horizontal axis is needed. For the  $C_2$  directions the amount of rotation is  $40^\circ$ .

#### - Late Tertiary:

The deviation of the  $C_1$ - $C_2$  directions relative to the present day

direction is due to a clockwise rotation which occurred probably in several phases in the Oligo-Miocene and more recently, since 5 Ma (Kissel et al., 1985). Fig. 4c.

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