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PALEOMAGNETISM OF SOME NORTHERN GREECE OPHIOLITES AND ASSOCIATED SEDIMENTS

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SUMMARY

The investigation of superimposed paleomagnetic imprints in the ophiolites of Northern Greece (Axios-Chalkidiki belt and Vourinos massif) is undertaken in the revisited frame of the regional tectonic and thermal history. Application of the fold test to four sites of the Kassandra peninsula, comprising pillow lavas and associated sediments demonstrates that the main regional magnetic component ($D=47.6°$, $I=47.1°$, $\alpha_{95}=8.3$) is a post-folding remagnetisation. A comparison with the directions found in the Sithonia granite shows that this component has been likely acquired during the emplacement of this granite (Eocene). An older component ($D=325.4$, $I=34.1$, $\alpha_{95}=18$) defined in the sediments of the Kassandra area is also present in the ophiolites. This direction has been probably acquired during Late Jurassic-Early Cretaceous times. Further comparisons with the directions found in the Axios-Chalkidiki and Vourinos ophiolites show that the Eocene remagnetisation is consistently found in the two belts while the older component is more scarce.

The Cenozoic clockwise rotation of about 45° shown by the Eocene remagnetisation has been widely described by various authors, but the Mesozoic rotation indicated by the oldest component has been less investigated. This counterclockwise rotation, though larger, is compatible with that of the African plate during Mesozoic. This suggests that i) Northern Greece was part of the African foreland before the alpine collision and ii) oceanic spreading south of the Pelagonian zone would have increased during Cretaceous time the rotational movement of the studied area with respect of Africa.

INTRODUCTION

Among the main geological issues in Northern Greece, the problem of the origin of the ophiolites occupies an important place since many years (Smith et al., 1975; Mountrakis, 1984; Vergely, 1984; Ferrière, 1985; Ricou et al., 1986; Robertson et al., 1991; Mountrakis et al., 1992). Do the eastern, Vardar-Axios ophiolites and the western, Vourinos-Pindos-Othrys ophiolites belong to a single Jurassic ocean, formerly located to the NE of the Pelagonian continental block, or do they belong to distinct oceanic basins located on the NE and SW sides of the Pelagonian domain, respectively? Paleomagnetic data can be used in discussing such geodynamic issues. Several paleomagnetic results are now available on the Pelagonian and Axios zones, either in the southern part

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(Turnell, 1988; Surmont, 1989; Surmont et al., 1991) or in the northern one (Edel et al., 1990, 1991/1992). In their study of the Chalkidiki ophiolites (Axios zone), Edel et al. (1991/1992) demonstrated that Northern Greece ophiolites present several superimposed directions of magnetisation, ascribed to Mesozoic and Cenozoic events. The importance of the Cenozoic remagnetisation most often hampers unravelling the orientation of the Mesozoic, primary components. Taking advantage of these previous works, we have undertaken the study of some selected sites in the ophiolitic massifs of northern Greece or in their associated sediments, identifying in every case the paleohorizontal in order to perform field tests. In the present paper, we focus on the discussion of the Cenozoic magnetisation, a prerequisite for further discussion of the Mesozoic components.

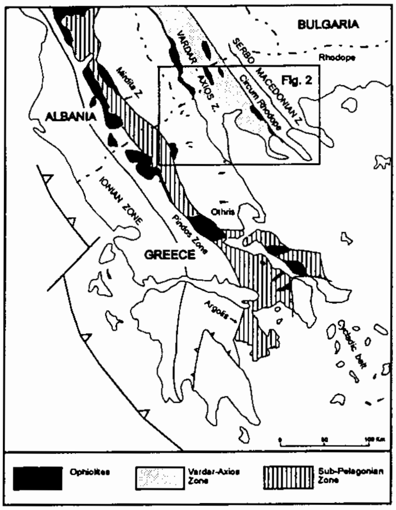

Fig. 1: Structural sketch map and location of studied area.

GEOLOGICAL SETTING

The studied sites encompass the two main ophiolitic belts of Northern Greece, namely the Vardar-Axios zone to the East of the Pelagonian zone, and the Sub-Pelagonian zone to the West (Fig. 1). In the Vardar-Axios belt, we collected samples from four areas located in the eastern part of the belt, here named Axios-Chalkidiki ophiolitic zone, which roughly corresponds to the Peonias zone of Mercier (1968) (Fig. 2). To the north of this zone the Gevgueli complex (four sites) offers a complete, although dismembered, ophiolitic suite, intruded by the Tithonian-Early Cretaceous Fanos granite (Bebien, 1982, 1991; Spray et al., 1984). More southward, the Oreokastro massif (one site) which belongs either to the Axios- Chalkidiki zone or to the External Circum-Rhodope zone (Kaufmann et al., 1976; Kockel et Mollat, 1977; Michard et al., 1994), corresponds to a solid gabbroic sliver vertically tilted together with its Late Tithonian conglomeratic limestones cover (Mercier, 1968; Kockel et Mollat, 1977). In the Gerakini massif (Gauthier, 1984; Edel et al., 1991/92), the Sonia site involves layered gabbros close to the paleo-Moho discontinuity. The Paliouri massif crops out at the southern tip of the Kassandra peninsula. On top of the spilitic pillow lavas of this small, and up to now neglected massif, we observed two distinct sedimentary formations (Fig. 3). The lower formation, here named the Paliouri flysch, consits of rythmic, volcano-clastic and pelagic layers, which were apparently deposited directly after the pillowed volcanic outpurs in deep-water environment. This volcano-clastic flysch is uncomformably overlain by shallow-water deposits, consisting of reefal limestones and conglomeratic calcarenites with pebbles from the underlying formations (diabases and flysch). We interpret these shallow-water sediments as post-obduction deposits, equivalent to the Oreokastro Late Tithonian-Early Cretaceous limy conglomerates. Our description modifies the conclusion of Kockel and Mollat (1977) who considered the «Prinochori beds» (equivalent to our Paliouri flysch) as younger than the Tithonian limestones.

In the Sub-Pelagonian zone, we cored samples from four sites in the Vourinos massif (Fig. 2). The ophiolitic suite is complete and almost undisturbed in the

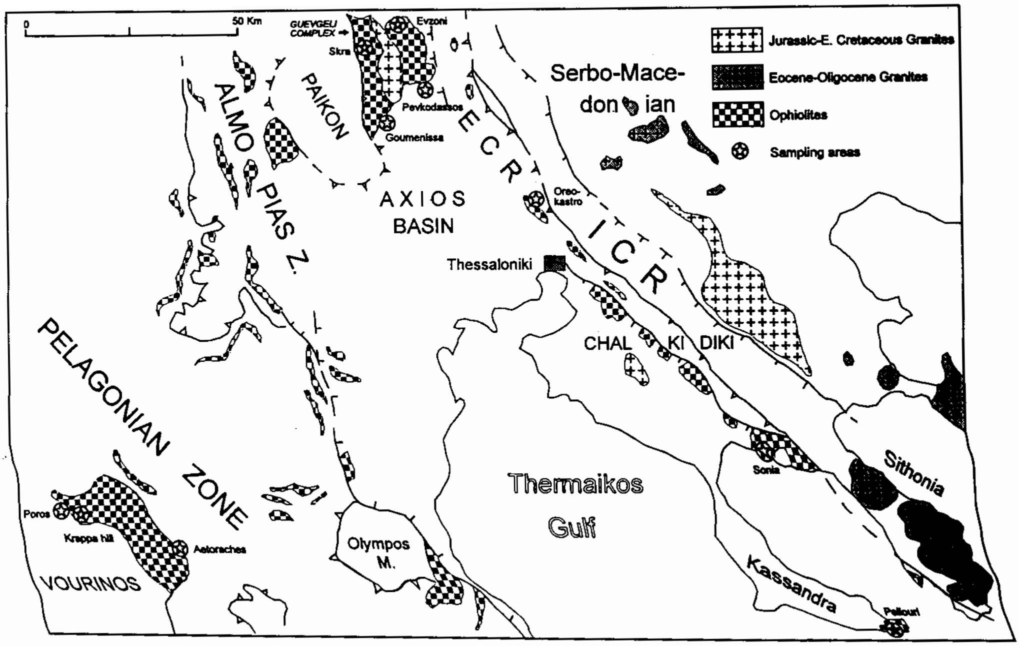

Fig. 2: Geological sketch map and location of sampling sites (ECR= External Circum Rhodope, ICR=Internal Circum Rhodope).

Vourinos from the harzburgitic tectonites with chromites pods (Aetoraches site) up to the volcanic sequence (Krapa hills dykes) (Moores, 1969; Rassios et al., 1983). The volcanics are in turn overlain by the Krapa hills limestones which include Calpionellids-bearing limestones at their base, followed by Early Cretaceous to Cenomanian Rudist-bearing layers (Mavrides, 1980). Amphibolite from the infra-ophiolitic sole was dated at 170 Ma (Spray and Roddick, 1980), giving an upper limit to the age of the ophiolite accretion and a lower limit to that of its obduction.

After the Tithonian obduction of the Vardar-Axios and Sub-Pelagonian ophioltes (Eo-Hellenic phase, Jacobshagen, 1986) and the subsidence of the whole area during Cretaceous-Paleocene time, the ophiolites and their substrate suffered westerly directed rethrusting during Eocene. This Meso-Hellenic phase was accompanied and followed by a metamorphic-magmatic evolution involving in the studied massifs a low-grade, greenschist-facies alteration. Several Eocene-Oligocene granitoids emplaced in the internal Circum-Rhodope zone and the juxtaposed Serbo-Macedonian zone, immediately to the East of the Chalkidiki ophiolites (Kondopoulou and Westphal, 1986; De Wet et al., 1989).

PALEOMAGNETIC STUDY: FIELD OBSERVATIONS DURING SAMPLING AND LABORATORY MEASUREMENTS

A constant sampling strategy was applied for this study. All possible indications of the paleohorizontal were searched and their orientation carefully measured. The most simple case was that of oceanic sediments associated with ophiolites. In general it was also possible to get values of dip and strike directly from the pillow lavas flattening planes, related to their initial emplacement. In the gabbros we tentatively used the cumulate which is considered as almost horizontal when far from the top of the magmatic chamber

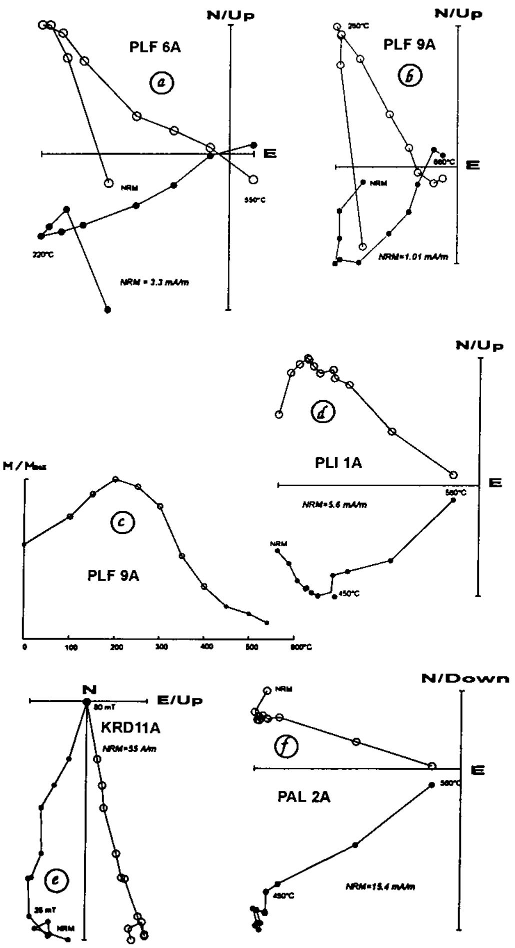

Fig. 3: Vector demagnetisation diagrams, full (open) circles correspond to projections onto the horizontal (vertical) plane, a-e samples thermally cleaned, f alternating field cleaning.

(Nicolas, 1989). When it was possible to assume an originally vertical setting (sheeted-dyke complex) the dykes orientation was also taken into consideration.

Paleomagnetic measurements were conducted on 150 cored samples, oriented using both magnetic and sun compasses. Predominantly thermal and in some case alternating field demagnetisations were performed on standard cores (25 mm of diameter) cut at 23 mm length. Natural remanent magnetisation (NRM) was measured at each step either with a cryogenic magnetometer or with a spinner one depending of the intensity of NRM. Bulk susceptibility was measured on pilot sample after each demagnetisation step to monitor possible mineralogical transformation during heating. Directions were analysed on orthogonal plots and selected with a least-squares routine. Demagnetisation and IRM (Isothermal remanent magnetisation) acquisition curves were performed on specimens representative of the differents types of sampled rocks to investigate the magnetic mineralogy.

RESULTS : THE PALIOURI KEY AREA

Four sites have been sampled at the tip of the Kassandra peninsula near the village of Paliouri (Fig. 2). Two sites, PLI (strike=60°, dip=30°) and PAL (strike=25°, dip=30°) correspond to relatively well preserved pillow lavas. The other two correspond to the «Paliouri flysch», defined in the preceeding section. PLR (strike=90°, dip =30°) was sampled in a pyroclastic rock in stratigraphic contact with the pillows while PLF (strike=70°, dip=15°) belongs to the true Paliouri flysch sequence with fine grained sandstones and slumps.

Samples coming from different sites show various behaviour during demagnetisation. The pillow lavas after the destruction of a viscous component display (Fig. 3f) only one direction between 200° and 580°C, while the sediments and specially those from site PLF exhibit two or three components. i) a viscous component destroyed before heating at 220°C, ii) an intermediate component with a negative inclination and a southwestward declination, completely unblocked below 500-550°C, iii) a high temperature normal component visible up 520°C (Fig. 3a-d). But it was not possible in general to perform a complete thermal cleaning of the sediments as mineralogical changes occurred during heating up to 570°C. The artificial production of magnetic minerals is indicated by a rapid increase of the susceptibility and of the remanent magnetisation. On the other hand it was impossible to use successfully the alternating field cleaning on this samples while this method gave good results with the pillow lavas.

In conclusion the main magnetic mineral of the effusive rocks from the Paliouri area likely corresponds to magnetite or titano-magnetite as the remanence shows a low coercivity and is completely destroyed at 580°C. Accordingly thin sections observed under reflected light show the common occurence of magnetite or more likely titano-magnetite in the pillow-lavas. The magnetic mineralogy of the sediments from the same place comprises a magnetic carrier with a high coercivity and intermediate to high unblocking temperatures, it might be hematite with different grain size populations.

Fold test

The intermediate unblocking temperature component present in the sediment is also visible in the pillow lavas with a very similar direction (Table 1)

Table 1: Paliouri intermediate direction

SITE	**N**	**Dg**	**Ig**	**Ds**	**Is**	**K**	**α_{95}**
PLF	15	223.6	-51.3	243.2	-55.7	79	4.1
PLR	3	204.9	-55.1	260.7	-75.9	64	12.4
PAL	14	219.6	-30.6	229.7	-14.3	29	6.9
PLI	9	232.0	-55.9	271.9	-49.1	17	10.7

N=Number of specimens, Dg, Ig = *in situ* Declination and inclination, Ds, Is = Declination and inclination after bedding correction (stratigraphic coordinates), K and á$_{95}$ = Fischer's parameters of confidence.

The application of the fold test on the four sites (Table 2 and Fig. 4) give a negative result at >95% confidence (McElhinny, 1964), thus the intermediate direction represents a post-folding remagnetisation. The overprinted character of this component can also be seen on some vectors diagram of the sediment samples where the intermediate direction appears not directed towards the origin during demagnetisation (Fig. 3a,b).

Table 2: Paliouri fold test

AREA	N	*Before unfolding*			*After unfolding*			**K_{max}/ K_{min}**	**Significance**
		Dec	**Inc**	**K**	**Dec**	**Inc**	**K**		
Paliouri	4	220.2	-47.3	35	247.0	-50.4	8	4.3	->95%

N=Number of sites, Dec and Inc = directions of the component, K=dispersion parameter, K_{max}/K_{min} = McElhinny (1964) precision parameter, result of test is negative (-) and related to 95% confidence factor.

High temperature component in sediments

It has not been possible to isolate very successfully the high temperature component occuring in a main part of the sediment samples as mineralogical changes occur during heating. However in PLF site, 9 samples over 15 allow the calculation of the following direction :

Table 3: Paliouri high temperature component (same conventions as table 1)

SITE	N/Nu	Dg	Ig	Ds	Is	K	α95
PLF	9/15	325.4	34.1	321.0	50.4	7	18

This older component is not seen in the Paliouri Pillow lavas. The remagnetisation which occurs in magnetite bearing samples has not been so complete in the flysch type sediment probably due to the composition of magnetic mineralogy.

Datation of the components

The intermediate temperature unblocking component is characterized by a southwest declination and a reversed inclination. We propose an Eocene age for this E component. This assumption is based on a comparison with the direction of magnetisation found in the Eocene (around 50Ma) Sithonia granite. The direction measured by Kondopoulou and Westphal (1986) in this rock is very close to the intermediate direction of Paliouri as it is shown in the final discussion. On the other hand the Sithonia massif intrudes the Chalkidiki ophiolitic belt (see before) and the thermal event related to the regional metamorphism and to the emplacement of granitic rocks appears as the best candidate for the origin of this extended phase of remagnetisation. Additionnally, the intrusion emplacement might explain the observed tilting of the volcano-sedimentary formations.

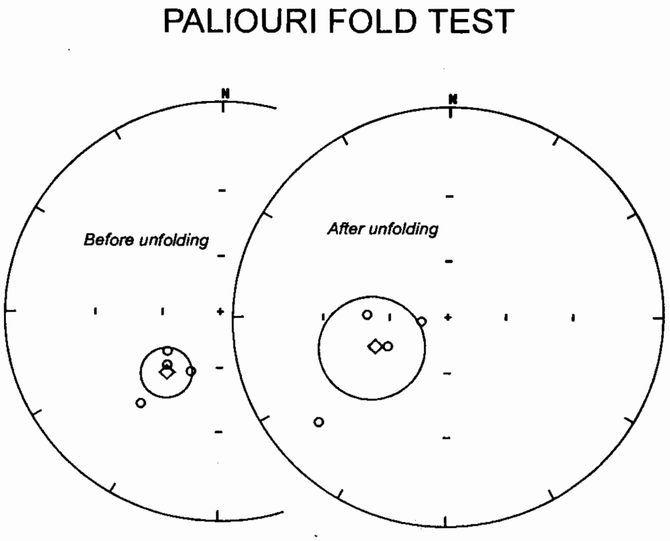

Fig. 4: stereographic projections of the intermediate direction found at the four sites of Paliouri, before and after tilt correction.

Following the datation of the E component an age older than Eocene can be attributed to the high temperature or «JC» component, but it remains difficult to decide wether this magnetisation has been acquired during the sedimentation of the Paliouri beds (Middle-Late Jurassic) or later (late Jurassic-Early Cretaceous) *i.e.* during the obduction phase of the ophiolites onto the Pelagonian domain. A remagnetisation during the Meso-Hellenic phase which produced granites and regional metamorphism is however the most plausible hypothesis.

E AND JC COMPONENTS IN THE OTHER CHALKIDIKI SITES AND IN THE VOURINOS

The Eocene overprinted component is well defined near the village of Skra (Vardar region). Two sites were cored in layered gabbros (magmatic bedding directions are: strike=10°, dip=70°). A total of 26 samples have been demagnetised and measured. The stable intermediate-temperature component shows a direction very close in geographic cordinates (*in situ)* from the Eocene direction evidenced at Paliouri (Fig. 4) but the application of tilt corrections following the magmatic bedding give unreliable results (see after).

Table 4: Eocene remagnetisation (E component) in Chalkidiki and Vourinos sites.

SITE	**N**	**Dg**	**Ig**	**Ds**	**Is**	**K**	**α_{95}**
SKA	8	51.1	43.7	62.1	-6.9	8	17.5
SKB	18	42.0	44.0	66.3	-11.9	8	11.8
ORE	9	29.5	39.2	51.8	-11.7	9	15.5
GO	4	78.7	46.4	89.3	49.2	25	14.1
AET	8	46.3	57.6	39.8	28.3	57	6.5
KRC	8	85.9	44.2	151.1	56.5	36	8.3
KRD	4	35.0	40.3	42.8	-17.0	8	28.3

SITES: SKA et SKB= Skra, ORE= Oreokastro, GO= Goumenissa, AET= Aetos Raches, KRC and KRD= Krapa hills limestone and dykes. (For the other columns same conventions as table 1)

In the Axios-Chalkidiki belt, the Eocene remagnetisation component has also been found at Oreokastro in gabbros (strike=10°, dip=85°) and at Goumenissa in layered gabbros (strike=300°, dip=30°). At Sonia, Evzoni and Pevkodassos the E component is only represented as a weak overprint, not listed in the table.

Bedding correction (Table 4) give in several sites a very shallow inclination which is related to the homogeneity of the structural directions used for unfolding. Taking into account the oldest possible age of magnetisation (Late Jurassic-Early Cretaceous) for these rocks, we think that these shallow inclinations are unrealistic as they indicate too low paleolatitude for both Africa and Eurasia.

In the Vourinos area, the Eocene component was also found as a significant component at Aetos Raches in chromite layered schlieren (strike=100°, dip=10°), in the Krapa hill district both in sheeted dykes (strike=340°, dip=65°) and in overlaying Jurassic-Cretaceous limestones (strike=130°, dip=49°). His occurence as a light overprint in the Poros limestone quarry was also quoted.

The following mean direction can be calculated for the four sites of Paliouri combined with seven other sites of the Chalkidiki and Vourinos belts (Table 4).

E component, mean direction : N=11, D=47.6°, I=47.1°, k=26, $á_{95}$=8.3

The Mesozoic JC component or «old direction» with west declination and normal inclination is more scarce and even when present it cannot be isolated in all the specimen of the site. It is noticeable that when the component JC occurs in a site, the component E is commonly also present as a light

Table 5: JC component

SITE	**N**	**Dg**	**Ig**	**Ds**	**Is**	**K**	**α_{95}**
KRD	5	257.6	63.1	64.8	51.6	12	18.2
SO	3	318.2	35.7	316.0	-13.3	10	25.0
ORE	4	338.8	42.1	55.0	26.2	68	8.5
EV	3	329.8	62.6	339.6	28.6	88	8.6

SITES: KRD= Krapa hills dykes, SO= Sonia, EV= Evzoni, ORE= Oreokastro. (same conventions as table 1).

overprint.

The rather scattered directions found for component JC are listed in table 5. This direction is present in the Krapa hill dykes (strike=340°, dip=65°) at Sonia in layered gabbros (strike=215°, dip=50°) and at Evzoni in a sheeted-dyke complex (strike=260°, dip=35°). Directions obtained after tilt correction are difficult to be interpreted. If the magmatic bedding gives often unrealistic tilt corrections for the E component (see before), the case is not so clear for JC component. It is possible that the JC magnetisation (Table 5) might have been recorded during the initial cooling of the gabbros at site Evzoni, but impossible at site Oreokastro. In the following we will use the direction of magnetisation JC in geographic coordinates.

The four directions of table 5 combined with the JC direction found in the Paliouri flysch give:

JC component, mean direction N=5, D=319.4°, I=50.1°, k=13, á$_{95}$=17.6

DISCUSSION : GEODYNAMIC IMPLICATIONS

1)The E component : Cenozoic clockwise rotation

The paleomagnetism of several batholiths of the Chalkidiki peninsula with ages ranging from 30 to 50 Ma, have been thoroughly studied by Kondopoulou and Westphal (1986). The best results have been obtained in Sithonia : D=37°, I=31°, a$_{95}$=9° (inverted through the origin, but directions were mostly reversed). This result, consistent with the overprint measured in the ophiolites of the present study, was interpreted in the same paper as a 30° post Eocene-Oligocene clockwise rotation of the area.

Table 6: Cenozoic directions of magnetisation in Northern Greece.

AREA	Rock Type	Age (Ma)	D	I	K	α_{95}	References
Chalkidiki	Batholith	40-50	37	31	28	9	Kondopoulou & Westphal (1986)
Mesohellenic Trough	Sediments	24-36	27	47	16	10	Kissel and Laj (1988)
Greek Rhodope	Plutonics + Volcanics	18-35	22	48	56	9	Atzemoglou *et al.* (1993
Strymon	Volcanics	20-30	26	47			Westphal *et al.* (1991)
Lemnos	Volcanics	18-22	34	48	18	15	Westphal & Kondopoulou (1993)
Axios	Sediments	4-11	20	46	30	17	Kondopoulou (1994)

We will now use a set of additional data obtained in a broader area (N. Greece), to better constrains this rotation (Table 6).

The following remarks can be made after a rough comparison between ages and available declinations for the Cenozoic formations:

-The value of the rotation angle increases almost always with the age of the magnetisation. This observation supports the hypothesis of an homogeneous rotational pattern from the Ionian Islands to the Rhodope during the whole Oligo-Mio-Pliocene period as it has been earlier suggested (Westphal et al., 1991).

-Some exceptions occur, e. g. the rotation of the Lemnos Island volcanic formations reaches an unexpected value of 34° for a 18-22 Ma age. This can be explained by the additional effect of a dextral movement along the North Anatolian Fault (Westphal and Kondopoulou, 1993).

2)The JC component : Mesozoic counterclockwise rotation

Evidence of Mesozoic westward directions of magnetisation has been already shown by Pucher et al. (1974), Turnell (1988), Surmont (1989b), Lauer & Kondopoulou (1991) and Edel *et al* (1992) and the fact that these directions might correspond to a large counterclockwise rotation has been proposed by the latter Authors.

In the present study the results obtained in the Paliouri area show that a component older than the Eocene remagnetisation might be present in the sedimentary cover of the pillow lava and that this direction is also found with consistency in the ophiolites of the Axios-Chalkidiki belt and Vourinos massif. The lumping of these data together with the one of Edel et al. (1992) give densily distributed westward directions over Axios-Chalkidiki and Florina areas. This whole set of data displays a remarkable similarity of in-situ mean directions over a broad area which can likely be considered as an «area-wide fold test». The large rotation implied by these results has not yet received an explanation. We will discuss now the possible mechanisms involved into this movement. Two types of mechanism can be considered. The first is linked to the regional tectonic evolution at a scale similar to that of the Cenozoic rotations. The second is more global and concerns the displacements of the Eurasian and African plates. Before the Alpine collision these two plates show quite different behaviours. While the Eurasian plate is fairly stable with only a moderate northward drift, the African plate undergone a more important northward drift combined with a large counterclockwise rotation. The direction expected at 140 Ma (Jurassic/Cretaceous boundary) in Chalkidiki is : D=332°, I=22° following Besse and Courtillot (1991) and D=337°, I=24° after Westphal et al. (1986), thus a 30° of counterclockwise rotation can be inferred from the African plate rotation. The whole rotation shown by the «JC» component is the sum of a near 40° deduced from the westward declination of JC and of a clockwise 30-40° rotation that occurred during the Cenozoic (see before). Several mechanisms must have been involved for such a large rotation (70-80°). The first mechanism is the general movement of the African plate involving 30° of counterclockwise rotation for Northern Greece. But 30-40° are still missing. The opening of the so-called Mesogee, proposed by Dercourt et al. (1984) to have occurred south of the Pelagonian-Tauric blocks during Cretaceous time can explain satisfactorily this additional counterclockwise rotation of Northern Greece with respect to Africa.

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