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MULTIPHASE PALEOMAGNETIC EVOLUTION OF THE CHALKIDIKI OPHIOLITIC BELT (GREECE). GEOTECTONIC IMPLICATIONS

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Abstract

Paleomagnetic investigations were undertaken in the Mesozoic ophiolitic belt of Chalkidiki (40.4°N, 23.3°E) in order to detect possible block motions (rotations, tilting) preceding the already established late Tertiary clockwise rotation. Thermal and alternating field demagnetization processes performed on 243 specimens from 15 sites sampled in serpentinized peridotites and in gabbros evidence a multiphase paleomagnetic history. Excepted a few recent remagnetizations, three main groups of *in situ* directions representative of the 60 km long belt were yielded. The best clusters display the following means: the T direction D=62°, I=27.5°, k=56, N=7 (31°N, 120°E), the TC_1 D=242°,I=30°, k=43, N=7 (8°S, 323°E) and the J_1 direction D=314°, I=34°, k=43, N=5 (45°N, 278°E). The TC and J directions are characterized by both, normal and reversed polarities. The T and J directions were already found in Permo-Mesozoic units from other zones of the Hellenides. The T directions, which are the youngest were probably emplaced in the early Tertiary. The J directions are interpreted as the oldest, Jurassic - early Cretaceous in age. The intermediate TC directions have to be interpretated as due to an important tilt of the ophiolitic belt in late Cretaceous-early Tertiary times. In addition, Chalkidiki has undergone two large rotations in opposite directions; the first counterclockwise, probably occurred in the late Cretaceous, the second clockwise in the Tertiary.

ΠΕΡΙΛΗΨΗ

Παλαιομαγνητική έρευνα έγινε στη Μεσοζωική οφιολιθική ζώνη της Χαλκιδικής με σκοπό να ανιχνευθούν πιθανές κινήσεις τεμαχών που προηγήθηκαν από την ήδη γνωστή δεξιόστροφη κίνηση του Τριτογενούς. Η απομαγνήτιση (θερμική και εναλλασσόμενου πεδίου) που πραγματοποιήθηκε σε 243 δείγματα από 15 θέσεις - περιδοτίτες και γάββροι- αποδεικνύουν μια πολυφασική παλαιομαγνητική ιστορία. Τρεις κύριες ομάδες διευθύνσεων in situ και αντιπροσωπευτικές της ζώνης έχουν προκύψει. Οι καλύτερες συγκεντρώσεις δίνουν τις παρακάτω μέσες τιμές:

- T διεύθυνση D=62° I=27.5° K=56 N=7
- Tc1 >> D=242° I=30° K=43 N=7
- J1 >> D=314° I=34° K=43 N=5

Οι δύο τελευταίες χαρακτηρίζονται από κανονικές και ανάστροφες πολικότητες. Οι T και J είχαν ήδη βρεθεί σε Περμοτριαδικούς σχηματισμούς άλλων Ελληνίδων. Οι T διευθύνσεις που είναι οι νεότερες δημιουργήθηκαν πιθανότατα στο κάτω Τριτογενές. Οι J ερμηνεύονται σαν οι παλαιότερες Ιουρασικές-Κάτω Κρητιδικές. Οι ενδιάμεσες Tc διευθύνσεις πρέπει να ερμηνευθούν σαν αποτέλεσμα μίας σημαντικής πτύχωσης της οφιολιθικής ζώνης στα όρια Κρητιδικού-Τριτογενούς. Επιπλέον, η Χαλκιδική έχει υποστεί δύο ευρείες περιστροφές αντίθετης φοράς, μία αριστερόστροφη (άνω Κρητιδικό) και μία δεξιόστροφη στο Τριτογενές.

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Introduction

This study is part of a systematic paleomagnetic investigation which aims at unravel the geodynamic evolution of the Pelagonian, Circum Rhodope and Serbomacedonian zones in Northern Greece. In Chalkidiki is already demonstrated (Kondopoulou and Westphal, 1986), that the Circum Rhodope has participated to the general post-Oligocene clockwise rotation that has affected different parts of the Hellenides as Epirus (Hörner and Freeman, 1983; Kissel et al., 1985) and Euboea (Kissel et al., 1986). Investigation of previous motions is hampered by the lack of rock units suitable for paleomagnetism; with exception of the Ammonitico Rosso series which have yielded reliable results in the sub-Pelagonian (Surmont, 1988; Turnell, 1988), most Mesozoic sedimentary units are metamorphic and/or too weakly magnetized. Consequently, one has to deal with magmatic rocks, volcanics, plutonics and ophiolites.

Concerning ophiolites, a poorly documented north-westerly direction but close to directions measured in Permo-Triassic volcanics from the Pelagonian (Lauer and Kondopoulou, 1987; Turnell, 1989) was obtained in gabbros from the Pindus (Pucher et al., 1974). The presence in Chalkidiki of a 60 km long ophiolitic belt (fig. 1) with a quite constant strike around N135° had to be turned to account. In a first stage, the material was checked. The occurence in different sites of close characteristic directions led to extended sampling. In the whole, 5 sites were collected in peridotites and 11 sites in gabbros.

In order to check or to establish the tectonic context of the sites, measurements of the anisotropy of susceptibility were also performed.

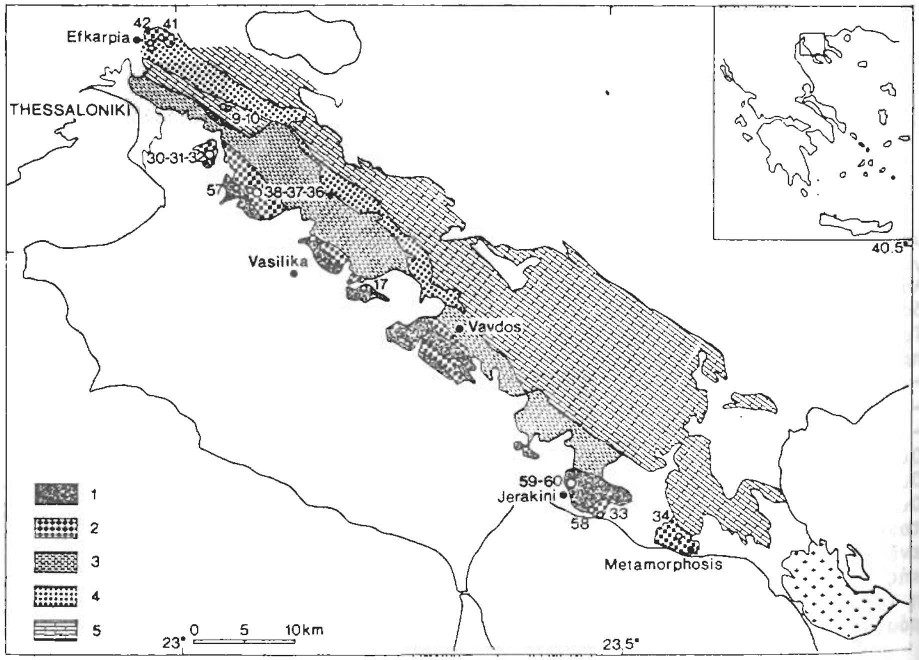

Fig. 1: Geological sketch map and location of the paleomagnetic sites. 1) peridotites, 2) gabbros, 3) gneisses, 4) phyllites, cherts, diabases, schists, crystalline limestones... 5) phyllites, limestones, marbles.

Geological setting

The ophiolitic belt of Chalkidiki (fig. 1) is part of the Circum-Rhodope zone which constituted during the Jurassic the continental slope of the Serbomacedonian massif and which ended to a trough in relation with the subducting Axios zone. Recent gravimetric and magnetic data demonstrate the continuity of the Vardar ophiolites with the Thessaloniki-Metamorphosis mafic and ultramafic belt (Kiriakidis, 1989). The ophiolites belong to the "Aspri Vrisi-Chortiartis" unit characterized by eugeosynclinal evolution during early-middle Jurassic (fig. 1). The lower levels of the unit are Permo-Triassic whereas the upper level is constituted of marine sediments. Ophiolitic bodies consisting mainly of mafic and ultramafic rocks (diabases, gabbros, diorites, serpentines) are interbedded in the upper layers. In the same sedimentary serie are interbedded metamorphosed rocks of acid magmatic origin.

Two major tectonic phases have affected the Circum-Rhodope belt. The first is contemporaneous with the metamorphism (late Jurassic-early Cretaceous) and related to emplacement of the ophiolites. The second, which is Tertiary, probably Paleocene-Eocene, lead to thrusting with SW vergence.

The age of the Thessaloniki gabbros is still debated. K/Ar dating ranging from 1400 to 42 Ma led Sapountzis (1973,1980) to consider them at least as Paleozoic. This interpretation is stongly questionned by Dimitriadis (1980, 1981) who states that the belt belongs to a subzone (Peonias) of the Vardar zone which is interpreted to have been an oceanic basin that disappeared during Mesozoic. The continuity of the Thessaloniki-Metamorphosis belt with the Guevgueli complex demonstrated by geophysical data (Kiriakidis, 1989) is in favour of the latter interpretation. This complex is intruded by a microgranite dated at 150 Ma (Borsi et al., 1966) which is considered to be contemporaneous with the basic hostrocks (Bebien and Mercier, 1977). Finally, unpublished K-Ar ages around 170 Ma by Kreuzer (1980), confirm the Jurassic age of the Chalkidiki gabbros.

Sampling and laboratory techniques

120 cores were drilled in 5 sites located in serpentinized peridotites and 11 sites in gabbros, scattered from Efkarpia in the north of Thessaloniki to Metamorphosis (fig.1) on the Kassandra gulf. Tilting was measured on layering in gabbros, on banding in peridotites. The macroscopic foliation is confirmed in several sites by the anisotropy of susceptibility. The samples were cut into 22mm long cores with a diameter of 25mm. The NRM and anisotropy of susceptibility measurements apparatus consist in modified Digico spinner magnetometers. An average of 2 specimens per sample (243 specimens) has undergone complete stepwise thermal demagnetizing in order to separate the different components of the Natural Remanent Magnetization. In a few sites, Alternating Field process was also efficient.

Paleomagnetic *in situ* directions (fig. 2; tab. 1)

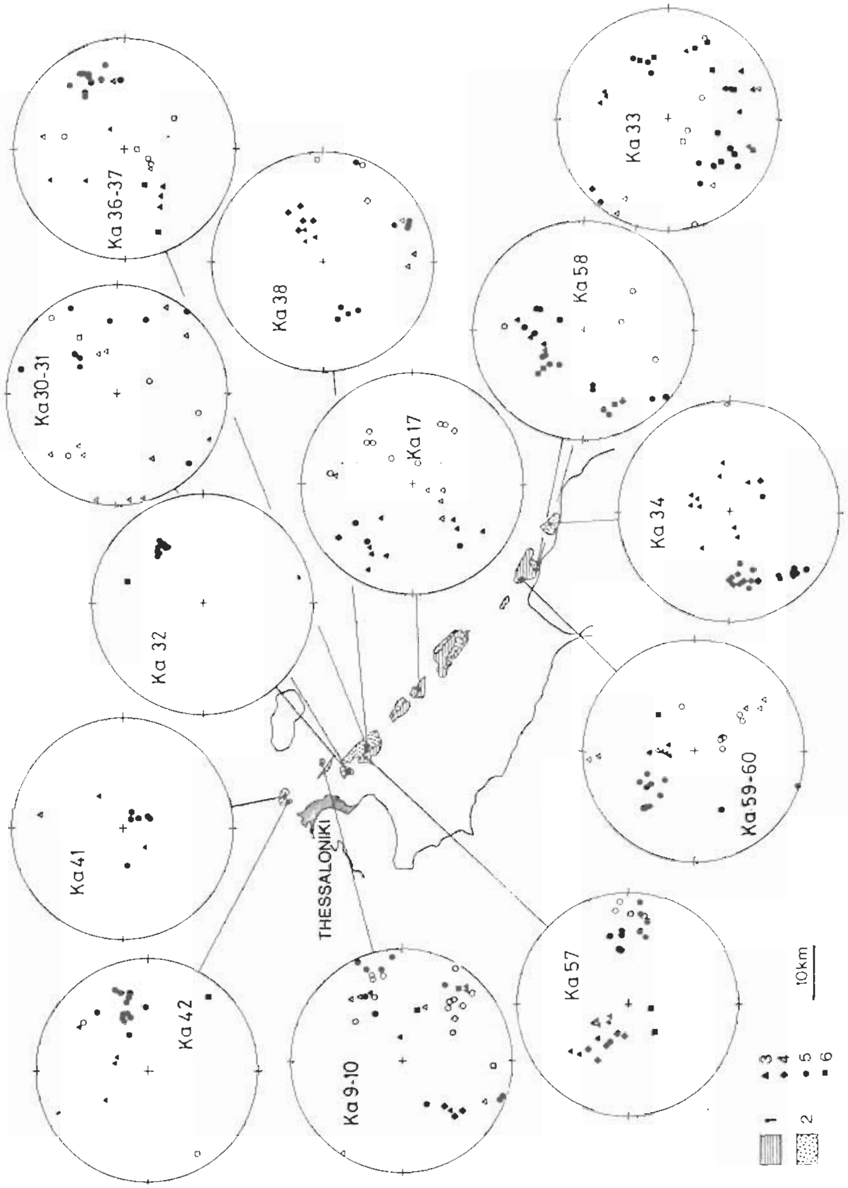

Fig. 2: Paleomagnetic directions obtained after thermal/alternating field processes on sites located 1) in peridotites, 2) in gabbros. Symbols depend on the maximum unblocking temperatures of the different components: 3) 300-400°C, 4) 500-560°C, 5) 570-585°C (magnetite), 6) 590-610°. Full symbols are in the lower hemisphere, open symbols, in the upper.

Tab.1

Site	Formation	L		bt °C	N/No	n	Do	Io	k	a_{95}
Ka 9-10	peridotite	TC1		350-580	5/13	11	59	-21	30	9
		T		400-580	4/13	6	69	31	53.5	9
		J1	1	350-580	6/13	9	129.5	-24	33	10.5
		J2	2	350-580	3/13	4	123	7	141	8
			1+2	350-580	7/13	10	129	-15	17	10
				580	4/13	4	199	- 5.5	43	12
Ka 57	peridotite	J1		550	7/8	13	313	53	24	8
		TC		580	3/8	5	91	- 7	61	10
		T		580	4/8	9	91	26	39	8
Ka 59-60	peridotite	P		400	3/14	5	359.5	60	21.5	8
		J1	1	580	6/14	7	320	34	51	8
		?	2	580	3/14	5	157	-57	88	8
		J1	3	400- 580	4/14	6	141	-27	48	10
		J1	1+3		8/14	11	322	31	47.5	7
Ka 41	gabbro			580	4/4	7	173	-72	23	13
Ka 42	gabbro	T		580	8/8	12	69	29	40	7
Ka 30-31	gabbro	J2	N+R	350-580	6/13	8	121	13	22	12
		T		350-580	5/13	6	47.5	19	11	20
		C1		350-580	2/13	3	64	-40.5	38	20
Ka 32	gabbro	T		580	7/7	11	54	24	277	3
Ka 36-37	gabbro	C1		350-400	2/9	3	231	33	94	13
				580	3/9	4	214	-65	42	14
		T		580	7/9	12	65	20	45	6
Ka 38	gabbro			520	2/6	3	62	60	106	12
		T		560	3/6	5	62.5	41	51	4
		J3		560	3/6	4	155	11	293	5
		C1		580	2/6	4	245	37	87	10
Ka 17	gabbro		1	350	5/11	8	308	21	27	11
			2	580	3/11	3	121	-27	159	10
		J1	N+R, 1+2		6/11	11	306	22	30	8
			3	350	4/11	4	224	26.5	41	14
			4	580	3/11	3	47	-32	139	10
		C1	N+R, 3+4		7/11	7	225	29	61	8
Ka 33	gabbro			350	2/9	3	20	23	124	9
		J3		350	5/9	8	159	23	46	8
		C2		580	6/9	10	210	16	25	12
		T		510-600	5/9	7	70	27	43	9
Ka 34	gabbro	C1		560	9/10	11	257	26	87	5
		C2		580	5/10	6	223	12	158	5
Ka 58	gabbro	J1		400-580	6/8	10	319	41	45	7
		C1		580-600	5/8	7	254	23.5	47	8

Means (40.4N, 23.3E)

Sites	Component	N	D	I	k	a	VGP
Ka 9-10,30-31,32,33,36-37,38,42	T	8	65	28	36	9	28N, 117E
57	T'	8	65	-16	6	22.5	
Ka 9-10,17,30-31,34,36-37,38,58	TC1	7	242	30	43	9	9S, 324E
	TC1'	7	312	68	7	23	
Ka 33,34	TC2	2	216.5	14	75	29	
Ka 9-10,17,57,59-60,58	J1	6	311	27	12	19	40N, 276E
	J1'	6	311	20	19	15	37N, 272.5E
Ka 9-10, 30-31	J2	2	122	10	329	14	
Ka 33,38	J3	2	157	17	83	28	35.5S, 52E
	J3'	2	124	30	139	21	
			304	-30			13N, 258E

Tab. 1: Mean *in situ* directions computed for the different components. bt: maximum unblocking temperatures; L: component label; N/N_0: number of samples containing the considered component/ total number of samples; n: number of specimens containing the considered component; D_0, I_0: declination, inclination; k, a_{95}: Fisher statistic parameters. Mean directions of mean site directions. T' is the mean T corrected for dip with the assumption of normal bedding. VGP: latitude and longitude of the virtual geomagnetic pole.

In most sites, demagnetizing evidences multicomponent magnetizations with unblocking temperature in the range 300-600°C (fig. 3). Different clusters can be observed. For mean calculation and interpretation, directions from close sites, sampled in the same unit, are set together (Ka 9-10, 30-31, 36-37). Plotting opposite directions in the same hemisphere sets more order in the rather scattered directions, so that three main groups of directions are evidenced (fig. 4).

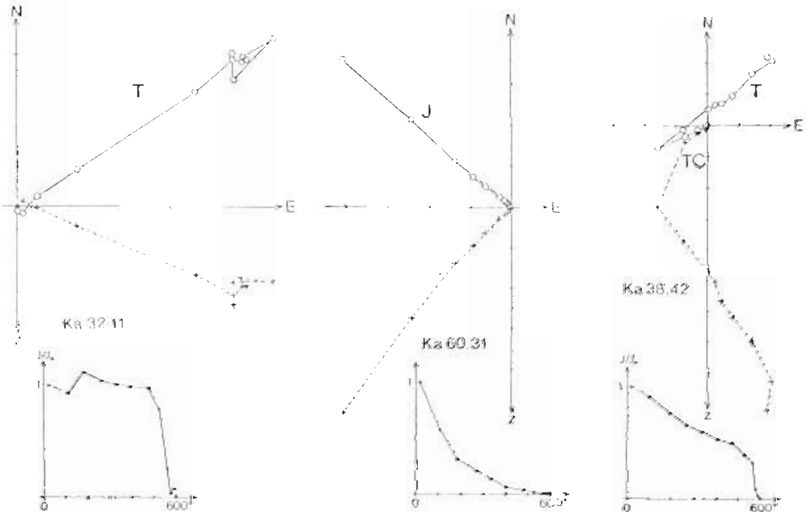

Fig. 3: Typical orthonal projections and thermal demagnetizing J/J_0 curves of T, J and C components. Dots are plotted in the horizontal plane, crosses in the WE vertical plane.

The T **directions** with ENE declinations and shallow inclinations occur in 7 sites located all along the belt (Ka 42, 32, 30-31, 36-37, 38, 9-10, 33) from Efkarpia to Metamorphosis. The maximum unblocking temperatures of 560-580°C reveal magnetite and titanomagnetites as carrier of the remanent magnetization (fig. 3; Ka 32.11). The easterly directions from Ka 57 and the steep directions from Ka 41 may be T directions deviated by local tectonics. For instance, when tilting site Ka 41 to the same dip as the neighbouring Ka 42, the directions come close to the T direction of Ka 42. For the 7 *in situ* T directions the mean is:

D=62°, I=27.5°, k=56.5, a=8°, (VGP: 31°N, 120°E).

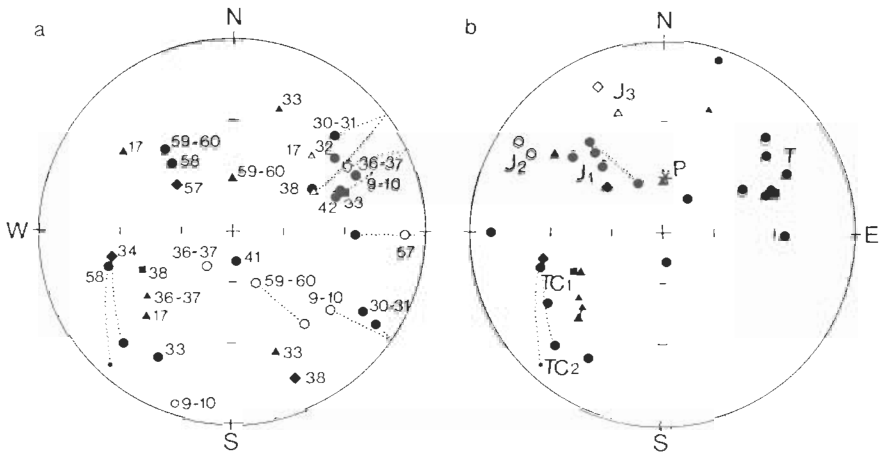

Fig. 4: Mean site directions. Dotted lines represent trends. Symbols are the same as in Fig. 2. In 4b, antiparallel directions are plotted in the same hemisphere. With exception of a few direction close to the present field, the most frequent mean directions belong to the T, C and J clusters.

The **TC directions** have similar ENE declinations than the T, but negative inclinations (Ka 9-10, 30-31, 17). The best clusters are characterized by reversed directions (Ka 38, 33, 34, 58). In sites Ka 33, 58 and particularly Ka 34, these reversed directions display a trend from WSW with intermediate inclinations to EW with shallow inclinations, likely on a great circle. The latter have the highest unblocking temperatures. The unblocking temperatures in the range 550-580°C are similar to those of the previous group of directions. The carrier of the magnetizations are titanomagnetites and magnetite. Several sites are characterized by both, T and TC directions (Ka 9-10, 30-31, 38). When both ENE strike ENE (Ka 9-10, 30-31), the separation is not evident, contrary to site Ka 38, characterized by very distinct ENE T directions and WSW C directions (fig. 3).

Two means have been computed, the TC_1:

D=242°, I=30°, k=43, a=9°, N=7 (VGP: 8°S, 323°E)

and the C_2:

D=216°, I=14°, k=75, a=29°, N=2 (VGP: 32°S, 339°E).

The **J directions** are characterized by NW and SE declinations and variable inclinations. They occur also all along the ophiolitic belt. Normal and reversed directions are present in sites Ka 17, 30-31, 58, 59-60. In the serpentinites Ka 9-10 and Ka 59-60, the reversed directions show a trend with one pole nearly antiparallel to the normal directions of Ka 17, 57, 58, 59-60 (fig. 4a). Plotted in the same hemisphere (fig. 4b), the 5 mean directions display a nice cluster around the mean

D=314°, I=34°, k=33.5, a=13°, (VGP: 45°N, 278°E).

When adding the J direction from site Ka 30-31 the mean becomes:

D=311°, I=27°, k=12, a=19°, N=6 (VGP: 40°N, 276°E).

The corresponding magnetizations are characterized by variable unblocking temperatures and consequently different magnetic minerals: 300-400° for gabbro Ka 17, 550° for the peridotite Ka 57 and magnetite temperatures of 580° in gabbro Ka 58 and peridotites Ka 9-10, 59-60 (fig. 3).

The second pole of the TC trend in Ka 9-10 lies close to the mean direction in Ka 30-31. Sites Ka 33 and 38 display SSE directions with shallow positive inclinations that are labelled J2. The difference with the mean computed above has to be discussed.

Discussion

The ophiolite belt of Chalkidiki has undergone at least two major tectonic phases, one in the late Jurassic-early Cretaceous, the second in the Tertiary. The present north-easterly to subvertical dip of the magnetic and macroscopic foliation in the gabbros is mainly the result of the Tertiary SW vergent thrusts. From a geological point of view it is impossible to quantify the different folding phases.

Paleomagnetic directions have to be corrected for the tilts that occurred posteriorly to emplacement of the magnetization. Due to the unclear tectonics a narrow-minded paleomagnetist would consider its results as not interpretable. Nevertheless the undetermination is not so severe.

Each one of the three groups of directions evidenced by the demagnetizing process is represented in different parts of the belt so that, in a first stage, relative motions between the different sites can be considered as negligible. The belt being 60 km long, the fold axis is nearly horizontal and the tectonic corrections are reduced in tilt corrections with a quite constant strike around N135°.

Such dip corrections will have a significant influence on the inclinations of the T and TC directions and will preserve the NW declinations and the intermediate to shallow inclinations of the J components.

Comparison of our *in situ* mean directions with published results from different parts of the Hellenides show some agreement (fig. 5). The T mean falls between directions obtained on Mesozoic mafic rocks and on Ammonitico-Rosso limestones from Argolis (Pucher et al., 1974, Turnell, 1988), on remagnetized Permo-Triassic volcanics from Atalandi (Turnell, 1984) and the directions considered as Eocene-Oligocene from Epirus (Horner and Freeman, 1983; Kissel et al., 1985). The direction of the Eocene-Oligocene plutonites from Chalkidiki (Kondopoulou and Westphal, 1986) is slightly less deviated.

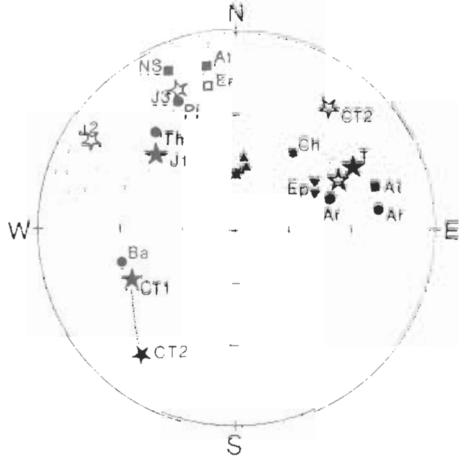

Fig. 5: Comparison of the mean T, J and C directions from the Chalkidiki ophiolites with results obtained on - Permo-Triassic volcanics from Atalandi (At, Turnell, 1984, 1988; Pucher et al., 1974), Eratyra (Er, Lauer and Kondopoulou, 1987), Nea Santa (NS, Lauer and Kondopoulou, 1990), - Mesozoic ophiolites from Pindus (Pi, Pucher et al., 1974) and limestones from Argolis (Ar, Turnell, 1988), Theopetra and Bafi (Th, Ba, Surmont, 1988), - Eocene-Oligocene sediments from Epirus (Ep, Horner and Freeman, 1983; Kissel et al., 1985) and plutonites from Chalkidiki (Ch, Kondopoulou and Westphal, 1986). Upright triangles represent directions measured in Plio-Pleistocene series.

The **T directions** becoming more scattered after dip correction, they are interpreted as overprints acquired during the Paleocene-Eocene compression phase. With respect to the directions measured in Epirus and Sithonia the inclinations are too low, 27.5° instead of 40°. Consequently, the ophiolitic belt has been tilted in post-Oligocene times, during the early Miocene clockwise rotation or later. When assuming that the T components had a 40° inclination in Eocene-Oligocene times one has to tilt the belt back. Then, the 60° to 90° N 40-50° dip of the layering in gabbros was about 15° steeper than presently (75°-105°N 40-50°).

A less probable solution is to consider the T components as pretectonic magnetizations which have to be corrected for dip. When assuming that the layering is parallel to bedding and that the series is in a normal position, then the mean T direction becomes

D=60.5°, I=-25.5°, k=12, a=19°

The opposite direction lies close to the mean TC_1 direction and to the direction measured in the carbonates from Bafi (Surmont, 1988)(fig. 5). In that case the T components have to be interpreted as Mesozoic. Relative to the Tertiary direction of the neighbouring Chalkidiki plutonites, the difference in declination is of about 180°. This would imply an unrealistic 180° rotation of Chalkidiki in Mesozoic-early Cenozoic times.

Concerning the **TC directions**, the negative fold test demonstrates that the corresponding magnetizations are also overprints. Two interpretations are proposed.

As the T and TC are located on a small circle with an axis parallel to the belt (fig. 5), the most probable solutionl is to consider the TC as T directions tilted before emplacement of the final T overprints. This hypothesis implies that the presently steep north-easterly plunging of the gabbros was south-westerly during emplacement of the TC magnetizations. Assuming a 40° inclination of the TC magnetization during emplacement, the layering in gabbros was then 50° to 20° N 220-230°. The presently SW plunging foliation of the magnetic anisotropy in the peridotites of sites 57 and 59-60° suggests that they have not undergone back thrusting as the gabbros. Consequently, the TC magnetizations are interpreted as pre- or syn-Paleocene-Eocene tectonic whereas the T magnetizations are post-tectonic.

The second solution consists in considering the TC directions as rotated J directions. The sole argument in favour of this unlikely solution is the very close inclinations of the mean TC_1 and J_1 directions which differ only by 4°.

The **J directions** fall into a group of north-westerly directions obtained on Permo-Triassic volcanics from Atalandi (Turnell, 1988), Eratyra (Lauer and Kondopoulou, 1987), Nea Santa (Lauer, 1990), on Mesozoic gabbros from Pindus (Pucher et al., 1974) and limestones from Theopetra (Surmont, 1988). All the available directions, including ours, seem to lie on a small circle corresponding to folding along the mean NNW-SSE strike of the Hellenides (fig. 5). So it is likely that a part of these magnetizations are syntectonic. Before and after tectonic correction, the J_1 mean direction lies close to the direction obtained by Surmont (1988) in the late Jurassic-early Cretaceous series from Theopetra. It is tempting to attribute to the J_1 magnetization a late Jurassic-early Cretaceous age, contemporaneous with the emplacement of the ophiolites.

Conclusion

The ophiolitic belt of Chalkidiki is characterized by three main groups of directions interpretable in terms of regional and global tectonics. These directions are also present in other zones of the Hellenides. A first conclusion is that these zones (sub-Pelagonian, Pelagonian, Circum-Rhodope) moved together since the Mesozoic.

The ophiolitic belt has undergone the following paleomagnetic and geotectonic history:

* Jurassic-early Cretaceous: - emplacement of the J components;
* late Cretaceous ?: - counterclockwise rotation of Chalkidiki;
* early Tertiary: - emplacement of the TC components;
- back-thrusting and tilting of the belt;
- emplacement of the T components;
* late Tertiary: - clockwise rotation of Chalkidiki.

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