

A COMBINED PALAEOMAGNETIC AND MAGNETIC MODELLING STUDY
OF THE LEPTOKARYA INTRUSION, EASTERN RHODOPE.

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A B S T R A C T

A well-defined mean Magnetization Direction of $Dec=202.8^\circ$, $Inc=-46.4^\circ$ ($\alpha_{95}=4.6^\circ$) was obtained for the granodioritic intrusion of Leptokarya, which is Oligocene in age and outcrops at the northern margin of the Kirki-Essimi volcanosedimentary basin in the Rhodope Massif. Comparison of this result with other published Palaeomagnetic data for the area, suggests that the small-scale clockwise rotation inferred for the body is associated with thrusting. This is further supported by modelling of the aeromagnetic anomaly associated with this body. The models produced, suggest a shallow body, which in no case exceeds 1.2 km in depth.

ΠΑΛΑΙΟΜΑΓΝΗΤΙΚΗ ΚΑΙ ΜΑΓΝΗΤΙΚΗ ΜΕΛΕΤΗ ΤΟΥ ΓΡΑΝΟΔΙΟΡΙΤΗ
ΤΗΣ ΛΕΠΤΟΚΑΡΥΑΣ, ΑΝΑΤΟΛΙΚΗ ΡΟΔΟΠΗ.

Σπαΐς, Χ. και Μαλτέζου, Φ.

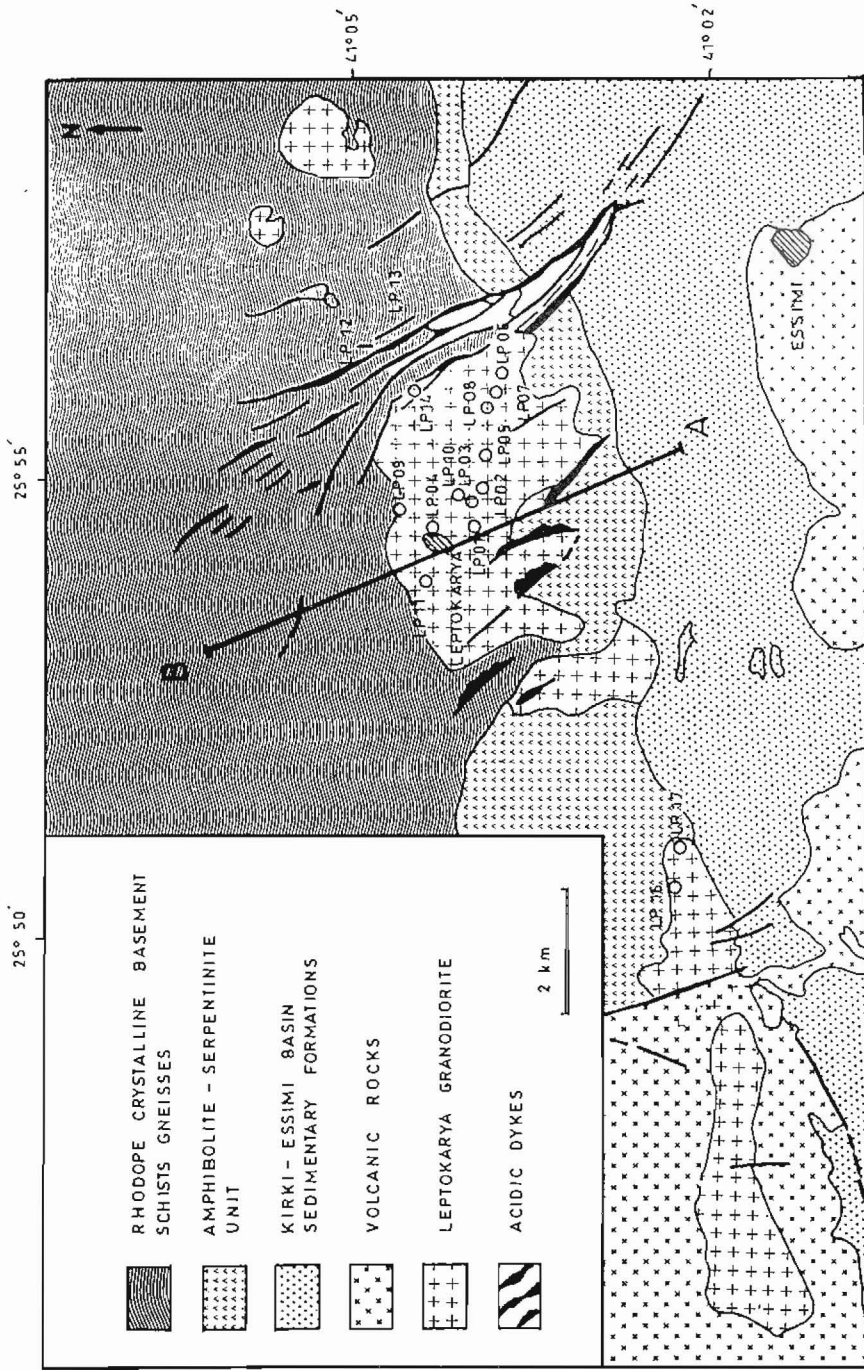
Π Ε Ρ Ι Λ Η Ψ Η

Παλαιομαγνητική ανάλυση δειγμάτων από το γρανοδιוריτικό σώμα της Λεπτοκαρύας κατέληξε σε μία μέση Διεύθυνση Μαγνήτισης με $Dec=202.8^\circ$, $Inc=-46.4^\circ$ ($\alpha_{95}=4.6^\circ$). Το σώμα είναι Ολιγοκαινικής ηλικίας και εμφανίζεται στο Βόρειο άκρο της ιζηματογενούς λεκάνης Κίρκης-Αισύμης της Ροδοπικής μάζας. Σύγκριση αυτού του αποτελέσματος με άλλες Παλαιομαγνητικές Διευθύνσεις, δείχνει μία μικρής κλίμακας δεξιόστροφη περιστροφή που οφείλεται σε τεκτονική κίνηση επώθησης. Το αποτέλεσμα αυτό ενισχύεται από την ερμηνεία της αερομαγνητικής ανωμαλίας που οφείλεται στον γρανοδιוריτή. Η ανάλυση των μοντέλων υποδεικνύει ένα αβαθές σώμα που δεν ξεπερνάει το βάθος των 1.2 km.

INTRODUCTION - GEOLOGICAL BACKGROUND

The Leptokarya intrusion is one of a series of plutonic bodies aligned in a 30 km long belt trending approximately SW-NE in the Eastern Rhodope area (Fig. 1). The zone of intrusion is revealed on the aeromagnetic anomaly map of the area as a series of SW-NE trending anomalies.

Some researchers have described the Leptokarya intrusion as a granodiorite (Maratos and Andronopoulos, 1964) and others as



being of monzodioritic composition (Katirtzoglou et. al., 1981). The Leptokarya body is intruded into the older basement metamorphics of the Leptokarya area and is the largest plutonic body in the Evros district with a surface outcrop of approximately 15km². The body is strongly discordant to the metamorphic formations it intrudes and, like the other plutonites of this series, it is petrochemically inhomogeneous. As regards the petrogenesis of these plutonites it has been suggested that crystallization occurred at a relatively shallow depth (Sideris, 1975). Radiometric dating by the K/Ar method on biotite has given an age of 28 Ma for the Leptokarya intrusion (Bitzios, 1973).

PALAEOMAGNETIC STUDY

Sampling Methods - Instrumentation.

Both oriented hand-samples and field-drilled cores have been utilized for the present study. The location of the sampling sites are shown in Fig.1.

Three oriented hand-samples were normally collected from each site, large enough to extract at least three 2.54 cm in diameter and 5-6 cm in length cores. Standard palaeomagnetic cylindrical specimens were cut from these cores. Field-drilled cores form a significant part of the sample collection. Orientation of these cores was achieved by using a standard core-orientation table. It is estimated that these cores are oriented to an accuracy of $\pm 2^{\circ}$ - 3° (Collinson, 1983). Magnetic bearing measurements were taken using a magnetic compass, whilst a sun compass was also used in the majority of the cases.

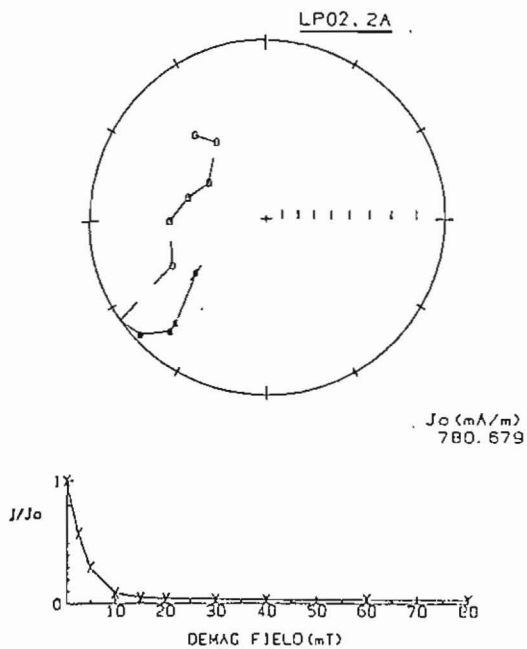
A DIGICO and a MOLPSPIN spinner magnetometer, were used to carry out the specimen magnetization measurements. A noise level ranging between 0.03 mA/m and 0.05 mA/m characterized these magnetometers for time corresponding to 2⁷ revolutions.

A.F. demagnetization has been completed on the majority of specimens (130) in order to isolate the remanent magnetization components. The specimens were successively demagnetized at peak fields of up to 80 mT using a Highmoor a.f. demagnetizer. Additionally, 62 specimens from selected sites have been thermally demagnetized to up to 600°C in order to compare the effectiveness of the two cleaning techniques and also seek confirmation of the stable remanent magnetization directions derived by the a.f. demagnetization.

Palaeomagnetic "magnitude" parameters - Demagnetization Behaviour.

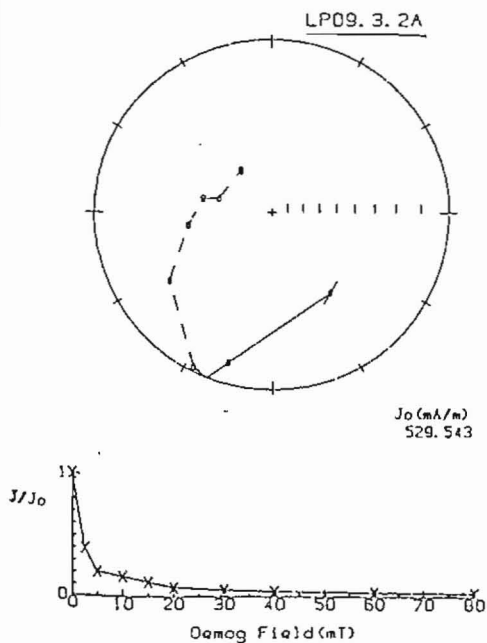
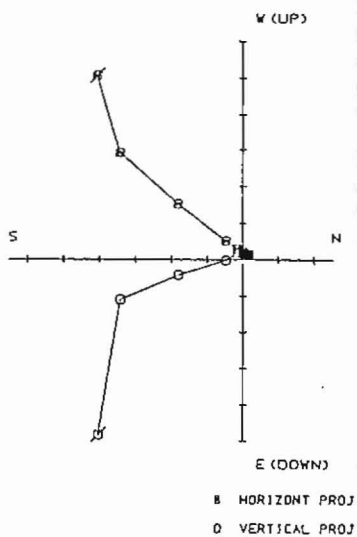
The NRM intensities range between 12 and 2260 mA/m. The scatter is mainly due to the non-uniform distribution of the sites within the Leptokarya intrusion and is attributed to the difference in grain size distribution between sites. It is also possible that the most strongly magnetized sites (e.g. LP01) have been affected by lightning.

The volume susceptibility values (k_v) generally range between 16 and 56 ($\times 10^{-3}$ SI). The majority of the specimens exhibit Koenigsberger ratio values (Q) ranging from 0.10 to a maximum of 0.65 with the majority of them being smaller than 0.50.



VECTOR DEMAGNETISATION PLOT

SCALE: 1 UNIT = 96.492



VECTOR END POINT PLOT

SCALE: 1 UNIT = 43.052

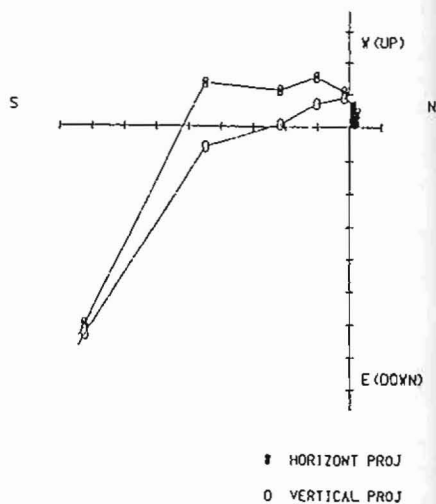
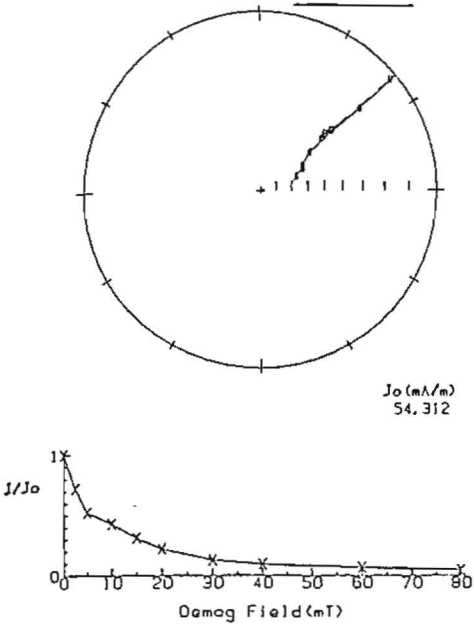


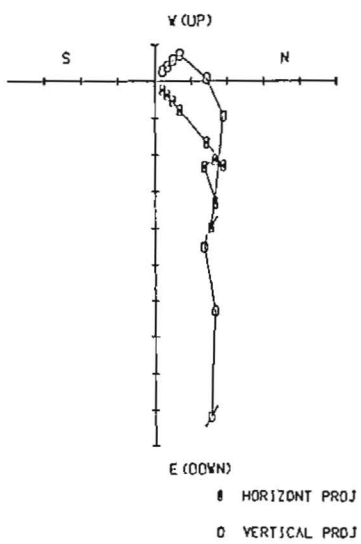
Fig.2. Demagnetization behaviour of specimens LP02.2A and LP09.3.2A

LP06.2.1B

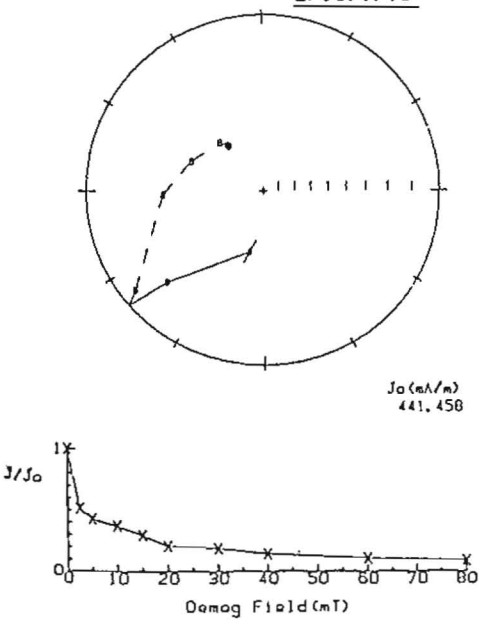


VECTOR END POINT PLOT

SCALE: 1 UNIT= 5.368



LP10.1.1C



VECTOR END POINT PLOT

SCALE: 1 UNIT= 50.685

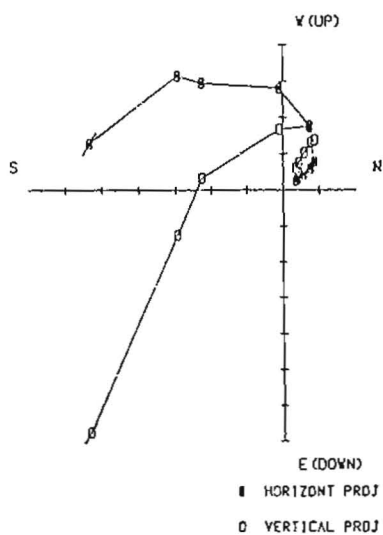


Fig.3. Demagnetization behaviour of specimens LP06.2.1B and LP10.1.1c.

Typical examples of the demagnetization behaviour of specimens from the Leptokarya intrusion are demonstrated in Figures 2 and 3. The intensity drops to about 20% of its initial value after the 20 mT demagnetization step and isolation of the stable remanent magnetization is clearly suggested both by stereographic as well as Zijdeveld plots, soon after this step. The presence of three components is revealed by the Zijdeveld plots. A very "soft" (low coercivity) component, probably due to remagnetization in the Earth's field, is quickly removed during the initial demagnetization steps, whilst the primary component is isolated after the 20 mT demagnetization step. This is indicated by the last linear segment, which points directly to the origin.

Stable Magnetization Direction - Palaeopole Position.

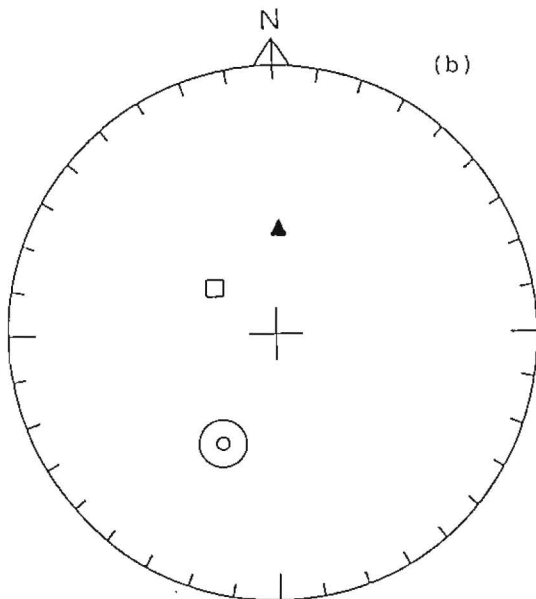
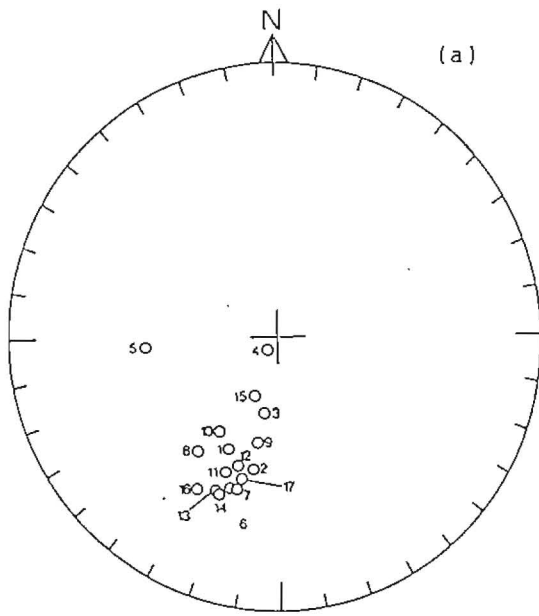
The stable magnetization direction for each of the Leptokarya sites are listed in Table 1 and also illustrated in Fig.4.

Table 1. Primary Magnetization Directions for all individual sites within the Leptokarya intrusion.

SITE	Dec(°)	Inc(°)	α_{95}	N (n)
LP01	206.8	-52.6	1.7	4 (8)
LP02	192.7	-50.4	3.4	4 (7)
LP03	192.8	-66.3	3.4	5 (9)
LP04	220.2	-85.2	4.8	4 (8)
LP05	267.5	-48.6	6.4	5 (9)
LP06	198.2	-40.9	3.9	3 (15)
LP07	196.9	-45.5	9.1	2 (11)
LP08	218.1	-46.7	3.2	3 (14)
LP09	193.2	-57.2	1.5	3 (11)
LP10	215.4	-56.3	3.5	2 (10)
LP11	204.4	-45.9	10.9	3 (15)
LP12	190.9	-41.1	8.1	3 (13)
LP13	204.8	-39.0	9.3	2 (11)
LP14	203.5	-38.1	4.5	3 (15)
LP15	205.5	-70.1	19.0	2 (12)
IP16	211.7	-36.7	14.0	2 (11)
LP17	199.9	-48.8	6.7	3 (13)

N: Number of cores for sites LP01, LP02, LP03, LP04 and LP05.
 Number of samples for the rest of the sites.
 n: Number of specimens measured from each site.

The mean stable direction for the intrusion calculated for all 17 sites is: Dec=206.8°, Inc=-52.2° (N=17, α_{95} =7.4°) and corresponds to a palaeopole position at 308.4°E, 67°W (δ_m =10.1°, δ_p =11.5°). As indicated by the α_{95} values, the majority of sites give reasonably well-defined mean magnetization directions except



- Mean Magnetization Direction
- ▲ Present Earth's Magnetic Field
- Palaeopole Position

Fig.4. Primary magnetization directions. (a) For all individual sites, and (b) mean for the intrusion, corresponding Palaeopole Position and present Earth's Field. The semi-angle of the cone of confidence is shown as a circle with radius equal to the a_{95} value.

for sites LP15 and LP16. In terms of directional consistency between sites, two points emerge: (a) Site LP05 exhibits the more westerly magnetization direction (by about 60°) compared with the rest of the sites, and (b) Sites LP03, LP04 and LP15 exhibit the steepest stable magnetization directions being the only sites associated with inclinations steeper than -60° .

For site LP05, although an orientation error can not be ruled out, on the basis of subsequent field observations concerning the position and form of the outcrop sampled, it is suggested that this site may not have been 'in situ'. The fact that no adequate demagnetization of the specimens from sites LP03, LP04 and LP15 could be achieved, within the limits of the experimental facilities available, suggests that the directions quoted for these sites may represent a very hard secondary magnetization component.

The mean stable magnetization direction for the intrusion, calculated for the 13 remaining sites is of $Dec=202.8^\circ$, $Inc=-46.4^\circ$ ($N=13$, $\alpha_{95}=4.6^\circ$). This well-defined magnetization direction clearly indicates that the Leptokarya intrusion is reversely magnetized and corresponds to a palaeopole position at $324.3^\circ E$, $67.0^\circ S$, with associated polar error parameters $\delta m=5.9^\circ$ and $\delta p=7.7^\circ$.

MAGNETIC MODELLING

In order to interpret the aeromagnetic anomaly associated with the Leptokarya intrusion a profile (AB) has been drawn across the main part of the elongated anomaly. Aeromagnetic data in this area have been collected by ABEM during a survey in 1966, at a flying height of (275 ± 75) m. The regional field has been removed from profile AB (Fig. 1) and the residual anomaly as well as the two interpretation models produced are shown in Fig. 5 (a and b). The residual field consists of a small positive anomaly of 95 nT in the southern part of the profile followed by a major positive anomaly of 250 nT (centered over Leptokarya village) and a negative anomaly of -100 nT to the north of Leptokarya.

The non-linear optimization method (Al-Chalabi, 1970; 1971, James, 1972) was used in the 2D aeromagnetic modelling rather than a classical method of interpretation. This is due to the inherent ambiguity mainly in the direction of magnetization vector.

With the non-linear optimization method, known magnetic properties can be used to specify some of the amplitudes and directions of the components of the magnetization vector, whilst the unknown parameters are allowed to vary within a reasonable range. The problem is usually reduced to that of minimizing a function which is some measure of the difference between the observed and the calculated anomaly. This is called the objective function. For magnetic modelling the objective function is defined as the sum of the squares of the residuals between the observed and the calculated anomaly values. The objective function is repeatedly evaluated at different points in the parameter hyperspace until a minimum value is obtained. By obtaining the minimum value of the objective function, the variable parameters controlling it can be subsequently obtained.

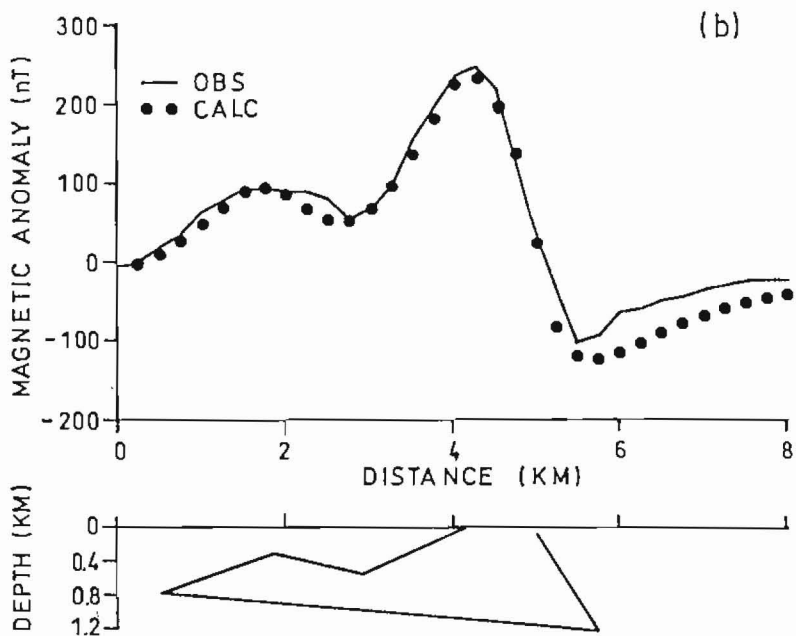
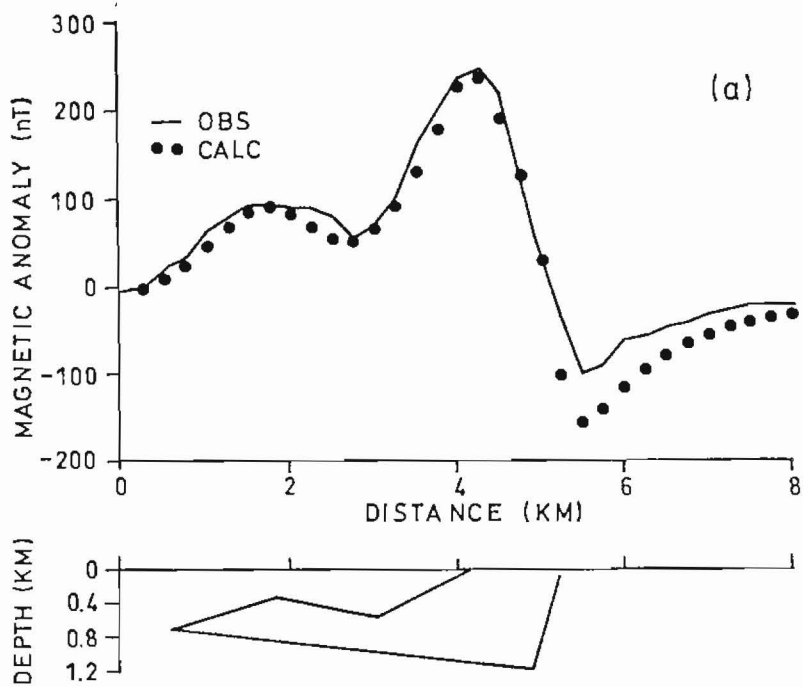


Fig.5. 2D models of Leptokarya granodiorite produced by the non-linear minimization method.

In our case the known component of induced magnetization was introduced as a constant (specified by its amplitude and direction) using a uniform susceptibility value of 38.5×10^{-3} SI, based on extensive laboratory measurements as previously stated. A typical intensity value of 500 mA/m (from the range of intensities measured) was assigned to the NRM vector. This amplitude value was kept constant although the direction of the NRM component was allowed to vary due to the large scatter ($\alpha_{95} > 90^\circ$).

The minimization approach which produced the models of Fig.5 suggested similar values for the inclination (-22.5° ; and -25.8° respectively) and a declination of 156° for the NRM vector in each case. The only point in which the two models appear to be different is the coordinates of body a. which were constrained for inward dip.

In both cases, the maximum depth to base is about 1.2 km and the RMS error of fit is less than 7% of the maximum amplitude of the anomaly.

DISCUSSION - CONCLUSIONS

Comparison of the mean remanence direction of the Leptokarya intrusion with other palaeomagnetic results (presented in Table 2 and demonstrated in Fig.6) suggests a clockwise difference of some 20° for the Leptokarya body. Other palaeomagnetic data also support that the Rhodope massif has not been affected by any rotation since Tertiary times and has a different rotation history than the Serbo- Macedonian massifs (Kissel et al., 1986; Spais, 1987; Kondopoulou and Pavlides, 1990).

Accepting that the radiometric dating of the Leptokarya body (Bitzios, 1973) is correct, the Essimi basin igneous activity predates the Leptokarya intrusion by approximately 2Ma. Therefore it ought to be expected that the older sites (Essimi igneous) would show the evidence of rotation. However, it is the younger Leptokarya intrusion which indicates this.

A possible interpretation is that after its intrusion in Oligocene times, the Leptokarya body was emplaced into the present position by thrusting. During this episode of thrusting, possibly associated with the final stage of basin closure, the body underwent a clockwise rotation, whereas the main part of the Essimi basinal sequence including the igneous masses, maintained a fixed longitudinal orientation and closure occurred in a predominant N-S direction.

This explanation is further supported by the interpretation of the geometric form of the Leptokarya intrusion from the modelling of the associated aeromagnetic anomaly, which demonstrates that it is a "shallow body" the depth of which does not exceed 1.2 Km and whose base may represent a thrust-fault contact. Studies of the Neogene deformation of the central and northern Aegean emphasize that normal faulting was interrupted by shorter periods of compression involving reverse faulting and thrusting (Angelier, 1978; Mercier, 1981). These compressional structures "appear to be quite small compared to the large ubiquitous normal faulting" (Le Pichon and Angelier, 1979). By accepting a model of thrust emplacement of the body an

explanation of the shallow inclination of the remanence direction with respect to the present Earth's field in the area is also provided.

Table 2. Palaeogene palaeomagnetic results for the N.E. Aegean area. (Rhodope and Serbo-Macedonian massifs).

	STBL.REMANENCE			PALAEOPOLE POSITION			
	D(°)	I(°)	α_{95}	Long	Lat	δp	δm
BULGARIA 1 Lozen rhyolites and volcanics. (Oligocene) Ref.1	0.6	54.8	16.3	201.1	83.4N	16.3	23.1
GREECE 2 Chalkidiki intrusives. (SM massif) (Eoc.-Olig.) Ref.2	37.0	31.0	9.0	139.0	50.0N	6.0	10.0
Leptokarya 3 granodiorite. (Oligocene) This study.	202.8	-46.4	4.6	324.3	67.0S	3.8	5.9
Essimi 4 volcanics/ intrusives. (Oligocene) Ref. 3	2.3	52.1	6.0	192.3	81.5N	5.6	8.2
Kirki-Essimi 5 basin sequence (Eocene) Ref. 3	10.3	62.8	7.5	89.0	81.7N	9.2	11.8
Ref. 1: cited in McElhinny and Cowley (1980). Ref. 2: Kondopoulou and Westphal (1986). Ref. 3: Spais (1987).							

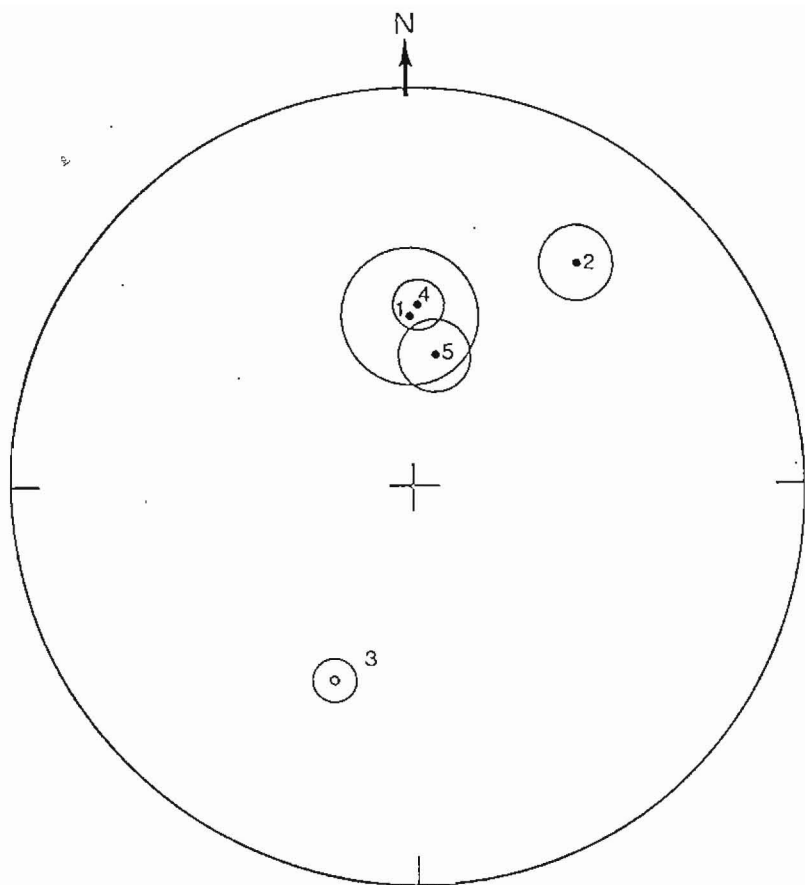


Fig.6. Comparison of directions of mean primary magnetization for the Leptokarya intrusion with directions of other studies. (As identified in Table 2.)

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