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THE METHOD OF ANISOTROPY OF MAGNETIC SUSCEPTIBILITY: THEORY AND APPLICATIONS. A CASE STUDY FROM THE RHODOPE MASSIF*

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ABSTRACT

The anisotropy of magnetic susceptibility is a physical property of the rocks widely used in petrofabric studies and other applications. It is based on the measurement of low-field magnetic susceptibility in different directions along the sample. From this process several scalar properties arise, defining the magnitude and symmetry of the AMS ellipsoid, along with the magnetic foliation and lineation, namely the magnetic fabric. A case study is presented, dealing with the deformation of the Mont-Louis-Andorra pluton. Finally, the method was applied in Tertiary magmatic rocks from the Rhodope Massif, revealing their magnetic character and internal structures.

KEY WORDS: Anisotropy of magnetic susceptibility (AMS), magnetic fabric, petrofabric, Rhodope Massif.

1. INTRODUCTION

The anisotropy of magnetic susceptibility (AMS) technique was early recognized as a powerful tool for structural studies in rocks (Graham, 1954). The AMS efficiency in determining the internal structures of plutonic rocks, especially the lineations that are difficult to determine in the field, has been demonstrated in plutons throughout the world (e.g. Balsley & Buddington, 1960; Bouchez et al., 1990; Archanjo et al., 1994; Cruden & Launeau, 1994; Saint-Blanquat & Tikoff, 1997). Moreover, AMS has proved to be useful for the recognition of multiple deformation episodes in granitoids (Bouchez & Gleizes, 1995; Borradaile & Henry, 1997). Finally, it can be used in order to approach some environmental problems.

However, this technique is quite new in Greece. A first attempt to apply the AMS in order to approach some tectonic problems was performed on Tertiary granitoids of the Rhodope massif.

2. THE THEORY OF AMS

2.1 Basic principles.

The magnetic susceptibility, k, which represents the response of a body when it is inserted in a magnetic field, and which is an intrinsic physical property of the minerals, is defined by the equation: $M = k H$,

where M is the induced magnetization and H is the force of the applied field. If the material is isotropic, then M and H are parallel and the susceptibility, k, is a scalar property. On the contrary, in the case of anisotropic materials, M and H are not parallel and the magnetic susceptibility can be regarded in a first approximation, in low-field and low temperature, as a symmetrical second rank tensor. Thus, it can be geometrically represented by a triaxial ellipsoid, of $K_1 = K_2 = K_3$ major axis, whose mean value $K = (K_1+K_2+K_3)/3$ represents the mean susceptibility.

The anisotropy of magnetic susceptibility (AMS) is a physical property of the rocks, widely used in petrofabric and tectonic studies (e.g. Rochette et al., 1994; Bouchez, 1997, 2000). The AMS technique favors great acceptance in various fields because: it is applicable to nearly all rock types, exhibits high sensitivity, is not time-consuming, allows quantitative-semi quantitative applications in the field of deformation, based on the strength and symmetry of fabric.

2.2 Magnetic behavior of minerals.

Minerals are classified in various categories according to their magnetic properties. A first division has been

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established between ferromagnetic minerals, which exhibit saturation of magnetization in high field, and the non-ferromagnetic ones, that do not show the above property, and are characterized as "the matrix", because they represent the bulk volume of the rock (Rochette, 1987).

The magnetic susceptibility of the matrix can be attributed to various sources. Therefore, we distinguish between diamagnetic and paramagnetic or antiferromagnetic behavior.

The ferromagnetic minerals, although they usually represent accessory minerals (less than 1% of the total volume of the rock), are mostly important for the rocks magnetic properties. In low-field and ambient temperature the ferromagnetic susceptibility is quite high, in the order of 10^{-3} to 1 SI. In granitic rocks magnetite (Fe_3O_4) is the most important ferromagnetic mineral. It is the only common mineral, where AMS is mainly controlled by the grain shape, rather than the crystallographic structure (Grιgoire et al., 1995, 1998; Uyeda, 1963).

2.3 Magnetic susceptibility of granitic rocks.

In low field the bulk magnetic susceptibility of a granitic rock is equal to the sum of all magnetic contributions: $K = K_{para} + K_{ferro} + K_{antiferro} + K_{dia}$, but since $K_{antiferro}$ and K_{dia} are generally negligible, the previous equation is finally transformed to $K » K_{para} + K_{ferro}$. Granitic rocks can be classified in three categories:

(1) Paramagnetic: a granitic rock is characterised as paramagnetic when the ferrous silicate minerals are almost the only carriers of magnetic susceptibility. In practice, that implies a rock without magnetite. Based on the Curie-Weiss law, Rochette et al. (1992) worked out the following equation, which is a very good approximation of the paramagnetic susceptibility: $K_{para} = -14.6 + d(25.2t + 33.4t' + 33.8t'')\ 10^{-6}SI$
where the diamagnetic susceptibility of quartz is used as a representative of all minerals, d is the rock density and t, t', t" are the concisions in g $g^{-1\%}$ for Fe^{2+}, Fe^{3+} and Mn^{2+} respectively. Thus, it is obvious that the susceptibility in paramagnetic rocks depends on the iron content. As a result, it is possible to map the main phases in a paramagnetic granitic pluton based on the content of ferrous, silicate minerals, as in the case of the Mont-Louis-Andorre (Bouchez & Gleizes, 1995). Generally $K_m < 500\mu SI$.

(2) Ferromagnetic: a granitic rock is considered to be ferromagnetic when it has on average =1% (per weight) magnetite. Its ferromagnetic susceptibility is usually several orders of magnitude greater than that of the matrix. Therefore, only a small number of ferromagnetic grains are adequate for the ferromagnetic fraction to dominate the total susceptibility of the rock. Generally $K_m > 1000\mu SI$.

(3) Mixed: the term mixed magnetic mineralogy is used when no family of magnetic minerals clearly prevails over the rest. There are two cases of mixed granitic rocks:
(a) The paramagnetic granites with various magnetocrystalline anisotropies. A very common case is the coexistence of biotite and amphibole. (b) The intermediate granitic rocks between the paramagnetic and ferromagnetic spectrum, that correspond to the presence of magnetite in small amounts. It has been observed in several cases that para- and ferro- subfabrics are coaxial (Archanjo et al., 1994), but it cannot be considered as a rule. Generally $500 < K_m < 1000\mu SI$.

2.4 Sources of the AMS in magmatic rocks.

The magnetic anisotropy of certain minerals, which are arranged or distributed not in a random way, is the basis of the magnetic fabric in a rock. In the grain scale it is essential to distinguish between the magnetocrystalline anisotropy, which is defined by the crystalline structure of the mineral, and the shape anisotropy of ferromagnetic minerals.

(1) Magnetocrystalline anisotropy: it has been experimentally shown that for certain crystals there are favorable directions of "easy" magnetization, relatively to the geometry of their crystallographic structure. The magnetocrystalline anisotropy is negligible for the minerals of the cubic system, but is quite important for the lower symmetry systems, like in the cases of hematite, pyrrhotite and ilmenite.

(2) Shape anisotropy: this kind of anisotropy is present only in minerals of high susceptibility. It arises in an uneven grain, as a result of the inequality of the intensity of the demagnetization field measured in different directions.

(3) Distribution anisotropy: it demands high concentration of ferromagnetic particles that exhibit interactions and can be considered as a special case of grain arrangement (Bhatal, 1971). Magnetic interactions between adjacent grains are supported by testing the alignments between grains whose center-to-center distance is less than a critical value (Grιgoire et al., 1995; Caϱση-Tapia, 1996). The resulting magnetic fabric may be modified in orientation and intensity (fig.1) when the intergrain distance is generally less than one grain size.

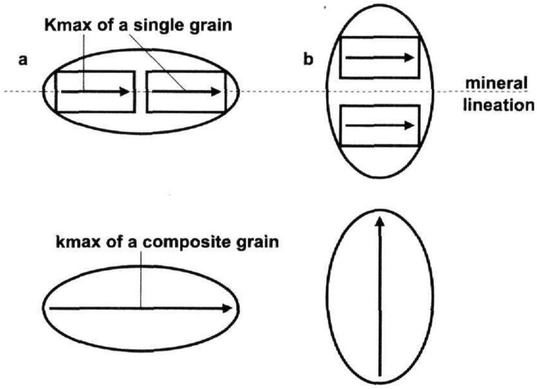

Figure 1: Typical configurations of interacting magnetite grains showing the (a) aligned; and (b) side-by-side configurations of Grıgoire et al. (1995). k_{max} is the maximum magnetic susceptibi-lity. (After Grıgoire et al., 1998)

2.5 Measurement schemes.

The low-field anisotropy of magnetic susceptibility can be represented by a second rank symmetric tensor:

$$\begin{pmatrix} k_{11} & k_{12} & k_{13} \\ k_{21} & k_{22} & k_{23} \\ k_{31} & k_{32} & k_{33} \end{pmatrix}$$

Thus, at least six equations are necessary in order to calculate the six independent components of this tensor. Each equation corresponds to the magnitude, M, of the magnetic susceptibility in a different direction along the sample. Performing measurements in more than six directions can ameliorate the solution only if chosen carefully. Hext (1963) suggested various measurement schemes, which involve 12 and 24 positions. Jelinek (1977) introduced a procedure with 15 positions. This is the process usually applied nowadays and is the one used in the current study. By solving and diagonalizing the magnetic susceptibility tensor, the following values are obtained: the magnitude of susceptibility along the major axis, expressed in 10^{-6}SI, and the orientation, according to the sample reference frame, of the three mutually orthogonal, major axis of the AMS ellipsoid. Each axis is defined by its declination (0°-360°) and inclination (0°-90°). After tectonic correction is performed, the above results are obtained in relation to the geographic coordinate system.

By treating the above properties it is possible to result in several parameters, scalar and directional. The most important ones, also used in the present study, are:

Scalar:

- $K_m = (k_1+k_2+k_3)/3$, the mean susceptibility (Nagata, 1961)
- $P = k_1/k_3$, the AMS degree (Nagata, 1961)
- $LS = k_1/k_2$, the linear anisotropy - magnetic lineation (Balsley and Buddington, 1960)
- $FS = k_2/k_3$, the planar anisotropy - magnetic foliation (Stacey et al., 1960)
- $T = LS/FS = k_1k_3/(k_2)^2$, the parameter of the shape of the AMS ellipsoid (Stacey et al., 1960). T ranges between –1 and +1 :

  $T = +1$: oblate ellipsoid ($k_1 \approx k_2 > k_3$)
  $T = -1$: prolate ellipsoid ($k_1 > k_2 \approx k_3$)
  $T = 0$: triaxial ellipsoid ($k_1 \geq k_2 \geq k_3$)

Directional:

- K_1 is the magnetic lineation, defined by its azimuth (in relation to the magnetic north) and its dip.
- The vertical to K_3 plane, containing K_1 and K_2 axis, is characterized as magnetic foliation.

3. AN APPLICATION OF THE AMS THEORY: THE CASE OF THE MONT-LOUIS-ANDORRA PLUTON (VARISCAN PYRENEES)

The Mont-Louis-Andorra pluton (Eastern Pyrenees) was the subject of a thorough study, by J.L. Bouchez and G. Gleizes (1995), where a two stage deformation was inferred from AMS measurements. With the magnetic susceptibility magnitudes ranging from 14 to 410 μSI, the susceptibility is of paramagnetic origin, i.e. due only to the contribution of the iron-bearing silicates (biotite and hornblende) and consequently proportional to the iron content. It was used, to a first approximation, as a petrographic index and the results were verified using conventional modal analysis. Thus, it was shown that the zoning in the susceptibility of the pluton corresponds to the surface distribution of rock types and a petrographic zoning.

The magnetic structures fell into two distinct families, which are observed in separate parts of the pluton and are accompanied by different microstructures. Fabrics of the first family are present throughout the pluton exhibiting NE-SW lineations and accompanied by magmatic to submagmatic microstructures. On the contrary the magnetic structures of the second type form NW-SE corridors, where solid-state and mylonitic microstructures are present. It was concluded that the two families of magmatic fabric correspond to two separate deformational events: the first one – associated with family I structures – being the main kinematic event, an early Variscan thrust (e.g. Bodin & Ledru, 1986) more precisely, during which the Mont-Louis-Andorra pluton was emplaced, and the second one (family II), a post-emplacement dextral shearing event, that was equated with the major phase of the Variscan Pyrenees.

4. RESULTS FROM THE RHODOPE MASSIF

Plutonic bodies emplaced in the Cenozoic are abundant in N.Greece. The emplacement mechanism of the Tertiary granitoids is very controversial and mechanisms ranging from diapirism, lateral extrusion of crustal blocks, gravitation spreading and transtension within a strike-slip regime have been proposed.

The Rhodope massif is an area that soon attracted the interest of various researchers. Consequently, there are plenty of petrological, geochemical, geochronological and tectonic data, as well as many models considering the emplacement of the Tertiary plutonic formations of the area.

The presence of these magmatic intrusions and many volcanic rocks of similar age in the Rhodope massif, allows us to examine if the method of AMS is applicable in this case and to what extent. Thus, the tectonic problems of the area are approached using a methodology completely different from the usual petrotectonic ones. The main aim was to check whether the results of AMS agree with the existing tectonic, mainly, data and if it is possible to verify or modify one of the preexistent tectonic models. Of course, solely the appliance of the AMS technique is not sufficient in order to solve the geotectonic problems. However, it can prove to be a powerful tool if combined with the classical methods of tectonic analysis.

Moreover, from the homogeneity of the AMS data it is possible to reach conclusions regarding the intensity and homogeneity of deformation in various plutonic bodies from the area, as well as in different sites in each one of the plutons.

Table 1: Mean magnetic properties for the various magmatic bodies of the Rhodope Massif inferred using the AMS technique.

Area	Age (Ma)	Rock Type	K_m (μSI)	P	Ellipsoid	K_1	K_2	K_3
Paranesti	39-47	Param.	38.50	1.072	Oblate	178/6	295/78	89/14
Elatia(pl.)	39-47	Ferrom.	4742.89	1.276	Oblate	251/12	344/15	126/71
Elatia(v.)	Oligocene	-	29270.59	1.027	Oblate	84/73	15/8	179/3
Xanthi	28	Ferrom	41920.85	1.103	Oblate	254/26	100/64	348/11
Kavala	13.9-19.5	Ferrom.-mixed	8795.14	1.330	Triaxial	49/14	143/24	299/65
Filippoi	26	Ferrom	166471.00	1.077	Varied	156/18	254/10	10/77
N. Vrondou	22	Ferrom.	14323.98	1.284	Varied	52/53	152/4	246/35
S. Vrondou	22	Ferrom.	13395.56	1.146	Triaxial	121/16	218/27	356/60
Gavra	22.7-24.7	-	244.16	1.045	Oblate	109/51	269/47	9/19

4.1 AMS sampling and measurement procedures.

Rock samples were gathered from various sites of the Elatia-Paranesti, Xanthi, Filippoi, Kavala and Vrondou granitic plutons. The AMS stations were sampled with a portable drilling machine or, in some cases, by collecting oriented samples that were re-oriented and core-drilled in the laboratory. The AMS measurements were performed on cylindrical samples (22X25mm), using the KLY-2 Kappabridge (Geofysica, Brno) equipment at the University Paul-Sabatier, of Toulouse (France). Moreover microscopic examination of thin sections and thermomagnetic analysis were carried out in order to investigate the magnetic mineralogy of the Rhodope granitoids.

4.2 Scalar properties.

The mean AMS data for each plutonic body are presented in table 1, along with the plutons ages. The magnetic susceptibility is generally high, with a mean value of 34869.8 μSI. Moreover the anisotropy degree, varying from 1.027 to 1.330, suggests moderate to high anisotropic formations. According to the limits set by Rochette (1987) these suggest ferromagnetic plutonic bodies, that is granites with magnetite.

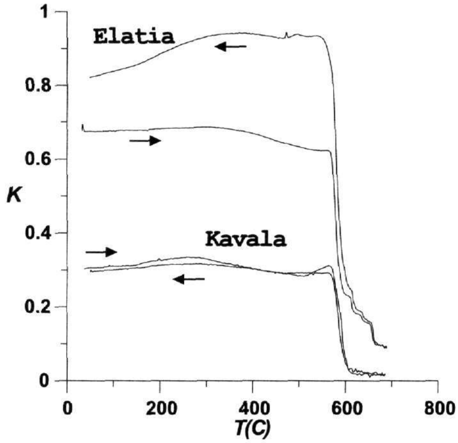

Figure 2: Representative thermomagnetic curves for samples of the Elatia and Kavala plutons, showing the magnetic susceptibility, K, changes with temperature.

This has been verified by examination of thin sections and determination of Curie temperatures. As shown in fig.2 the magnetic susceptibility decreases near zero at 580°C, which is the Curie point of magnetite. Before reaching 580°C, the magnetic susceptibility shows a slight increase related to the Hopkinson effect. The only exception is the Paranesti pluton (fig.3b) exhibiting paramagnetic behavior, K_m = 38.50 μSI and P = 1.072.

The Xanthi pluton is a typical ferromagnetic body (fig.3a), moderately anisotropic. However, the anisotropy degree remains constant, irrespective of the change in the magnetic susceptibility, contradictory to what has been stated for the cases of magnetite plutons (Bouchez, 1997). The increase of K_m can be attributed to the high variation in mineralogy throughout the pluton.

The Vrondou ferromagnetic pluton (fig.3f) appears to be very anisotropic. However, the magnetic susceptibility does not exhibit a high variation. Thus, the rise in P cannot be attributed solely to the magnetic mineralogy, but its sources lie mainly in the deformation of the pluton.

The Kavala plutonic complex (fig.3c) is an extremely interesting case of a ferromagnetic, highly anisotropic pluton. The anisotropy degree increases almost linearly with the total susceptibility, as expected for the case of magnetite-bearing plutons. However, two distinct behaviors can be observed: firstly, a slight rise and afterwards a steep increase in P. This can be attributed to possible magnetic interactions of the adjacent magnetite grains, but more data are necessary to establish such a case. Moreover, the increase of K_m by two orders of magnitude results from the variation in the magnetite content throughout the pluton.

The plutonic formation of Elatia (fig.3e) is clearly ferromagnetic and quite anisotropic, with the anisotropy degree increasing linearly and rather rapidly with the total susceptibility. On the contrary, the volcanic formations of the area exhibit constant and very low P, but a great variance in K_m.

The Filippoi pluton (fig.3d) shows extremely high magnetic susceptibility, but rather constant and low

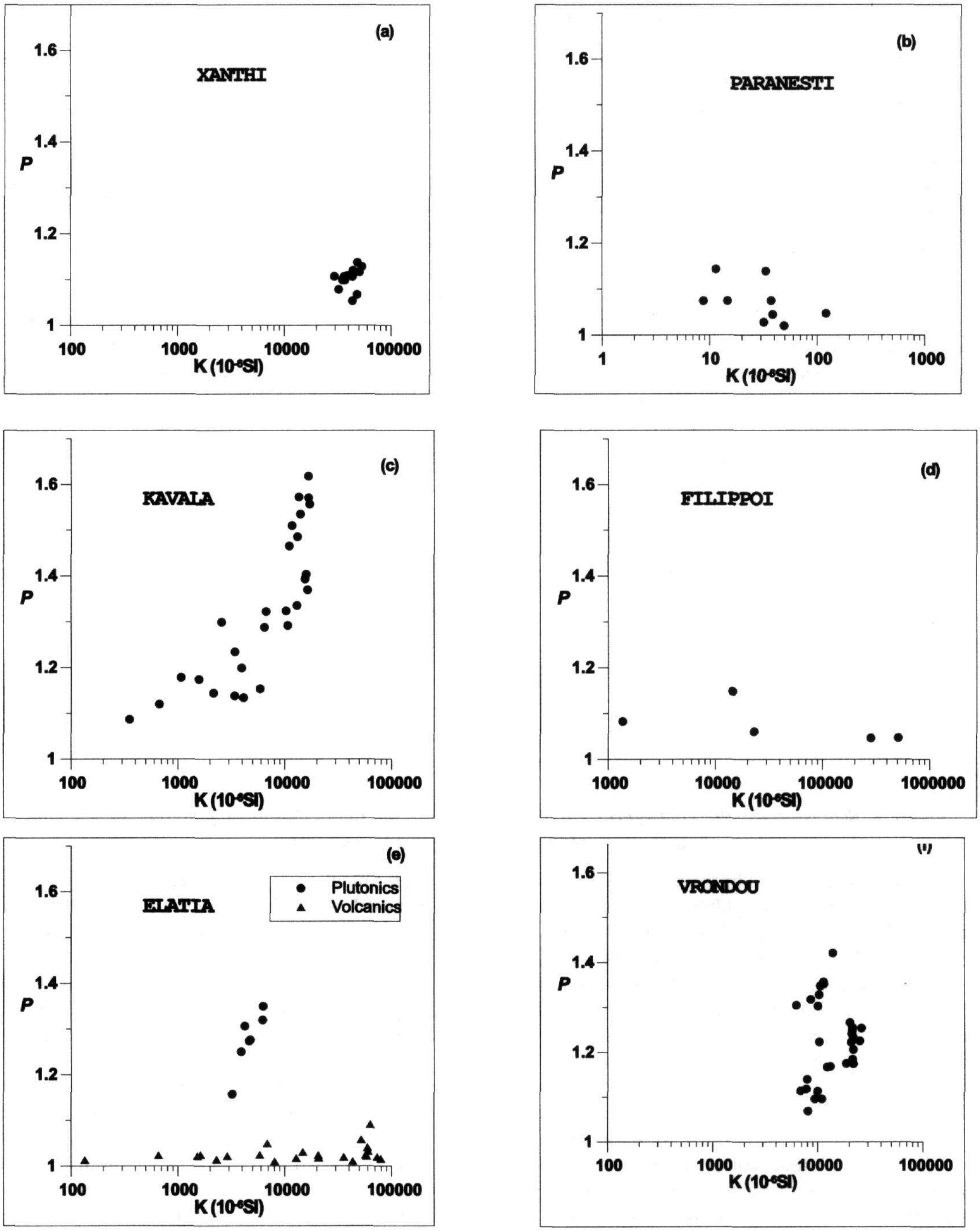

Figure 3:Anisotropy degree (P) versus magnetic susceptibility (K) plot. Roughly, according to Rochette (1987) the upper limits of the paramagnetic contribution are K >300-500 10^{-6}SI and P >1.2.

anisotropy degree. The correlation of P and K_m is different from that usually observed in ferromagnetic plutons, implying a possible case of grain interactions, but the limited data do not allow any final deductions.

4.3 Directional data.

As previously mentioned by implementing the AMS technique some directional data also arise: the magnetic foliation and lineation. The magnetic fabric was well defined throughout the plutons, with a very small scatter. The K_{max} axes, usually defining the magnetic lineation, varied from gently to medium plunging. The directional data obtained were compared to the macroscopic structural data from the Rhodope massif.

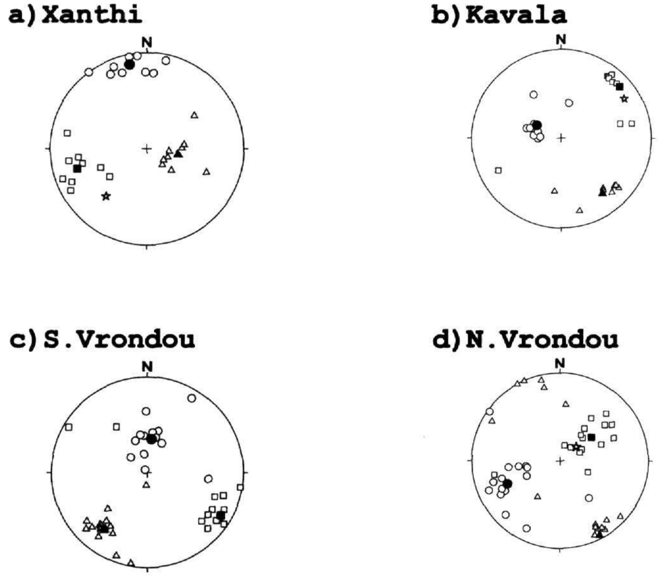

Figure 4: Representative lower-hemisphere stereoplots of AMS fabrics with well clustered principle axes for sites of the Xanthi and Kavala granites, and samples of North and South Vrondou. (squares = K_1 axes, triangles = K_2 axes, circles = K_3 axes, filled symbols correspond to the mean values, ? = structural lineation, A= structural foliation).

The usual relationship between AMS and petrofabrics, namely the "normal magnetic fabric", corresponds to the situation where K_1 is parallel to the structural lineation and K_3 is perpendicular to the structural foliation. Conversely, the symmetry of the AMS ellipsoid mimics the petrofabric symmetry. This is the case of the Xanthi and Kavala plutons (fig.4a-b). In the Xanthi pluton K_1 (254/26) is very close to the structural lineation (220/35 S). Similarly, the macroscopic lineation of Kavala (18N 58 E, Dinter, 1995) nearly coincides to the magnetic one (49/14).

However, AMS studies sometimes reveal "inverse fabrics" where K_1 and K_3 axes and symmetry are inverted (Rochette, 1988). In other cases, labeled "intermediate fabrics", K_1 and K_2 or K_2 and K_3 are exchanged. Such a complex behavior was observed in the case of the Vrondou plutonic complex, where intermediate magnetic fabric in the southern part and inverse magnetic fabric in the northern part was observed (fig.4c-d). Since the magnetic susceptibility of the pluton is generally high, the inverse fabric could be attributed to single domain (SD) magnetite grains (Rochette et al., 1999). Concerning the intermediate fabric pattern a possible cause is the distribution anisotropy (Hargraves et al., 1991) due to dipolar interactions between adjacent magnetite grains. Moreover, interactions between AMS and remanent magnetization can also lead to abnormal magnetic fabrics (Rochette et al., 1992). Such a correlation can be checked by measurements of the remanence anisotropy.

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