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MAGNETIC FABRIC OF PYRRHOTITE-BEARING ROCKS

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## 1. INTRODUCTION

This report is one of a series on magnetic properties of pyrrhotite-bearing rocks. Because pyrrhotite is common in mineralised terrains and is frequently responsible for observed magnetic anomalies, pyrrhotite-bearing rocks are often sampled in order to provide input to magnetic interpretation.

Although the rock units may have been sampled primarily for determination of susceptibility and remanence, it is desirable to extract as much additional information as possible from the samples. The susceptibility anisotropy of the rocks, which in most cases is too low to significantly influence magnetic interpretation, nevertheless contains valuable information concerning geological structure. For example the magnetic fabric of disseminated pyrrhotite in metasediments generally reflects the strain ellipsoid. Magnetic fabric of massive pyrrhotitic ores reflects the genesis and deformation of the orebody.

This report first discusses the relationship between the intrinsic magnetic properties of pyrrhotite grains and the magnetic anisotropy arising from preferred orientation of the grains.

Mechanisms for producing preferred orientation of pyrrhotite grains are described and interpretation of the resulting fabric is discussed in the context of a review of conventional petrofabric studies carried out on pyrrhotite-bearing rocks. Previous magnetic fabric studies are also summarised. Finally, three examples of the magnetic fabric of pyrrhotite-bearing rocks from Australia are discussed.

General reviews of magnetic fabric studies have been given by Clark and Embleton (1980) and Hrouda (1982).

## 2. MAGNETIC ANISOTROPY AND MAGNETIC FABRIC

In general the induced magnetisation of a rock sample and the applied field are not strictly parallel and the measured susceptibility value depends on the direction of the applied field. In anisotropic rocks the relationship between magnetisation and applied field components is essentially linear in the weak field range and the low-field susceptibility can be expressed as a tensor  $k_{ij}$ , defined by

$$J_i = \sum k_{ij} H_j \quad (i, j = x, y, z)$$

In all cases of interest the susceptibility tensor is symmetric ( $k_{ij} = k_{ji}$ , for all  $i$  and  $j$ ) and can therefore be diagonalised. This means that three mutually perpendicular directions called the principal susceptibility axes can be found for which the induced magnetisation is parallel to the field. The principal susceptibility axes lie along the eigenvectors of the matrix  $\{k_{ij}\}$ . The susceptibilities along the principal axes are the corresponding eigenvalues and are known as the principal susceptibilities  $k_1, k_2, k_3$ .

We define

$k_1$  = major susceptibility (along easiest direction of magnetisation)

$k_2$  = intermediate susceptibility (orthogonal to  $k_1$  and  $k_3$ )

$k_3$  = minor susceptibility (along hardest direction of magnetisation)

$k_0$  = bulk susceptibility =  $(k_1 + k_2 + k_3)/3$

The susceptibility ellipsoid is defined to have semi-axes  $k_1$ ,  $k_2$ ,  $k_3$  and is a convenient concept for visualisation of magnetic fabric type. The magnetic foliation plane contains the major and intermediate susceptibility axes. The minor susceptibility axis is therefore the pole (normal) to the magnetic foliation plane. The magnetic lineation is parallel to the major axis and therefore lies within the foliation plane. If the susceptibility ellipsoid is a sphere the specimen is isotropic and the fabric has rotational symmetry. If it is a prolate spheroid the specimen exhibits a pure lineation and if it is an oblate spheroid the specimen has a pure foliation (in both these cases the fabric has axial symmetry).

If the susceptibility ellipsoid is triaxial, the magnetic fabric has orthorhombic symmetry and consists of a lineation lying within a foliation plane. Fabrics of lower symmetry than orthorhombic (monoclinic, triclinic) are aliased into a magnetic fabric of apparently higher symmetry. For instance two intersecting foliations will appear as a single foliation lying between the two with an artefactual lineation along the line of intersection.

It should be noted that the susceptibility ellipsoid is not the same as the representation ellipsoid of the susceptibility tensor, which has more elegant geometrical properties (Runcorn, 1967, and Fig. 1) but which is less amenable to comparison with rock fabric and the strain ellipsoid and therefore has less intuitive appeal.

The following parameters are frequently used to characterise magnetic fabric

Degree of anisotropy  $A = k_1/k_3 > 1$

Magnetic lineation  $L = k_1/k_2 > 1$

Magnetic foliation  $F = k_2/k_3 > 1$

Prolateness  $P = L/F = k_1k_3/k_2^2 > 0$

When  $P > 1$  the susceptibility ellipsoid is said to be prolate (lineation dominant) and when  $P < 1$  the ellipsoid is oblate (foliation dominant).

Highly anisotropic rocks can significantly deflect the direction of induced magnetisation away from the Earth's field, complicating magnetic interpretation. Knowledge of susceptibility anisotropy may therefore aid interpretation of magnetic surveys. Anisotropy also causes difficulties for palaeomagnetism, as discussed in Clark and Embleton (1980).

However magnetic anisotropy, even where it is very weak, is important for another reason. Anisotropy implies the existence of a preferred orientation in a rock which reflects the forces acting to align particles during the formation, deformation or alteration of a rock. Measurements of magnetic anisotropy, in low or high fields, can provide information on the nature and magnitude of these forces and has the potential to reveal rock fabrics which are too faint to detect by conventional methods. The aim of structural petrology is to make inferences concerning the thermal and deformational history of a rock from the fabric diagram. The conventional methods of structural petrology are tedious and time-consuming (optical methods) or relatively insensitive

to faint fabrics (X-ray goniometry). Magnetic fabric studies therefore offer an attractive alternative, or supplementary, technique for elucidation of geological structure.

The magnetic fabric of pyrrhotite-bearing rocks can arise in several ways:

- (i) Preferred crystallographic orientation
- (ii) Textural anisotropy
- (iii) Shape anisotropy

Strain anisotropy is negligible in pyrrhotite because of the relatively weak magnetostriction.

Monoclinic pyrrhotite grains exhibit very high intrinsic anisotropy, having high susceptibility in the basal plane and low susceptibility along the c-axis. Taking the basal plane susceptibility of MD grains as 0.015-0.15 and  $k_c$  as  $\sim 0.001$  gives the intrinsic anisotropy  $P'$  as 15-150. Uyeda et al. (1963) have shown that for 3 single crystals of natural pyrrhotite with unspecified compositions  $P' > 100$ . A slight tendency for preferred orientation of c-axes of monoclinic pyrrhotite therefore produces substantial magnetic anisotropy. Magnetic fabric of monoclinic pyrrhotite is thus a very sensitive indicator of petrofabric.

The bulk susceptibility of intermediate pyrrhotite and troilite is much lower than that of monoclinic pyrrhotite. Intergrowths of intermediate pyrrhotite with monoclinic will therefore have little effect on the overall anisotropy. Moreover measurements of susceptibilities parallel and normal to c-axes of synthetic iron sulphide crystals show that the susceptibilities of FeS and annealed  $Fe_9S_{10}$  are slightly

higher in the basal planes than along the c-axes, by factors of  $\sim 3$  and  $\sim 1.3$  respectively (Hihara, 1960), indicating that the susceptibility anisotropy of the antiferromagnetic natural phases should be in the same sense as that of strongly magnetic monoclinic pyrrhotite.

Fuller (1963) and Hrouda (1980) have shown that, whereas for near-perfect alignment of c-axes the susceptibility anisotropy of an assemblage of grains is essentially determined by the intrinsic anisotropy, in the case of weak preferred orientation the anisotropy of the assemblage reflects mainly the scatter of c-axes and is practically independent of  $P'$ . Considering a hemisphere only and assuming a truncated Fisher distribution of c-axis directions about the foliation pole, the precision parameter  $\kappa$  can be estimated directly from the susceptibility anisotropy of the rock, provided  $P'$  is greater than  $\sim 50$ . For example, Hrouda (1980) has shown that typical values of  $A$  for pyrrhotite-bearing rocks in the range  $1.1 < A < 3.5$  correspond to  $1 < \kappa < 7$  and that direct measurements of crystallographic orientations in three pyrrhotitic ores by Bayer and Siemes (1971) yield values of 1.25, 2 and 3 for  $\kappa$ , corresponding to  $A = 1.3, 1.5, 1.85$  respectively.

Although field evidence for alignment of crystallographic a- and b-axes is not as definitive, it may nevertheless account for some features of magnetic fabrics, in particular anisotropy within the foliation plane. It will be shown in a subsequent report that the susceptibility  $k_a$  of MD grains parallel to the magnetic domains is higher than the susceptibility  $k_b$  normal to the



domains, the ratio depending on grain size and magnetic hardness. For fine grains ( $\sim 10\mu\text{m}$ )  $k_a/k_b \approx 1.3$ , but the ratio ranges up to  $\sim 10$  for very coarse grains. Perfect alignment of a-axes with random scatter of c-axes would in principle produce a pure magnetic lineation of intensity  $2 < L < 20$ . Twinning of pyrrhotite grains about the c-axis greatly reduces the potential for operation of this mechanism as grains with equal proportions of each of the three twin members are isotropic in the basal plane. However it is probable that deformation of grains or crystallisation in a stress field leads to preferential growth of favourably oriented twin members.

Textural anisotropy arises from arrangement of strongly magnetic minerals into sheets or lines. The anisotropy is due to self-demagnetisation. In the case of segregation of randomly oriented monoclinic pyrrhotite crystals into thin monomineralic bands separated by non-magnetic layers the magnetic fabric due to textural anisotropy is a pure foliation with  $F = A = 1 + 4\pi\bar{k}$ , where  $\bar{k}$  represents the bulk susceptibility of massive pyrrhotite. As  $\bar{k} < 0.1$  (Kropacek 1971) the maximum anisotropy from this cause is  $A = 2.3$ , but with the more typical values  $0.01 < \bar{k} < 0.05$ ,  $A = 1.1-1.6$ . The rather unrealistic case of fabric due to parallel strings of pyrrhotite grains produces a pure lineation with  $L = A = 1 + 2\pi\bar{k} < 1.6$ .

Anisotropy values greater than  $\sim 2$  obviously require significant crystallographic alignment and cannot be attributed purely to textural anisotropy. Textural anisotropy makes

negligible contribution to the magnetic fabric of disseminated pyrrhotite.

Shape anisotropy is also due to self-demagnetisation and contributes to magnetic fabric via preferred dimensional orientation of grains with high intrinsic susceptibility. Considering the most favourable, albeit unlikely, case of thin platy grains elongated along the c-axis and intrinsically isotropic within the basal plane, the shape anisotropy of the grains is  $1 + 4\pi k_{ab}$ , where  $k_{ab}$  is the intrinsic susceptibility within the basal plane. Thus the maximum possible value of  $P'$  in this case is  $\sim 6.1$ , corresponding to  $k_{ab} = 0.4$ . The anisotropy of an assemblage of such grains is greatly attenuated by scattering of grain dimensional axes.

A slightly more realistic possibility is an assemblage of rod-like or platy grains aligned within the foliation. If the crystallographic axes are uncorrelated with grain shapes, the anisotropy of a well-aligned assemblage of such grains is  $1 + 2\pi\bar{k}$  ( $< 1.6$ ) for rods and  $1 + 4\pi\bar{k}$  ( $< 2.3$ ) for plates. The values of self-demagnetising factors are based on the assumption of uniform magnetisation, which requires domain structure on a sufficiently fine scale relative to grain size.

Uyeda et al. (1963) noted that the maximum susceptibility within the basal planes of two pyrrhotite crystals coincided with the long dimensions of the crystals, and surmised that the anisotropy within the basal planes arose from shape.

However the measured susceptibility values within the basal plane are far too small to account for the observed anisotropy by self-demagnetisation. The basal plane anisotropy must therefore be attributed to coincidence of easy crystallographic axes with the elongations of the crystals.

Strong magnetic foliations are often associated with pyrrhotite and are usually due to clustering of c-axes about the foliation pole. Magnetic lineations within the foliations are also commonly observed and can be produced in a number of ways. Apart from alignment of a-axes or shape anisotropy within the basal plane, lineations may result from the presence of non-parallel foliations.

Consider two foliations of equal intensity  $F = k_1/k_3$  separated by acute angle  $\alpha$ . The resultant fabric is a foliation  $F'$  bisecting the two component foliation planes plus a lineation  $L'$  along the intersection of the planes. It is easily shown that

$$L' = k_1 / [k_1 \cos^2(\alpha/2) + k_3 \sin^2(\alpha/2)]$$

$$(\alpha \leq 90^\circ)$$

$$F' = [k_1 \cos^2(\alpha/2) + k_3 \sin^2(\alpha/2)] / [k_1 \sin^2(\alpha/2) + k_3 \cos^2(\alpha/2)]$$

When the two component foliations are parallel ( $\alpha=0$ )  $L' = 1$  and  $F' = F$ , as expected. The maximum value of  $L'$  occurs when the component foliations are orthogonal ( $\alpha=90^\circ$ ). For this case  $L' = 2k_1/(k_1+k_3)$  and  $F' = 1$ , i.e. the fabric is a pure lineation. This linear parallel fabric is similar to that produced by an assemblage of grains having isotropic

basal planes parallel to a common direction, with c-axes randomly oriented perpendicular to this direction, for which case  $L' = 2$  and  $F' = 1$ .

Magnetic fabric can also be determined by torque meter measurements made in high fields. However the fields easily attainable in the laboratory are insufficient to saturate pyrrhotite and the spontaneous magnetisations of pyrrhotite grains in the specimen remain essentially confined to the basal planes. Porath and Chamalaun (1966) have shown theoretically that torque curves under these conditions are complicated and cannot be simply interpreted in terms of fabric. Their conclusions were supported by experimental measurements on haematite crystals. Therefore the high-field method is not suitable for determination of magnetic fabric in pyrrhotite-bearing rocks.

### 3. PYRRHOTITE AND PETROFABRIC

It is important to ascertain the structural significance of preferred crystallographic and dimensional orientations of pyrrhotite so that magnetic fabric data can be interpreted in terms of geological structure.

Sulphide ores commonly possess pronounced compositional banding. The mineralogical banding of stratiform orebodies is generally interpreted as bedding of syngenetic mineralisation, but fine conformable mineral bands can also be produced epigenetically by lateral flow of metalliferous fluids through permeable sediments (Bubela, 1981) or by post-ore metamorphic segregation. Pyrrhotite-rich layers in ores may exhibit textural anisotropy.

In sulphide ores pyrrhotite grains tend to be flattened in the plane of layering with c-axes perpendicular to the layering (see Ostwald and Lusk (1978) for references). In this case the preferred lattice and dimensional orientations act in concert to produce a pronounced magnetic foliation. A number of specific examples of pyrrhotite fabrics will now be given to illustrate this point.

Ostwald and Lusk (1978) studied 9 samples of nickel sulphide ore from Kambalda, W.A. The deposits consist of regionally metamorphosed massive monoclinic pyrrhotite-pentlandite assemblages occurring in conformable tabular bodies locally displaced by faults. The bodies exhibit mineralogical banding (thin pentlandite-rich bands and massive pyrite lenses) tending to parallel upper and lower contacts of the conformable ore, but which may locally be parallel to the margins of footwall penetrations of massive sulphide, fault planes and surfaces of post-ore intrusives.

The pyrrhotite has responded to metamorphism by developing preferred dimensional and crystallographic orientation with basal planes parallel to the foliation defined by elongation of pentlandite grains and sub-parallel to the layering.

Pyrrhotite grains are of two types: platy and equant. Dimensional ratios of platy grains are 3:1 normal to foliation but the grains are more or less equidimensional within the foliation, with the exception of one sample which exhibits a lineation defined by elongation of pyrrhotite grains within the foliation.

The platy grains exhibit a strong preferred crystallographic orientation which corresponds closely with the dimensional fabric. The angular deviations of long dimensions and basal planes of individual grains from the overall foliation have very similar standard deviations, indicating a close correspondence between the two fabric elements. The equant pyrrhotite grains, which represent a later, post-foliation generation of pyrrhotite, do not display a preferred crystallographic orientation.

There is no evidence of preferred crystallographic orientation within the foliation, although the optical technique employed is rather insensitive and the possibility of a weak anisotropy within the foliation cannot be ruled out.

The results are interpreted as indicating development of pentlandite and pyrrhotite foliations superimposed on, but sub-parallel to, the pre-existing mineralogical layering that generally parallels bedding. The fabric may have resulted from shear deformation or may represent dynamic equilibrium configurations produced by annealing under anisotropic stress conditions accompanying deformation.

Larson (1973) reported optical reflectance and X-ray goniometry measurements on a sample of massive intermediate pyrrhotite from Ducktown, Tennessee. The sample has a distinct planar fabric due to thin parallel bands of silicates. The foliation in the ore is defined by mineralogical banding (silicates/sulphides), sphalerite and chalcopyrite in "stringers" elongated parallel to mesoscopic fabric and rare

brecciated pyrite grains strung out parallel to the layering.

The pyrrhotite grains have attained a distinct preferred dimensional orientation with grain elongation parallel to the silicate laminae. There is also a strong preferred crystallographic orientation of pyrrhotite, with basal planes parallel to the foliation. Within the foliation a preferred orientation of crystallographic a-axes was also observed.

The sample was taken from a fault zone and the texture is interpreted as a sulphide mylonite formed by recrystallisation under stress during plastic deformation accompanying a post-ore, late structural, probably late metamorphic event. The mechanism of plastic deformation was probably slip on basal planes of pyrrhotite grains, with evidence of flow being later obliterated by recrystallisation.

Campbell et al. (1980) described the fabric of massive pyrrhotite, from the Sullivan orebody, British Columbia. The pyrrhotite grain elongation coincides with the mica foliation and the enclosing stratigraphy, probably representing relict bedding. The evidence also favours preferential alignment of pyrrhotite basal planes parallel to bedding.

Bayer and Siemes (1971) also found coincidence of dimensional alignment and basal planes in 4 separate pyrrhotite ores.

These examples suffice to illustrate the general correlation between shape and crystallographic fabrics in pyrrhotitic ores. A number of possible mechanisms could apparently account for generation of these fabrics:

- (i) Rotation of rigid platy grains in response to deformation of the matrix.
- (ii) Production of preferred orientation by plastic deformation of pyrrhotite grains.
- (iii) Crystallisation or recrystallisation in a stress field.
- (iv) Mimetic fabric due to grain growth controlled by pre-existing fabric of other minerals.

Useful discussions of microfabric generation are to be found in the monographs by Hobbs, Means and Williams (1976) and Nicolas and Poirier (1976).

Passive rotation of rigid rods and plates on a deforming matrix has been theoretically treated by Owens (1974) in a generalisation of the well-known March model. "Passive" here implies there is no mechanical interaction between the matrix and the rigid grains. The response of the assemblage to uniaxial compression is to produce preferred alignment of grain elongations normal to the direction of greatest shortening. Experimental results from mica aggregates conform quite well to this model and this mechanism is thought to be important, perhaps dominant, in the formation of slaty cleavage.

If this mechanism is responsible for pyrrhotite fabrics there are important implications for magnetic fabric. Uniaxial compression will produce a foliation defined by grain elongation but the magnetic fabric will depend on the morphology of the grains. If the grains have predominantly platy habit the magnetic foliation corresponds to the grain shape foliation, whereas if the rarer prismatic (rod-like)



habit happens to be dominant the magnetic fabric will consist of a pure lineation directed along the axis of maximum shortening.

However experimental studies (e.g. Clark and Kelly, 1973; Atkinson, 1974) indicate that pyrrhotite is a weak ductile material under practically all conditions in the Earth's crust. Plastic deformation occurs by slip on (0001)  $\langle 11\bar{2}0 \rangle$  (i.e. on the basal plane parallel to the a-axis of the orthorhombic cell), by twinning (probably only above the transition temperature to the 1C superstructure) and by kinking. The evidence suggests that pyrrhotite is markedly plastically anisotropic, being plastically "soft" when compressed at an angle of  $55^\circ$  to the basal plane and plastically "hard" when compressed along the c-axis.

The ductility of pyrrhotite implies that the March model is inapplicable and that pyrrhotite fabrics in metamorphosed ore deposits probably develop through plastic deformation of pyrrhotite grains. Shearing of pyrrhotite grains by slip on the basal plane is an obvious candidate for production of preferred orientation. Hobbs et al., (1976, pp. 122-125) explain very lucidly the effect of compression on an equant grain with slip planes oblique to the compression axis.

The grain is flattened perpendicular to the compression and the slip planes (in pyrrhotite, the basal planes) are rotated towards the resulting foliation. This mechanism explains the platy morphology of pyrrhotite grains in deformed ores and the coincidence of dimensional and crystallographic fabrics.

Amongst the minerals for which development of preferred orientations have been extensively studied, micas provide the closest analogue to pyrrhotite. Other mechanisms for production of preferred orientation in pyrrhotite can therefore be suggested by analogy with micas. Nucleation of grains in a stress field may possess preferred orientation in the foliation, with grains in unfavourable orientations being preferentially dissolved. The orientation of new grains may be controlled by the orientation of pre-existing grains or aggregates. In fact mimetic fabric of pyrrhotite has been described by Fuller (1964) (see next section). During deformation grains with basal planes roughly parallel to the direction of maximum shortening may tend to kink whereas grains which are more steeply inclined rotate, either as rigid or ductile particles. Subsequent recrystallisation would then preferentially consume the kinked grains, which have large strain energy density.

Assessment of the importance of these, or other, mechanisms of fabric development must await further advances in theoretical, experimental and field studies.

#### 4. PREVIOUS MAGNETIC FABRIC STUDIES

Fuller (1963, 1964) investigated the magnetic fabric of pyrrhotite-bearing Welsh slates from a number of localities. Principal susceptibility ratios ranged up to 2: 1.7: 1 but the anisotropy of the more weakly magnetic samples, containing less pyrrhotite, was diluted by the paramagnetic susceptibility of the matrix.

The minor susceptibility axis is due to alignment of c-axes of pyrrhotite grains normal to the cleavage. Within the cleavage-parallel magnetic foliation the maximum susceptibility corresponds to the direction of alignment of the long axes of pyrrhotite grains. The average dimensional ratio of the pyrrhotite grains parallel and normal to the lineation is 1.7: 1. The magnetic lineation may therefore be due to shape anisotropy within the basal plane.

The observed magnetic lineations are clearly related to geological structure, lying parallel to regional fold axes and mesoscopic lineations developed along the intersection of bedding and cleavage planes, although the magnetic lineation itself does not arise from intersection of foliations.

It should be noted that this magnetic fabric pattern agrees well with that found by Fuller (1964) and numerous other workers in magnetite and haematite-bearing slates. The susceptibility ellipsoid axes coincide with the axes of the strain ellipsoid, the magnetic foliation coinciding with the cleavage developed perpendicular to the maximum compression and the magnetic lineation lying along the direction of maximum extension. The stages of development of this deformational fabric are discussed by Graham (1966) and Hrouda (1976).

Fuller (1964) also discussed the magnetic fabric of rocks containing secondary pyrrhotite. In a limestone unit of the Niesen flysch the magnetic foliation due to

pyrrhotite is controlled by an incipient axial plane cleavage. Some slates with secondary pyrrhotite have also developed a cleavage-parallel magnetic foliation. In these cases the magnetic fabric due to pyrrhotite is mimetic and does not reflect deformation directly. The symmetry of the mimetic fabric conforms to the deformational fabric and therefore can be qualitatively interpreted in the same manner. Quantitative empirical or theoretical relationships between deformational fabric and strain cannot be applied to mimetic fabrics, however.

Schwarz (1974) investigated the magnetic fabric of massive sulphides from 4 mines in the Sudbury area and 2 deposits in the Timmins area (Ontario). The generally high anisotropy values indicate magnetocrystalline anisotropy is dominantly responsible for the magnetic fabric, particularly since the anisotropy of the pyrrhotite assemblage is somewhat diluted by the presence of a few per cent magnetite in the samples.

The magnetic fabric varies from deposit to deposit reflecting differing geological settings. For instance, at Strathcona there is a well-defined magnetic foliation sub-parallel to the lower norite contact.

The Falconbridge mine lies within a NE-SW trending fault system and the deposit is cut by a fault. The overall magnetic foliation is parallel to the fault plane and within this foliation there is a bimodal distribution of magnetic lineations  $\sim 90^\circ$  apart. This implies interchange between major and intermediate susceptibility axes within the foliation

for different samples. There is also evidence of interchange of intermediate and minor axes in a few cases. This pattern strongly suggests partial overprinting of fabrics, with variation of the degree of overprinting through the deposit. For an initially orthorhombic fabric, interchange of susceptibility axes during the course of continuing coaxial strain is well documented by Graham (1966) and Owens (1974).

The Copper Cliff North and Little Stobie deposits exhibit an essentially uniaxial fabric with prolate susceptibility ellipsoids. The magnetic lineations are sub-vertical, with minor and intermediate axes randomly oriented in the horizontal plane. These examples illustrate the principle that the form of the fabric is not controlled by the form of the grain anisotropy (which is oblate), but by the symmetry of the forces producing the fabric - with the constraint that the resulting symmetry must be consistent with the grain anisotropy. It is suggested that the fabric of these deposits reflects small-scale folding about vertical axes.

The magnetic fabric at Alexo consists of a sub-vertical NE-SW foliation roughly parallel to the country rock contacts, containing a sub-horizontal lineation parallel to the regional axis of folding.

These examples serve to establish the potential of magnetic fabric studies for elucidating geological structure, particularly as part of integrated investigations. However much work remains to be done before interpretation of magnetic fabric data from pyrrhotite-bearing rocks can be placed on a firm footing, particularly with regard to quantitative interpretation.

## 5. MAGNETIC FABRIC OF SOME PYRRHOTITE-BEARING ROCKS

The magnetic fabric of pyrrhotite ore from the Cleveland Tin Mine was studied as part of a general petrophysical investigation (see Clark, 1983 for discussion of the palaeomagnetism of this body).

The ore samples generally have quite high susceptibility anisotropy as evidenced by the data presented in Tables 1 and 2 for 24 Level (18 samples) and 20 Level (4 samples) respectively. Furthermore the magnetic fabric is consistent from specimen to specimen within a sample and there is definite evidence of overall preferred orientation of magnetic minerals.

Low-field thermomagnetic analysis of a Cleveland ore sample reveals the presence of only a single magnetic mineral - monoclinic pyrrhotite with an apparent Curie temperature of 320°C. Therefore the magnetic fabric arises either from preferred crystallographic orientation of pyrrhotite or from textural anisotropy due to compositional banding. In Table 3 the magnetic lineation directions and foliation poles are given. The samples from 24 Level exhibit a very consistent fabric with well-grouped foliation poles plunging shallowly to the SE (Fig. 2). The lineations are randomly dispersed within the corresponding foliation plane, which strikes NE and dips steeply to the NW. Consistent with this planar parallel fabric, the susceptibility ellipsoids of individual samples are predominantly oblate ( $P < 1$ ).

X-ray goniometry work on a few ore samples from the mine is described by Falvey (1966) and the results indicate preferred alignment of pyrrhotite c-axes in close agreement with the mean magnetic foliation pole shown in Fig. 2. Thus the magnetic fabric is probably due to crystallographic alignment of pyrrhotite.

The magnetic foliation is approximately parallel both to the bedding and to the sub-parallel cleavage in the wall rocks. The origin of the fabric is not certain, but strong field evidence of a post-deformational epigenetic origin for the mineralisation (Collins, 1981) implies that the magnetic fabric is mimetic.

By contrast, the 4 samples from 20 Level have prolate susceptibility ellipsoids and randomly scattered foliation poles. The overall lineation appears to plunge shallowly to the NNW, roughly parallel to the trend of regional and local faulting. The reason for the difference between the fabrics found at 24 Level and 20 Level is not clear, but may be related to relative proximity to a fold hinge or to a fault with consequent variation of the strain ellipsoid.

During the course of a petrophysical study of the Mt. Isa area, 5 block samples of pyrrhotite-bearing Urquhart Shale were collected from 13 Level of the Isa mine. The mineralisation consists of a semi-massive pyrite-monoclinic pyrrhotite-galena-sphalerite assemblage in dolomitic shale of Mid-Proterozoic age. A large collection of metabasalts and shales from the mine and nearby localities was also made,

allowing comparison of the magnetic fabrics of the different lithologies (pyrrhotite-bearing Urquhart Shale, magnetite-bearing Eastern Creek Volcanics and magnetite-bearing Magazine Shale).

The Urquhart Shale samples possess pronounced susceptibility anisotropy ( $\bar{A}=1.4$ ) with triaxial susceptibility ellipsoids ( $P \sim 1$ ). The magnetic foliation plane dips steeply to the west parallel to bedding and to the nearby major Mt. Isa Fault. The magnetic lineation plunges steeply to the NW parallel to regional fold axis plunges.

The site mean magnetic foliation poles and lineations for the Urquhart Shale, Eastern Creek Volcanics and Magazine Shale are plotted in Fig. 3. The consistency of magnetic foliations for all sites is apparent. In most cases magnetic lineations within each site are well-grouped but overall the site mean magnetic lineations are rather scattered within the foliation plane with a slight preference for steep plunges.

The magnetic fabric of samples of C.S.A. Siltstone from Magnetic Ridge, near Cobar, has also been determined. These samples contain disseminated pyrrhotite and thermomagnetic analysis reveals monoclinic pyrrhotite as the only magnetic mineral present in detectable quantity. The palaeomagnetism of these samples is discussed in Clark (1983).

Susceptibility axis directions from 31 specimens cut from 7 oriented samples were well-grouped. The minor and major axis directions from all specimens are plotted in



Fig. 4. The anisotropy is high ( $\bar{A} = 1.45 \pm 0.02$ ) indicating distinct preferred crystallographic orientation of the pyrrhotite grains. Large (up to 2mm) grains visible in hand samples are elongated within the magnetic foliation and the incipient cleavage, but are slightly oblique to bedding.

The mean magnetic foliation pole is  $\text{dec} = 286^\circ$ ,  $\text{inc} = +12^\circ$  ( $\alpha_{95} = 4^\circ$ ) and the mean magnetic lineation direction is  $\text{dec} = 46^\circ$ ,  $\text{inc} = +68^\circ$  ( $\alpha_{95} = 4^\circ$ ). The  $\alpha_{95}$  values are cited as indicators of the high precision of the data but cannot be taken too literally, as it is clear from Fig. 4 that the scatter of directions is non-Fisherian.

The magnetic foliation plane therefore strikes slightly east of north, dipping  $78^\circ$  to the west. This is approximately parallel to the regional cleavage but oblique to the bedding which dips steeply east. Regional fold axes are subhorizontal and tend N-S. The simplest interpretation of the magnetic fabric is that it is deformational with susceptibility ellipsoid axes parallel to the strain ellipsoid axes. The magnetic foliation represents an analogue of cleavage perpendicular to maximum compression and the magnetic lineation lies along the axis of maximum extension, as found by Fuller (1964) for slates.

## 6. CONCLUSIONS

- (i) Monoclinic pyrrhotite has very high intrinsic anisotropy, with high susceptibility in the basal plane and very low susceptibility along the c-axis. Thus a slight tendency for preferred orientation of c-axes of monoclinic pyrrhotite produces substantial susceptibility anisotropy. Magnetic fabric of monoclinic pyrrhotite is therefore a sensitive indicator of petrofabric.
- (ii) Magnetic fabric in pyrrhotite-bearing rocks predominantly reflects preferred crystallographic orientation. The magnetic foliation corresponds to the preferred direction of c-axes, the magnetic foliation plane coinciding with the preferred orientation of basal planes. Textural anisotropy may sometimes contribute to the magnetic fabric of massive pyrrhotitic ores. Magnetic lineations within the foliation may arise from shape anisotropy of inequidimensional monoclinic pyrrhotite grains, preferred orientation of crystallographic a-axes within the foliation, or from the presence of non-parallel foliations.
- (iii) In sulphide ores pyrrhotite grains tend to be flattened in the plane of layering with c-axes perpendicular to the layering. In this case the preferred lattice and dimensional orientations act in concert to produce a pronounced magnetic foliation parallel to the mineralogical layering and foliation of silicate minerals. The correspondence between crystallographic and shape fabrics of pyrrhotite reflects the predominantly platy habit of

the mineral. The evidence suggests that pyrrhotite fabrics in metamorphosed ore deposits develop through plastic deformation of pyrrhotite grains whereby slip along basal planes leads to flattening of the grains perpendicular to the compression and rotation of the basal planes towards the resulting foliation.

- (iv) The magnetic fabric due to disseminated pyrrhotite in metasediments is generally found to reflect the deformation of the rocks. The magnetic foliation is parallel to the cleavage and the magnetic lineation lies along the direction of maximum extension. This relationship is also consistent with magnetic fabric exhibited by magnetite and haematite-bearing rocks. In some cases the magnetic fabric may be mimetic.
- (v) Numerous examples of correlation between geological structure and pyrrhotite fabric have been cited. In some cases magnetic anisotropy reveals fabric elements (particularly magnetic lineations) which are not otherwise apparent. Overall magnetic fabric studies of pyrrhotite-bearing rocks have great utility as an aid to structural interpretation.

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TABLE 1 SUSCEPTIBILITY ANISOTROPY PARAMETERS (24 LEVEL, B LENS)

Sample	N	Anisotropy	Lineation	Foliation	Prolateness
1*	8	1.09	1.03	1.06	0.97
2	3	1.21	1.06	1.14	0.94
3	9	1.56	1.13	1.37	0.86
4	16	1.31	1.09	1.22	0.90
5	8	1.29	1.06	1.21	0.89
6	6	1.13	1.05	1.08	0.98
7	4	1.18	1.08	1.10	0.98
8	5	1.41	1.11	1.26	0.90
9	24	1.29	1.11	1.16	0.97
10	18	1.21	1.17	1.04	1.13
11	25	1.24	1.07	1.15	0.94
12	7	1.11	1.07	1.05	1.02
13	23	1.38	1.15	1.20	0.97
14	7	1.29	1.11	1.16	0.98
15	4	1.37	1.11	1.25	0.89
16	14	1.31	1.07	1.21	0.90
17*	6	1.08	1.04	1.04	1.00
18	8	1.47	1.09	1.35	0.86
19	7	1.28	1.08	1.18	0.93
20	22	1.55	1.10	1.39	0.91

\*barren shale samples

Ore samples (N = 18):  $\bar{A} = 1.31 \pm 0.03$  (SD = 0.13)  
 $\bar{L} = 1.10 \pm 0.01$  (SD = 0.03)  
 $\bar{F} = 1.20 \pm 0.02$  (SD = 0.10)  
 $\bar{P} = 0.94 \pm 0.02$  (SD = 0.07)

TABLE 2 SUSCEPTIBILITY ANISOTROPY PARAMETERS (20 LEVEL, B LENS)

Sample	N	Anisotropy	Lineation	Foliation	Prolateness
1	4	1.74	1.33	1.29	1.02
2	4	1.39	1.11	1.26	0.93
3	2	1.28	1.17	1.09	1.07
4	5	1.45	1.28	1.14	1.13

$$\bar{A} = 1.47 \pm 0.10 \quad (\text{SD} = 0.20)$$

$$\bar{L} = 1.22 \pm 0.05 \quad (\text{SD} = 1.10)$$

$$\bar{F} = 1.20 \pm 0.05 \quad (\text{SD} = 0.10)$$

$$\bar{P} = 1.04 \pm 0.04 \quad (\text{SD} = 0.08)$$



TABLE 3 MAGNETIC FABRIC OF CLEVELAND MINE SAMPLES

24 Level, B Lens

Sample	Lineation	Foliation Pole	Remarks
	( $\alpha_{95}$ )	( $\alpha_{95}$ )	
1	( $20^{\circ}$ , $+78^{\circ}$ ) ( $12^{\circ}$ )	( $149^{\circ}$ , $+7^{\circ}$ ) ( $9^{\circ}$ )	
2	( $55^{\circ}$ , $+56^{\circ}$ ) ( $39^{\circ}$ )	( $185^{\circ}$ , $+22^{\circ}$ ) ( $23^{\circ}$ )	
3	-	-	No distinct fabric
4	-	( $158^{\circ}$ , $+14^{\circ}$ ) ( $9^{\circ}$ )	Maximum susceptibility axes dispersed about girdle
5	( $76^{\circ}$ , $-17^{\circ}$ ) ( $15^{\circ}$ )	( $164^{\circ}$ , $+7^{\circ}$ ) ( $23^{\circ}$ )	
6	( $59^{\circ}$ , $-12^{\circ}$ ) ( $14^{\circ}$ )	( $135^{\circ}$ , $+47^{\circ}$ ) ( $17^{\circ}$ )	
7	-	-	No distinct fabric
8	-	( $158^{\circ}$ , $-43^{\circ}$ ) ( $40^{\circ}$ )	Maximum susceptibility axes dispersed about girdle
9	( $18^{\circ}$ , $0^{\circ}$ ) ( $9^{\circ}$ )	( $108^{\circ}$ , $+11^{\circ}$ ) ( $10^{\circ}$ )	
10	( $42^{\circ}$ , $-14^{\circ}$ ) ( $6^{\circ}$ )	( $141^{\circ}$ , $-1^{\circ}$ ) ( $13^{\circ}$ )	
11	( $91^{\circ}$ , $-57^{\circ}$ ) ( $11^{\circ}$ )	-	Minimum susceptibility axes either NE or SE with shallow dips
12	( $38^{\circ}$ , $+20^{\circ}$ ) ( $29^{\circ}$ )	( $144^{\circ}$ , $+20^{\circ}$ ) ( $32^{\circ}$ )	
13	( $43^{\circ}$ , $-18^{\circ}$ ) ( $11^{\circ}$ )	( $135^{\circ}$ , $+5^{\circ}$ ) ( $11^{\circ}$ )	
14	-	( $63^{\circ}$ , $+12^{\circ}$ ) ( $30^{\circ}$ )	Maximum susceptibility axes dispersed about girdle
15	-	( $109^{\circ}$ , $+19^{\circ}$ ) ( $19^{\circ}$ )	Maximum susceptibility axes dispersed about girdle
16	( $116^{\circ}$ , $-19^{\circ}$ ) ( $21^{\circ}$ )	( $112^{\circ}$ , $+70^{\circ}$ ) ( $15^{\circ}$ )	
17	( $66^{\circ}$ , $-32^{\circ}$ ) ( $24^{\circ}$ )	( $149^{\circ}$ , $+2^{\circ}$ ) ( $24^{\circ}$ )	
18	-	( $121^{\circ}$ , $-8^{\circ}$ ) ( $25^{\circ}$ )	Maximum susceptibility axes dispersed about girdle

TABLE 3 continued

Sample	Lineation	Foliation Pole	Remarks
19	(332°, +61°) (32°)	(157°, +25°) (40°)	
20	(46°, -12°) (18°)	(125°, +16°) (17°)	
20 Level, B Lens			
1	(321°, +49°) (17°)	-	Minimum susceptibility axes dispersed about girdle
2	(302°, +43°) (29°)	-	Minimum susceptibility axes dispersed about girdle
3	(323°, +7°) (27°)	-	Minimum susceptibility axes dispersed about girdle
4	(19°, -3°) (41°)	-	Minimum susceptibility axes dispersed about girdle

24 Level: Mean foliation pole (141°, +14°),  $\alpha_{95} = 15^\circ$

N = 16, K = 7.0

Directions are quoted in the form (declination, inclination) with declination measured positive clockwise from north, and inclination defined as positive downwards.

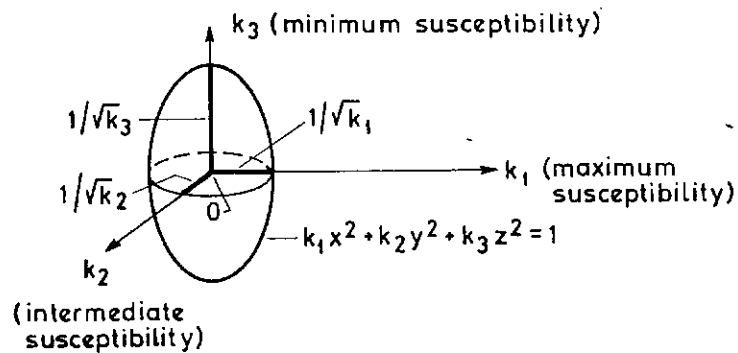
$\alpha_{95}$  is the radius of the error circle about the mean direction, at the 95% confidence level.

Fig. 1. Definitions of the representation ellipsoid of the susceptibility tensor and the susceptibility ellipsoid (magnetic fabric ellipsoid).

# SUSCEPTIBILITY ANISOTROPY

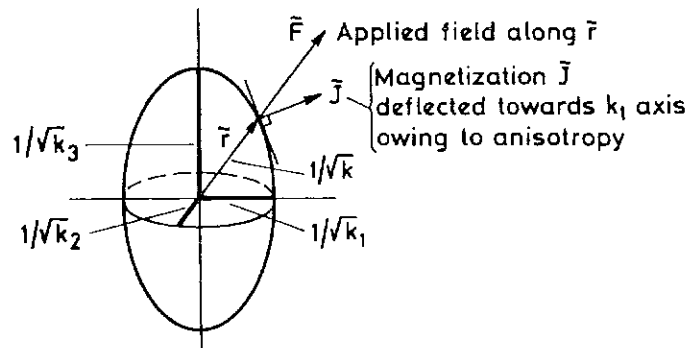
REPRESENTATION ELLIPSOID:  $k_1 x^2 + k_2 y^2 + k_3 z^2 = 1$

## DEFINITION



Bulk susceptibility  $\bar{k} = (k_1 + k_2 + k_3) / 3$

## DEFLECTION OF MAGNETIZATION

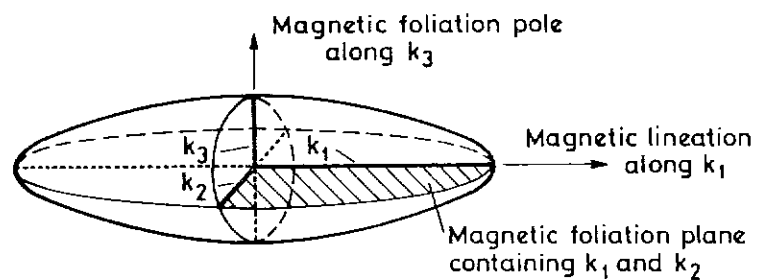


$k(\vec{r}) = k_1 l^2 + k_2 m^2 + k_3 n^2 = 1 / r^2$

$l, m, n =$  direction cosines of  $\vec{r}$

## SUSCEPTIBILITY ELLIPSOID: MAGNETIC FABRIC

(not to be confused with representation ellipsoid)



Anisotropy Magnitude  $A = k_1 / k_3$

Lineation Magnitude  $L = k_1 / k_2$

Foliation Magnitude  $F = k_2 / k_3$

Ellipsoid Prolateness  $P = L / F$

$\left\{ \begin{array}{l} P = 0 \text{ uniaxial oblate} \\ \text{ellipsoid (disc)} \\ P = \infty \text{ uniaxial prolate} \\ \text{ellipsoid (needle)} \end{array} \right.$

FIG. 1

Fig. 2. Magnetic fabric of the Cleveland orebody. Magnetic foliation poles and lineations plotted are sample mean directions from 24 Level. Equal area lower hemisphere projection. The primitive represents the present horizontal.



Fig. 3. Magnetic fabric of rocks from the Mt. Isa area. Circles represent site mean minor susceptibility axes (magnetic foliation poles), squares site mean major axes (magnetic lineations). The lithologies represented are the pyrrhotite-bearing Urquhart Shale (US), the magnetite-bearing Magazine Shale (MS) and magnetite-bearing metabasalts of the Eastern Creek Volcanics (unlabelled). The mean foliation pole is indicated by the asterisk and the corresponding foliation plane is shown as the dashed great circle arc. Note the agreement between magnetic foliations of the magnetite- and pyrrhotite-bearing rocks. Stereographic lower hemisphere projection. The primitive represents the present horizontal.

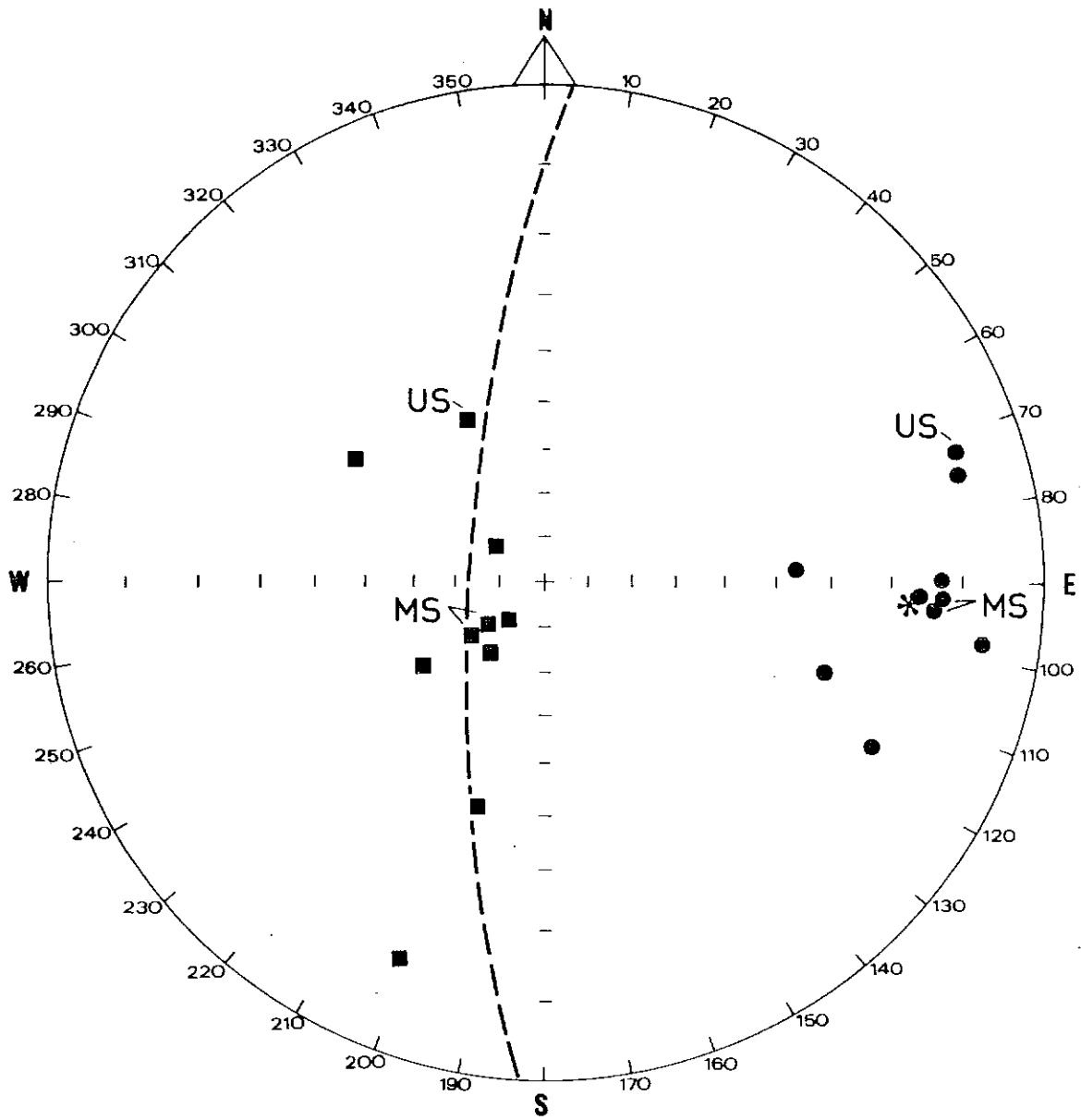


FIG. 3



Fig. 4. Magnetic fabric of Magnetic Ridge samples. Circles represent magnetic foliation poles (minor susceptibility axes) and squares represent magnetic lineations (major susceptibility axes) of individual specimens. Equal area lower hemisphere projection. The primitive represents the present horizontal.

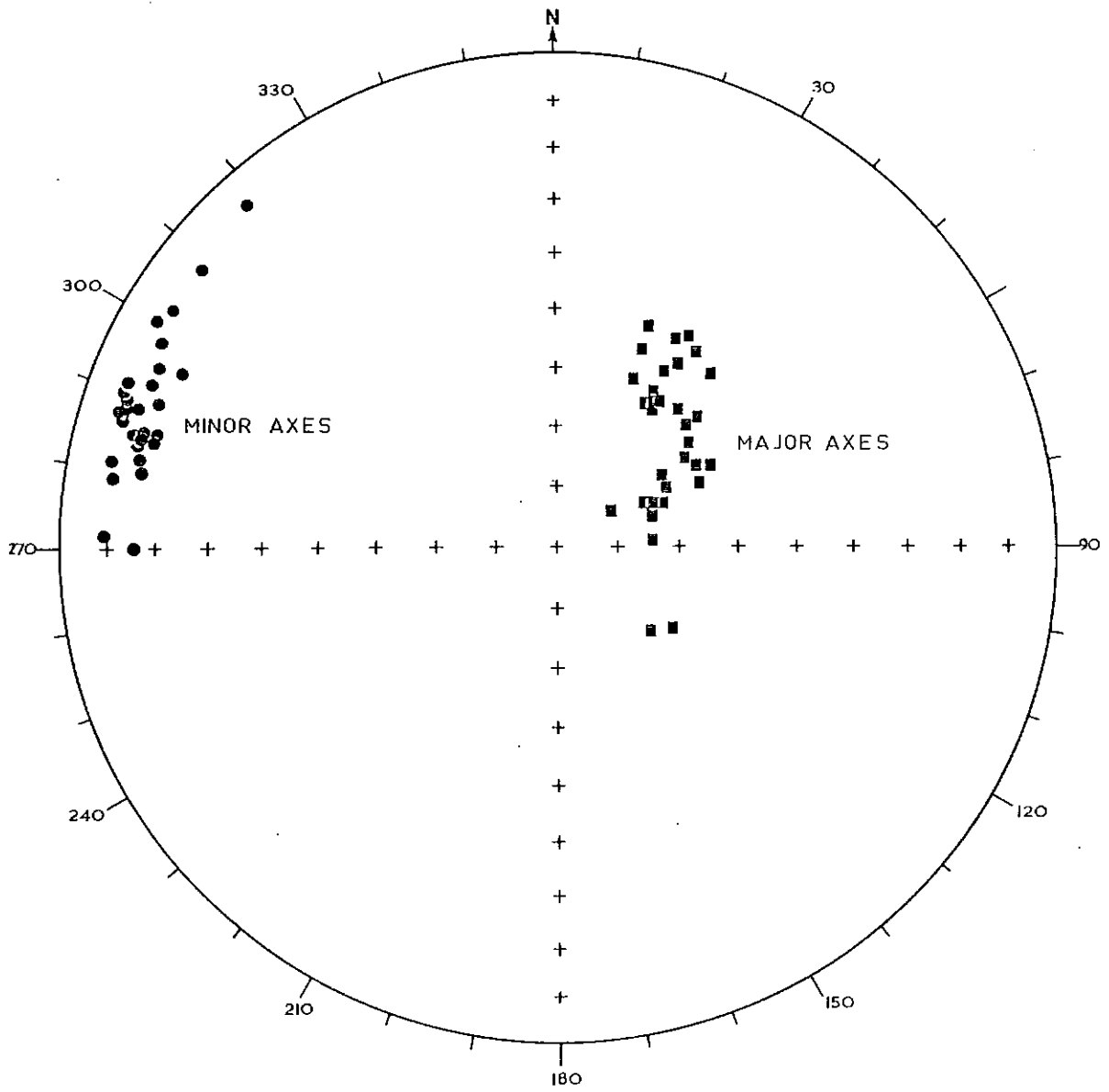


FIG. 4