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APPLICATIONS OF ROCK MAGNETISM TO
MINERAL EXPLORATION

D.A. CLARK and B.J.J. EMBLETON

CSIRO Division of Mineral Physics
PO Box 136
North Ryde, NSW
AUSTRALIA 2113

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1. INTRODUCTION

It is generally recognised that magnetic remanence, as well as bulk susceptibility and susceptibility anisotropy, can significantly influence magnetic response. With this in mind collaboration was sought with mineral exploration companies through the AMIRA interface, to establish a research programme to assess the role of magnetic remanence in the interpretation of magnetic surveys. Of necessity many of the conclusions regarding specific exploration areas must remain confidential for a specified period, however a large amount of information has been collected as a direct result of company collaboration. This report describes results of general interest and application, and provides a brief outline of concepts and techniques commonly employed in rock magnetic and palaeomagnetic studies.

Magnetic interpretation is afflicted by ambiguity and in general many subsurface configurations of sources could account for observed anomalies. Therefore input from measurements of magnetic properties can guide and constrain interpretation, greatly reducing the ambiguity inherent in the method. A good example of non-uniqueness in interpretation is afforded by the commonly applied 2D thin-sheet model, representing a dyke or vein. The dip of the thin-sheet is indeterminate from modelling if the direction of magnetisation is unknown. However if the inclination of the magnetisation component normal to the strike is known, the dip is determined. In addition, knowledge of the magnitude of magnetisation allows estimation of the thickness of the sheet. This illustrates a general principle that several geologically plausible models may account for the observed magnetics and that knowledge of magnetic parameters may discriminate between them.

Reconnaissance sampling of rocks from a particular area provides information on which lithologies are likely sources of magnetic anomalies and enables better correlation of geology with observed magnetic signatures. In addition, knowledge of likely magnetisation directions and magnitudes can improve modelling of buried magnetic sources.

Input from magnetic measurements is also valuable when a drill-hole has been targeted on a modelled magnetic source. It is important to ascertain whether or not the intersected material accounts for the anomaly. The results may show, for instance, that disseminated magnetite in barren rock explains the anomaly and that further drilling is not justified. Alternatively the results may suggest the target has been missed altogether, or the intersected body only partly accounts for the anomaly. This would encourage drilling to locate a discrete nearby source, which could be an ore body.

In the course of this project a number of other applications and potential applications of rock magnetism to the minerals industry have been suggested. These include:

- (i) Palaeomagnetic dating of mineralisation
- (ii) Magnetostratigraphy as a tool for geological correlation
- (iii) Magnetic fabric studies for structural interpretation (see section 4)
- (iv) Magnetic property measurements as input to magnetic survey design. As a simple illustration, in an area where a banded quartz magnetite formation is a marker bed which can be traced by ground magnetometry, we demonstrated that a fluxgate magnetometer is essential as the remanent magnetisation is so intense anomalies comparable to, or even greater than, the Earth's field are expected, making total field measurements almost meaningless.
- (v) Investigation of possible spurious components of magnetisation produced by drilling in massive ores (see section 5).
- (vi) Investigation of the relationship between magnetic properties of surface samples and fresh rock (see section 6).
- (vii) Study of magnetic viscosity of superparamagnetic material in overburden, and its effect on TEM response (see section 7).
- (viii) Redox chemical remanence as an indicator of sulphides beneath volcanics.

(ix) Magnetic mineralogy - analysis of composition and structure of magnetic minerals in rocks by magnetic methods. This would aid understanding of the relationship between geology and magnetic response in a given area. Although magnetic minerals do not figure in lithological classification schemes, significant geological information can often be gleaned from a knowledge of the magnetic mineralogy, such as tectonic setting of igneous rocks, palaeoenvironments of sedimentary rocks, geothermometry, correlation of subtle lithological variations within formations, and zoning in ore bodies. Analysis of magnetic minerals may also have applications in the handling and treatment of minerals. For instance the efficacy of magnetite used in coal washeries is very dependent on grain structure and composition, which are reflected in the magnetic properties. Pyrrhotite creates problems for storage and treatment of sulphide ores because of spontaneous combustibility and deleterious effects on flotability. Different varieties of pyrrhotite have markedly different metallurgical responses, and magnetic methods of analysis could potentially guide ore treatment.

2. MAGNETISM IN ROCKS

2.1 Types of Magnetisation

All rocks bear a spontaneous magnetisation the intensity of which varies considerably from one rock type to another. There are three main classes of magnetisation used to describe the magnetism in rocks (i) thermoremanent magnetisation (TRM), (ii) chemical remanent magnetisation (CRM), (iii) depositional remanent magnetisation (DRM).

Thermoremanent Magnetisation

The magnetisation acquired by a rock when it cools from the Curie point to room temperature is called the total TRM. A spontaneous magnetisation appears at the Curie point T_c , and assumes an equilibrium state in the presence of an applied field. Iron oxide grains with different volumes v and structures will each have different blocking temperatures T_B and as the temperature is lowered from T_c and passes through T_B , the relaxation time τ of each of the grains increases rapidly. Below T_B the magnetisation is 'blocked' or 'frozen in'. Field changes that may occur below T_B do not affect the direction of magnetisation. Since a range of grain sizes and structures will exhibit a spectrum of blocking temperatures, the total TRM may not be acquired until cooling to room temperature. The fraction of TRM acquired in a given temperature interval is called the partial TRM. Thus on reheating to a temperature $T < T_c$, the original magnetisation of the grains with $T_B \leq T$ will be destroyed. This property of TRM is important in relation to magnetic stability and forms the basis for the thermal demagnetisation (cleaning) technique.

Chemical Remanent Magnetisation

CRM is acquired at low temperatures, e.g. ambient temperatures in a depositional environment, by a process of grain-growth, i.e. nucleation. This may occur during the oxidation of magnetite to haematite, titanomagnetite to titanohaematite or titanomagaemite. CRM in red-beds is considered to be acquired through the dehydration of iron oxyhydroxide following $2\text{FeOOH} \rightarrow \text{Fe}_2\text{O}_3 + \text{H}_2\text{O}$ and the subsequent growth of haematite grains. During the early stages of diagenesis grains are sufficiently

small that their relaxation times are short and exhibit superparamagnetism. This may be considered the analogue of spontaneous magnetisation acquired by an igneous rock between T_c and T_B . As grain growth proceeds, the critical volume v_B is exceeded and the relaxation time of the spontaneous magnetisation undergoes rapid increase. The equilibrium magnetisation is thus 'frozen in' and as with TRM, subsequent field direction changes will not affect the directional stability of the CRM.

The magnetic characteristics of CRM are similar to those of TRM and experimental work has confirmed that the intensity of both is proportional to the applied field (for small fields, e.g. <1 oe).

Depositional Remanent Magnetisation

DRM describes the alignment of magnetic particles under the influence of an applied field, e.g. as the grains fall through water. Alignment during sedimentation is termed DRM whereas the rotation of the grains into the field direction in the water-filled interstices of a wet sediment undergoing compaction and consolidation is called post-depositional remanent magnetisation.

2.2 Stability of Magnetisation

Laboratory testing of the stability of magnetisation is carried out using thermal and alternating field techniques. The basis for thermal cleaning has been discussed above and relies on investigating the spectrum of blocking temperatures T_B . Alternating field (AF) demagnetisation or 'magnetic cleaning' investigates the coercive force spectrum of the magnetic grains. If a rock specimen is placed in an alternating field with a peak value H , all magnetic domains with coercive forces $< H \cos \theta$ (θ is the angle between the domain coercive force and H) will follow the field as it alternates. As the alternating field is progressively decreased those domains with progressively lower coercive forces will be randomised. Low coercive force is equated with short relaxation time. Thus, if a rock can withstand high alternating fields, this demonstrates that those grains possess long relaxation times capable of retaining their magnetisation for considerable periods of time.

2.3 The Axial Geocentric Dipole Field

In order to analyse and compare palaeomagnetic results from different localities spaced over one continent and from different continents we require a field model that describes the long-term average behaviour of the geomagnetic field. The model used is called the axial geocentric dipole field. It is known from palaeomagnetic measurements that for the past few million years, the earth's magnetic field, when averaged over about 10^4 years, has conformed to this model. The average earth's field is represented by a geocentric dipole directed along the rotation axis. The geomagnetic and geographic axes coincide. The geomagnetic and geographic latitudes also coincide as do the two equators. Therefore, by definition the declination = 0° and the magnetic inclination is related to latitude according to the expression $\tan I = 2 \tan \lambda$, I = inclination, λ = latitude. This relationship is very important in palaeomagnetism, stating simply that the palaeolatitude can be calculated from a knowledge of the inclination of magnetisation acquired by a rock unit when it was formed.

In order to compare palaeomagnetic results from widely separated localities, we require to calculate a parameter which is independent of the value of the magnetic field at the sampling locality. The parameter used is the palaeomagnetic pole. By definition it is a time-averaged result and represents the point where the dipole axis intersects the surface of the earth. The magnetic poles are the points of the earth's surface where the magnetic inclination is observed to be $\pm 90^\circ$. The geomagnetic poles are the points of intersection with the earth's surface of the axis of the calculated best fitting dipole. A virtual geomagnetic pole (VGP) represents the position of the geomagnetic pole calculated from a spot reading of the palaeomagnetic field, e.g. from the direction measured in a single lava flow. A VGP is an instantaneous pole.

3. SINGLE DOMAINS, MULTIDOMAINS AND SUPERPARAMAGNETISM

All substances exhibit a magnetic susceptibility, which is negative for diamagnetic materials and positive for paramagnetic materials. Ferro- and ferrimagnetic substances are distinguished by large susceptibilities, many orders of magnitude greater than the values typical of normal paramagnetics ($k_{\text{emu}} \sim 10^{-6}$); by the existence of a spontaneous magnetisation; and by hysteresis, or irreversibility of magnetisation.

The spontaneous magnetisation, which arises from the tendency for alignment of atomic magnetic moments, is a function of temperature and disappears at the Curie point. In spite of the existence of a spontaneous magnetisation, a ferromagnetic specimen may have zero magnetic moment in the absence of an applied field if, for example, it has been cooled in a field-free space from above its Curie temperature. If a large magnetic field is then applied and subsequently removed, the specimen will exhibit a remanent magnetisation. Therefore there are at least two states corresponding to $H = 0$.

The explanation of these phenomena lies in the presence of domains each of which is spontaneously magnetised, but which do not necessarily have parallel directions of magnetisation. Non-parallel domain magnetisations reduce the magnetostatic energy associated with free poles at the surface of the magnetic grain. The actual domain configuration of the material is that which minimises the total energy associated with the interactions affecting alignment of atomic moments (exchange energy, magnetocrystalline energy, magnetostatic energy and magnetoelastic energy).

To facilitate discussion of domain structures it is necessary to define the parameters characterising the hysteresis of a ferromagnetic specimen.

Saturation magnetisation J_s - the asymptotic magnetisation of the specimen as the applied field increases to large values.

Saturation remanence J_{rs} - the residual magnetisation following removal of the applied field after the specimen has been saturated.

Coercive force H_c - the back-field which reduces the magnetisation to zero after saturation of the specimen.

Coercivity of remanence, or DC demagnetising field, H_{cr} - the back-field upon removal of which an originally saturated specimen returns to the demagnetised state.

Initial susceptibility k_o - the slope at the origin of the M-H curve for an initially demagnetised specimen.

A large crystal consists of many domains in order to minimise magnetostatic energy. As the dimensions of the magnetic grain decrease, the domain wall energy, which is a surface energy, dominates the magnetostatic (volume) energy, and it becomes energetically favourable to eliminate domain walls altogether. Thus the whole particle is a single domain. The maximum diameter of a spherical ferromagnetic particle for which a single domain structure is possible is known as the critical single domain size.

Clearly the magnetostatic energy of an elongated particle (a prolate spheroid, for instance) magnetised along its major axis will be less than that of a spherical particle of the same volume. Thus single domain (SD) particles of greater than the critical size can exist provided they are elongated.

In the absence of other effects the minimum energy state of a prolate SD grain corresponds to spontaneous magnetisation directed along the major axis. Deflection of the magnetisation away from the axis increases the magnetostatic energy. The maximum energy difference associated with rotation of the magnetisation from the easy direction is known as shape anisotropy energy, K_s . In small particles of magnetite, shape anisotropy controls the hysteresis properties. The coercive force of a randomly oriented assembly of elongated grains with shape anisotropy is given by

$$H_c = 0.96 K_s / J_s \quad (1)$$

Because ferromagnetic materials are crystalline their properties are directionally dependent. The spontaneous magnetisation tends to lie along certain crystallographic axes. For instance at room temperature the easy directions of magnetisation for spherical magnetite grains are the $[1, 1, 1]$ axes, whereas for haematite and pyrrhotite the magnetisation is confined to the basal planes by a strong magnetocrystalline anisotropy. A weaker basal plane anisotropy controls the hysteresis properties of the latter two minerals.

The above discussion of single domain particles neglects the effects of thermal fluctuations. If the SD grain is sufficiently small or the temperature sufficiently high, thermal agitation can cause the magnetisation direction to flip between stable positions. If an assembly of such particles reaches thermal equilibrium in a time short compared with the duration of an experiment, the particles are said to exhibit superparamagnetism. Superparamagnetic behaviour may be characterised by a relaxation time τ which is a function of the energy barrier between stable states ($E = KV$, where K is the anisotropy constant and V the particle volume) and the temperature

$$\tau = (1/f_0) \exp(KV/kT) \quad (2)$$

where $f_0 \sim 10^9 \text{ s}^{-1}$ and k is Boltzmann's constant.

Because of the exponential dependence τ changes very rapidly with V and thus for a particular temperature there is a well-defined critical volume below which $\tau \ll t$ and above which $\tau \gg t$, where t is a typical laboratory measurement time. Conversely, for a particular volume there is a critical temperature, known as the blocking temperature T_B , below which the particle is a stable SD grain and above which it is superparamagnetic, with high susceptibility but incapable of retaining a stable remanence.

These ideas may also be expressed in terms of coercive force. Stable single domains resist rotation of the magnetisation away from the easy directions and thus exhibit high coercive force and low susceptibility. The effective coercive force is dependent on temperature, however, and

may be expressed as the difference between the intrinsic coercivity of the grain (a function of the anisotropy energy and saturation magnetisation) and a thermal fluctuation term. As the temperature rises, the thermal fluctuation "field" increases until the blocking temperature is reached, when it cancels the intrinsic coercivity, the effective coercive force goes to zero and the susceptibility increases sharply due to the disappearance of energy barriers opposing alignment of the particle moments with an applied field.

In multidomain grains the dominant response to an applied field is domain wall movement rather than rotation of the magnetisation. The domains with magnetisation more or less parallel with the applied field grow at the expense of those aligned antiparallel to the field. Because the energy barriers opposing domain wall movement are relatively small multidomain grains have lower coercive force and higher intrinsic susceptibility than stable SD grains.

The hysteresis characteristics of SPM, SD and MD magnetite grains are summarised in Table 1.

Small multidomains (for instance particles smaller than 20 microns in magnetite) exhibit some single domain properties. These pseudo-single domain (PSD) particles have stronger thermoremanence than large multidomains, the Koenigsberger ratio having values greater than the range applicable to true multidomains ($0.2 \leq Q_{\text{TRM}} \leq 1.0$).

Single domain magnetite has $Q_{\text{TRM}} > 1$, a typical range of values is $5 < Q_{\text{TRM}} < 50$. Minerals with high magnetocrystalline anisotropy such as haematite and pyrrhotite can exhibit much higher Koenigsberger ratios, as large as 200-500. This means that haematite bearing rocks can bear a relatively strong remanence in spite of their low susceptibility. The effect is most prominent for very fine-grained haematite. Consider grains which have grown just larger than the critical blocking volume in an ambient field of 0.5 Oersteds. They acquire a chemical remanent magnetisation (CRM) given by $J_{\text{CRM}} \approx 0.04H$ (M.W. McElhinny,

1973, p. 61). Then a rock containing 10% of these grains by volume will bear a remanence of 2000×10^{-6} Oersteds, although the contribution to the emu susceptibility is only 6×10^{-6} . A similar result will apply for thermoremanence, as shown by the data of Dunlop (1971, Fig. 8, p. 280).

Note this result pertains to pure haematite - intermediate composition ilmeno-haematites are much more magnetic, and can produce large anomalies if present in sufficient quantity.

Table 1
Hysteresis Properties of Magnetite

	Superparamagnetic	Single domain	Multidomain
H_c	0	200-400 Oe	$\lesssim 100$ Oe
H_{cr}/H_c	-	1.09-~2	~5
J_{rs}/J_s	0	~0.5	$\lesssim 0.1$
k_o (emu)*	$VJ_s^2/3kT \approx 18$	$0.35J_s/H_{cr} \approx 0.1-1.0$	$1/\bar{N} \approx 0.25$

*the susceptibility values refer to unit volume of magnetite

\bar{N} is the effective average self-demagnetising factor of MD grains,

$$\bar{N} \approx 4\pi/3$$

Table 2.

Single Domain Size Limits

	Superparamagnetic threshold	Critical single domain size
Magnetite	320Å (0.032 μm) ¹	570Å (0.057 μm) ²
Titanomagnetite (60% Usp)	660Å (0.066 μm) [*]	1.5 μm ³
Maghaemite	200Å (0.02 μm) ⁴	400Å (0.04 μm) ⁴
Haematite	275Å (0.028 μm) ⁵	15 μm ⁵
Pyrrhotite	180Å (0.018 μm) [*]	1.6 μm ⁶

1 D.J. Dunlop, J. Geophys. Res. 79 (1974), p. 5538.

2 D.J. Dunlop, Science, 176 (1972), pp 41-43.

3 R. Day et al., Phys. Earth Planet. Int., 13 (1977), p. 266.

4 D.J. Dunlop and G.F. West, Rev. Geophys., 7 (1969) p. 717.

5 S.K. Bannerjee, Nature Phys. Science, 232 (1971), pp 15-16.

6 H. Soffel, J. Geophys., 42 (1977), pp 351-359.

* Estimated from $\tau = 1/f_0 \exp(E/kT)$, assuming $K_1 = -6 \times 10^4 \text{ erg cm}^{-3}$ for TM60, and $K_1 = 3 \times 10^5 \text{ erg cm}^{-3}$ for po.

4. MAGNETIC FABRIC

4.1 Susceptibility anisotropy

In an isotropic rock specimen the induced magnetisation is always parallel to the applied field (neglecting demagnetisation effects due to specimen shape). Thus the susceptibility of a rock may be represented by a scalar k , such that $\underline{M} = k\underline{H}$.

In general, however, the magnetisation 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 and the low-field susceptibility can be expressed as a tensor k_{ij} , defined by

$$M_i = \sum k_{ij} H_j \quad (i, j = x, y, z) \quad (4-1)$$

The susceptibility tensor is symmetric ($k_{ij} = k_{ji}$, for all i and j) and can therefore be diagonalised. Physically, this means that three mutually perpendicular directions called the principal susceptibility axes can be found for which the 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

k_3 = minor susceptibility (along hardest direction of magnetisation)

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

A = susceptibility anisotropy = $k_1/k_3 \geq 1$

For most rocks the anisotropy is small ($A \approx 1$) and the susceptibility measured along any direction is close to the bulk susceptibility value. Even very weak anisotropies can be accurately measured, however, and this information can be useful to structural interpretation.

Susceptibility anisotropy is important for the following reasons:

(i) Anisotropy implies the existence of a preferred orientation in a rock which must reflect the forces acting to align particles during the formation or alteration of the rock. Thus susceptibility anisotropy can provide information on the nature of these forces, and has the potential to reveal rock fabrics which are too faint to detect by conventional methods.

(ii) Highly anisotropic rocks can significantly deflect the direction of induced magnetisation away from the Earth's field, complicating magnetic interpretation. If the susceptibility anisotropy is known it can be incorporated into the interpretation in the following way.

Given principal susceptibilities (k_1, k_2, k_3) along principal axes defined by unit vectors $\underline{u}_i = (l_i, m_i, n_i)$ ($i = 1, 2, 3$), and given the Earth's field $\underline{H} = (H_x, H_y, H_z)$ we have

$$\underline{M} = (k_1 H_1 \underline{u}_1 + k_2 H_2 \underline{u}_2 + k_3 H_3 \underline{u}_3)$$

where

$$H_i = \underline{H} \cdot \underline{u}_i = H_x l_i + H_y m_i + H_z n_i \quad (i = 1, 2, 3)$$

$$\therefore \underline{M} = (\sum k_i H_i l_i, \sum k_i H_i m_i, \sum k_i H_i n_i) \quad (4-2)$$

where the summation is over $i = 1, 2, 3$

Because \underline{M} is not parallel to \underline{H} it is erroneous to simply plug-in a value for bulk susceptibility into a modelling program. The correct approach is to set the model susceptibility to zero, and treat \underline{M} given by (4-2) as a "remanence" component added vectorially onto the remanence (assigned or measured) which would normally be incorporated into the model.

Quite large anisotropy values are required to produce significant deflection of induced magnetisation. The maximum possible deflection of the induced magnetisation towards the easiest direction of magnetisation (the major susceptibility axis) is given by (McElhinny (1973) p 66)

$$\theta = \tan^{-1}[(A-1)/2\sqrt{A}] \quad (4-3)$$

In the worst possible case, therefore, an anisotropy as high as 50% ($A = 1.5$) would produce a deflection of only 12° . The effect depends on the relative orientation of the Earth's field and the principal susceptibility axes. For example, in the relatively common case of an isotropic

plane of high susceptibility with significantly lower susceptibility normal to the plane, there is no deflection if the field is either in the plane or normal to it. Maximum deflection occurs when the field makes an angle of 45° to the plane of maximum susceptibility.

(iii) Anisotropy of susceptibility hinders interpretation of palaeomagnetic data because the magnetisation direction observed may not accurately reflect the palaeofield direction. The effect is more critical for palaeomagnetism than for magnetic modelling, both because of the greater precision required in palaeomagnetic interpretation and because the parameter in question is the susceptibility anisotropy at the blocking temperature, or blocking volume, for a TRM or CRM respectively. Just before the remanence of a magnetic grain is blocked, the grain is superparamagnetic and has very high intrinsic susceptibility. This accentuates the anisotropy relative to the room temperature value and increases the possible deflection of the remanence direction from the ambient field direction at the time of remanence acquisition (Stacey, 1960). However it is sometimes possible to correct palaeomagnetic directions for the effects of anisotropy (e.g. Hargraves, 1959).

4.2 Origin of Anisotropy

Susceptibility anisotropy observed in rocks can stem from several causes

(i) Shape anisotropy. Inequidimensional grains of strongly magnetic minerals exhibit an anisotropy due to directional dependence of the demagnetising field within the grain. The demagnetisation factors are least along the long axis of the grain and greatest along the short axis. Therefore any tendency for alignment of long axes will be expressed in susceptibility anisotropy. For multidomain grains, which normally dominate the susceptibility, the major susceptibility axis coincides with the preferred orientation of long axes of the grains, the minor susceptibility axis with alignment of the short axes. Elongated monodomain grains, which may dominate the remanence but only make a minor contribution to the total susceptibility, have maximum susceptibility normal to the long axis, and zero susceptibility along the major axis.

This mechanism is important for the titanomagnetite series and maghaemite. Haematite is too weakly magnetic for shape anisotropy to be significant.

(ii) Textural anisotropy. Any tendency for aggregation of strongly magnetic grains into strings or layers will be reflected in susceptibility anisotropy. As for shape anisotropy the effect is due to self-demagnetisation. Stringing together of magnetic grains produces a magnetic lineation, with the major susceptibility axis along the preferred direction of the strings. Magnetite bearing BIFs afford a good example of anisotropy due to layering, with a plane of maximum susceptibility parallel to the bedding and lower susceptibility normal to the bedding. Layered igneous rocks with cumulitic texture, some finely-bedded sedimentary rocks, and some schistose rocks may also exhibit this sort of textural anisotropy.

(iii) Magnetocrystalline anisotropy. The non-cubic magnetic minerals such as the haematite-ilmenite series and pyrrhotite exhibit strong magnetocrystalline anisotropy with an easy plane of magnetisation (the basal plane). The susceptibility along the crystallographic c-axis is much lower than that in the basal plane. Thus a preferred orientation of crystal axis of these minerals in a rock produces an anisotropy of susceptibility.

(iv) Domain alignment. The intrinsic susceptibility of multidomain grains is dependent on the direction of measurement with respect to the domain orientation. The magnetising process involves rotation of the magnetisation when the applied field is perpendicular to the domain walls, but involves domain wall displacement when the field is parallel to the domains. There is therefore a difference between susceptibilities measured parallel and perpendicular to domain walls because of the differing mechanisms of acquisition of magnetisation.

If the domains in the large magnetic grains are significantly aligned, the rock will be anisotropic. Domain alignment can be produced by subjecting the rock to a strong field - aligning the domains

with the field direction. Alternating field demagnetisation along a single axis has produced observable anisotropy in rocks (Bhathal and Stacey, 1969 ; Violat and Daly, 1971). Thus it is advisable to measure the susceptibility anisotropy of rock specimens before 3-axis AF cleaning is carried out. An advantage of tumbling the specimen during AF demagnetisation is that this effect is eliminated.

4.3 High-Field Anisotropy

Magnetic anisotropy is also apparent in high magnetic fields. The technique employed to measure magnetic anisotropy is the high field torque method. The torque on an anisotropic specimen varies as a function of the angle between the easy axis of magnetisation (within the plane of rotation) and the field. Torque curves about three mutually perpendicular axes determine the magnetic fabric, and a Fourier analysis of the components present can in some cases distinguish between the various types of anisotropy discussed in 4.2.

The cubic minerals are intrinsically isotropic in low field and therefore only the high field method can reveal any preferred crystallographic orientation in magnetite bearing rocks. The shape anisotropy gives rise to a $\sin 2\theta$ dependence of the torque, whereas alignment of cubic crystal axes adds a $\sin 4\theta$ term (Stacey, 1960). However no evidence of significant crystallographic alignment in cubic magnetic minerals has yet been found.

The fields usually attainable in the laboratory are too low to saturate haematite and pyrrhotite. The magnetic moment in these minerals therefore remains confined to the basal plane. Under these circumstances Porath and Chamalaun (1966) have shown that, in addition to the $\sin 2\theta$ term, there will be significantly higher harmonics present in torque curves, and therefore recommend low field methods for the estimation of magnetic fabric in haematite-bearing (and, by implication, pyrrhotite-bearing) rocks.

4.4 Characterisation of Magnetic Fabric

Given the principal susceptibility axes we may define an ellipsoid whose semi-axes are k_1, k_2 and k_3 directed along the corresponding principal susceptibility axis directions. The susceptibility ellipsoid thus defined is a convenient concept for visualisation of fabric type.

It must be noted that the radius of the susceptibility ellipsoid defined in this way is not a measure of the susceptibility along that direction (except along the principal axes). The susceptibility k measured along a direction given by the unit vector (l, m, n) with respect to the principal axes, is

$$k = k_1 l^2 + k_2 m^2 + k_3 n^2 \quad (4-4)$$

If the susceptibility ellipsoid is a sphere, the specimen is isotropic, 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.

The following parameters are frequently used to characterise magnetic fabric

Degree of anisotropy	$A = k_1/k_3$	(≥ 1)
Lineation	$L = k_1/k_2$	(≥ 1) or $L^1 = (k_1 - k_2)/k_0$ $(0 \leq L^1 < 3)$
Foliation	$F = k_2/k_3$	(≥ 1) or $F^1 = [\frac{1}{2}(k_1 + k_2) - k_3]/k_0$ $(0 \leq F^1 < 3/2)$
Prolateness	$P = L/F = k_1 k_3 / k_2^2$	$P^1 = L^1 / F^1$ $(P > 0)$ $(P^1 > 0)$

When the prolateness is greater than one, the susceptibility ellipsoid is prolate (lineation dominant), and when the prolateness is less than one the ellipsoid is oblate (foliation dominant).

A triaxial susceptibility ellipsoid has two circular sections which are isotropic, each of which is inclined at an acute angle, V , to the minimum axis, given by

$$\tan^2 V = (k_2 - k_3) / (k_1 - k_2) \quad (4-5)$$

V varies from 0° to 45° for prolate ellipsoids and from 45° to 90° for oblate ellipsoids. The extreme values 0° and 90° correspond to prolate and oblate ellipsoids of rotation (spheroids) respectively.

The magnetic fabric of a rock is dependent on both the shapes and the orientations of the susceptibility ellipsoids of individual specimens. Susceptibility axis directions can be categorised into three groups:

- (I) k_3 axes of individual specimens tightly clustered about their mean direction; k_1 and k_2 axes dispersed about a great circle to form a partial or complete girdle.
- (II) k_1 , k_2 and k_3 axes of individual specimens all grouped about their respective site means
- (III) k_1 axes tightly clustered about their site mean; k_2 and k_3 axes dispersed about a great circle.

Each of these groups can be subdivided into three subclasses on the basis of ellipsoid shapes. The combinations of ellipsoid shapes are: (a) all prolate, (b) some prolate and some oblate, or (c) all oblate. We can then refer to a fabric type by employing a Roman numeral followed by a letter suffix. For example an undeformed primary sedimentary fabric is usually type Ic. Of the nine possible combinations, types Ia and IIIc are unlikely to occur. Grouping of intermediate axes only is uncommon.

A plot of magnetic lineation versus foliation is commonly employed to analyse anisotropy data. A tendency for the plotted points to be strung along a relatively narrow track is frequently observed. These points define a susceptibility path, leading outwards from the origin in the direction of increasing anisotropy, which is interpreted in terms of increasing deformation. This interpretation depends on the assumption that progressive deformation produces greater magnetic anisotropy. This is true for an initially isotropic rock. If there is initial anisotropy, the total anisotropy may first decrease slightly before increasing with continuing deformation.

The form of the susceptibility ellipsoid does not reflect the shape or symmetry of the individual magnetic grains, but rather the symmetry of the processes which form the fabric. For example an assemblage of prolate grains with their major axes randomly aligned within a plane will produce an oblate susceptibility ellipsoid with minor axis normal to the plane. This fabric can arise by the settling of elongated detrital magnetite grains in a quiet sedimentary environment, because the grains tend to lie flat. There is one axis of symmetry (vertical) because of the unidirectional aligning force (gravity). There is rotational symmetry about this axis unless there is an aligning force within the foliation plane, such as a bottom current. The ellipsoid is oblate because gravity aligns the short axes of the grains. A process which preferentially aligns long axes of magnetite grains will produce a linear fabric with a prolate susceptibility ellipsoid, whether the grains themselves are predominantly prolate or oblate. For instance very fine single domain grains in interstitial pores of a sediment will tend to align with their magnetic moments, and hence their long axes, parallel to the Earth's field. In the absence of other effects it has been shown by Noltimier (1971) that assemblages of prolate or oblate grains will both produce a preferred orientation of major axes along the field. In practice this effect is nearly always masked by the influence of larger grains and the more powerful forces aligning them, although the phenomenon of field-induced alignment is important in producing a stable detrital remanent magnetisation (DRM).

The assumption that the susceptibility of a rock can be represented by a symmetric tensor or, equivalently, an ellipsoid places a fundamental limitation on the complexity of the rock fabric that can be described by the susceptibility anisotropy. The most complex fabric that can be described by the susceptibility ellipsoid is that in which there is a plane of foliation defined by the principal axes of intermediate and maximum susceptibility, and a lineation in the direction of the maximum within that plane. Petrofabrics of lower symmetry than this will be aliased into a magnetic fabric of higher symmetry and some information

will be lost in the process. For example, two non-parallel foliations will be expressed magnetically as a single foliation lying between the two planes, with a lineation along the intersection of the foliations. Similarly, a lineation oblique to a foliation plane will appear as a magnetic foliation lying between the true lineation and foliation, containing a magnetic lineation along the projection of the true lineation onto the magnetic foliation plane. This ambiguity is inherent in susceptibility anisotropy data, although superposed fabrics can in principle be resolved by harmonic analysis in sufficiently large (saturating) fields. Examples of complex overprinted fabrics which are merely averaged by the magnetic method, with consequent loss of information, are given by Stacey et al. (1960). Thus care must be taken in interpreting magnetic fabric. However the fabric of most rocks seems to be well defined by magnetic data. In the case where a rock has two or more superimposed well-developed fabrics, the degree of overprinting should vary from specimen to specimen, producing a scatter in the magnetic axis directions. Therefore well-grouped directions are evidence that the observed fabric reflects a single phase of fabric development.

Because the principal axes are undirected lines, rather than vectors, there is an arbitrary choice of which end of a line to take in representing an axis. It is conventional to use either the downward- (or upward-) pointing sense for all the axes and plot them on a lower (or upper) hemisphere projection.

4.5 Interpretation of Magnetic Fabric

Because of the ambiguity inherent in the use of magnetic anisotropy for characterisation of rock fabric, it is essential to use all the data available when interpreting magnetic fabric. Internal consistency or inconsistency of results, anisotropy magnitudes, susceptibility ellipsoid shapes, nature of the lithology, magnetic mineralogy and other geological information should all be considered in the interpretation. In particular any microfabric or structural studies in the area involved should be integrated with the magnetic data from nearby localities.

In the absence of good geological control, magnetic anisotropy data still serve to provide working hypotheses regarding structural relationships. In the case where structural petrological work has been carried out in some localities within an area, the magnetic fabric can be correlated with petrofabric at those localities and the magnetic data can then be used to extrapolate rock fabric-structure relationships throughout the area. A number of studies have combined magnetic anisotropy and petrofabric data to elucidate mechanisms of deformation, emplacement tectonics, and so on.

A great deal of work has been carried out on the magnetic fabric of sediments and metasediments (e.g. Graham (1966), Hrouda (1976a).

The degree of anisotropy is low in undeformed sediments ($A < 1.05$) and the susceptibility ellipsoids are predominantly oblate (fabric type I-IIc). The k_3 axes are usually well-grouped normal to the bedding and thus define the bedding pole. The k_1 and k_2 axes are either dispersed about a girdle which defines the bedding plane, or else show a tendency to cluster within the bedding plane. The magnetic lineation parallel to the k_1 directions, which is apparent in the latter case, is usually parallel to the palaeocurrent direction (e.g. Rees (1965), Gough et al. (1977)), although a number of exceptions have been noted where the k_1 axes are perpendicular to the current flow. In one case (Hrouda and Janak, 1971) the orientation of the magnetic lineation perpendicular to the current has been attributed to the rolling of platy detrital haematite grains which dominate the fabric of the red sediment. In the case of a magnetic fabric due to a fine-grained haematite coating on quartz grains (Gough et al. (1977)), the magnetic lineation is parallel to the palaeocurrent direction. The explanation is that the current aligned the long axes of the quartz grains, and the magnetic fabric results from a faint shape anisotropy superimposed on the isotropic susceptibility due to randomly aligned haematite crystals which subsequently coated the quartz grains. This suggests that study of the magnetic mineralogy may help to distinguish between the two relative orientations of lineations and palaeocurrents. Consistency of k_1 directions between different rock

types should increase confidence in associating the lineation with flow direction.

However an important fact emerges from all the work that has been carried out. This is that the magnetic foliation in an undeformed sediment is parallel to the bedding, whether the dominant magnetic mineral is magnetite or haematite, and that the magnetic foliation can be used to determine the bedding plane in poorly bedded or poorly exposed sedimentary rocks. This relationship appears to hold for sediments as diverse as shales, sandstones, conglomerates, greywackes, limestones, redbeds, glacial tills; and even anthracite and bituminous coals (Ellwood and Noltimier, 1978).

Deformation and metamorphism of sediments change the magnetic fabric of sediments markedly. Graham (1966) has described the magnetic fabric associated with progressive deformation of sediments. Under the action of compression in the bedding plane there is a lateral shortening and associated thickening of the beds, with a vertical plastic flow leading to reorientation of the magnetic grains. The deformation is thus modelled as a pure shear. (see figure 4-2).

Initially the magnetic lineation is aligned normal to the compression axis and the prolateness of the ellipsoids increases, but the magnetic foliation remains bedding parallel. As the compression proceeds the minimum and intermediate axes approach each other in magnitude and eventually interchange, with the k_3 direction aligning with the compression axis. The magnetic foliation now lies in the axial plane and the magnetic lineation is parallel to the axis of the subsequent folding. With continuing deformation the ellipsoids become progressively more oblate and the major and intermediate axes eventually interchange, whilst the k_3 axes remain parallel with the compression axis. Thus the primary sedimentary fabric has been transformed into a purely deformational fabric with the susceptibility ellipsoid aligned with the strain ellipsoid - k_3 parallel to the direction of maximum compression, k_1 parallel to the direction of maximum extension. The sequence of fabric types is then:

- (1) Primary I-IIc. Foliation parallel to bedding; lineations scattered or related to palaeocurrents. Anisotropy $\lesssim 1.05$.
- (2) IIb. Foliation bedding parallel; lineation perpendicular to compression, within bedding plane.
- (3) IIIa. Lineation perpendicular to compression, within bedding plane.
- (4) IIb (Deformational). Lineation perpendicular to compression, within bedding plane; foliation normal to compression axis.
- (5) I-IIc. Foliation normal to compression axis; lineation parallel to major principal strain axis (vertical). $A \gtrsim 1.07$.

Hrouda (1976a) has documented the development of a deformational magnetic fabric during the progressive metamorphism of greywackes, siltstones and shales to slates and phyllites. The Ic sedimentary fabric transforms to IIb, c in rocks exhibiting fracture cleavage, with k_3 remaining perpendicular to the bedding while a well-defined lineation appears, parallel to the delta axes (the lines of intersection of bedding and cleavage planes). In rocks with well-developed slaty cleavage, there is a IIc fabric with the magnetic foliation now parallel to the cleavage planes, while the lineation remains aligned with the delta axes. Further metamorphism produces phyllites exhibiting a metamorphic foliation. The magnetic fabric is Ic, and the magnetic foliation is parallel to the metamorphic foliation. The magnetic data shows that the metamorphic foliation developed from the slaty cleavage with continuing deformation, rather than from the bedding; and that slaty cleavage is essentially a product of irrotational strain with maximum compression normal to the cleavage. Rocks with slaty cleavage have very high susceptibility anisotropy ($A \gtrsim 1.15$).

A number of authorities have studied magnetic anisotropy in slates (e.g. Fuller (1964), Hrouda (1976a), Wood et al. (1976), Rathore (1979)). Slates are of particular interest because of the occasional presence of natural strain markers which allow direct determination of the principal strains, permitting investigation of the quantitative correlation of magnetic fabric with strain.

It is interesting to note that the relationship of magnetic fabric in slates to the major structural elements is, at least qualitatively, independent of the dominant magnetic mineralogy. The magnetic ellipsoid axes coincide with the strain axes - the magnetic foliation parallel to the cleavage; the lineation parallel to the maximum extension, which frequently corresponds to the delta axes and the regional trend of folding.

In magnetite-bearing slates the long axes of magnetite grains are preferentially aligned in the cleavage plane. The basal planes of haematite, in red slates, and pyrrhotite, in pyrrhotite-bearing slates, are aligned parallel to the cleavage. The lineation arises from shape anisotropy in the case of magnetite, but its origin is more obscure in the cases of haematite or pyrrhotite. Fuller (1964) observed that the long axes of pyrrhotite crystals were preferentially aligned with the magnetic lineation and attributed the lineation to shape anisotropy within the plane of high susceptibility, the basal plane. Wood et al. (1976) explain the magnetic lineation of red slates on the basis of a uniaxial, stress-induced basal plane anisotropy of haematite.

Rathore (1979) determined the mathematical relationship between susceptibility anisotropy and strain for some Welsh slates and found a simple power law. The data suggest the magnetic fabric results from passive rotation of rigid magnetic grains in a ductile matrix, as was independently concluded by Hrouda (1976b). The anisotropy-strain relationship would have to be recalibrated for each rock type, as it is dependent on the alignment process.

A number of alignment mechanisms can be envisaged to explain the response of the magnetic grains in a rock subject to deformation including viscous fluid flow according to pure shear or simple shear models, rotation of long axes of rigid grains in a ductile matrix, or passive deformation of magnetic grains together with the matrix. Owens (1974) has shown that any of these mechanisms will produce the sequence of fabric types observed by Graham (1966) and Hrouda (1976a), but that quanti-

tatively the models are very different. For instance the anisotropy and prolateness due to a given strain are very sensitively dependent on the alignment mechanism. Passive deformation of magnetite grains, even at low strains, would produce anisotropies far greater than ever observed, so this mechanism can never be dominantly responsible for magnetic fabric.

Metamorphism involves obliteration of a primary fabric with concomitant development of a metamorphic fabric. Therefore examples of partially overprinted fabrics are frequently observed in metamorphic rocks of grade intermediate between those exhibiting a primary fabric and those with a purely metamorphic fabric. Some examples are discussed by Hrouda (1978). Goldstein (1980) discussed the use of matrix algebra to resolve a partially overprinted fabric into pre-deformational and deformational components, which pertain to the fabric of pre-mylonitic gneisses and mylonites respectively. The gneisses (sillimanite grade tectonites) have a well-developed magnetic fabric which conforms to the mesoscopic rock fabric - k_1 axes parallel to sillimanite and hornblende lineations which lie along the axes of isoclinal folding associated with the high grade metamorphism, and k_3 axes normal to the axial plane foliation. The magnetic fabric is due to haematite laths within garnets. The mylonites have a quite distinct magnetic fabric, which is due to magnetite produced during mylonitisation, in which the k_1 axes are directed parallel to a mylonitic lineation defined by quartz and feldspar rods and there is an intense magnetic foliation parallel to the axial planes in neighbouring tectonites. In a narrow transitional zone between gneiss and fully developed mylonite the magnetic fabric is at variance with the rock fabric due to superposition of the non-parallel magnetite and haematite fabrics. During the initial stages of mylonitisation the haematite grains are protected by their resistant garnet hosts and the magnetite fabric only partially overprints the pre-mylonitic haematite fabric. In fully developed mylonites the garnets have broken down, and the overprinting is complete. Separation of the hybrid fabric into pre- and post-mylonitic components

shows that the initial mylonitic fabric is parallel to the fabric found well inside the mylonite zone, as expected, and that the prolateness of the associated ellipsoid is approximately unity, consistent with a plane strain. This is interpreted as initiation of mylonitisation by simple shear, followed by flattening with progressive deformation, producing the very oblate susceptibility ellipsoids observed within the mylonite zone.

Although many studies of magnetic fabric in igneous rocks have been carried out, the interpretation of the results is often not straightforward. One problem is the paucity of petrofabric studies due to the difficulty of observing weakly developed fabrics of igneous rocks by conventional means. Thus our understanding of fabric-forming processes is as yet not advanced.

However the great sensitivity of the magnetic method makes it an ideal tool for the study of fabrics in igneous rocks. The magnetic minerals need not be primary to be useful in defining the fabric associated with the formation of the rock. A number of workers, including Ellwood and Whitney (1980), Heller (1973) and Hrouda et al. (1971), have described mimetic fabrics due to secondary magnetic minerals which greatly amplify the weak primary fabric of rock-forming minerals. The magnetic fabric is likely to be modified, however, if the secondary magnetic minerals are associated with metamorphism and/or deformation.

The fabric of igneous rocks reflects the emplacement dynamics. Layered basic intrusives exhibit a pronounced sub-horizontal foliation due to crystal settling under gravity. Ignimbrites exhibit a foliation in the palaeohorizontal plane analogous to that of sediments. The dominant alignment mechanism in igneous rocks, however, is usually magma flow. There is a tendency for crystals to take up an orientation with their long axes in the plane of flow. When this process is very pronounced flow banding is observed.

A number of studies of plutons have revealed the same general pattern of fabric in different rock types. A strong magnetic foliation is

observed near the margins of the intrusion, parallel to the contact with country rock and any visible foliation of the rock forming minerals. The magnetic foliation becomes weaker away from the margins, but is usually still detectable throughout the intrusion, whereas the conventional petrofabric is usually too weak to be observed. There is often a magnetic lineation, parallel to any visible mineral lineation, which is commonly in the direction of steepest plunge within the foliation.

This general pattern of magnetic fabric has been found for example in granites (Duff (1975), Ellwood and Whitney (1980), King (1966)), a diorite (Birch (1979)) and a phonolite (Stone (1962)).

Attempts have been made to determine the mode of emplacement of basalts using susceptibility anisotropy data (Ellwood and Watkins (1973), and Ellwood (1978)). Dykes and sills tend to exhibit significant clustering of susceptibility axis directions with either k_1 or k_3 directions normal to the plane of the body, while the other axes form a partial or complete girdle in the plane of the intrusion. Sub-aerial lavas generally possess scattered susceptibility axis directions, attributed to grain disorientation during degassing, convection, late stage plastic deformation etc. Where there is significant clustering of directions in lava flow, the magnetic foliation lies in the plane of flow. Extrusive rocks are less anisotropic in general than intrusives, and a parameter defined in terms of principal susceptibility differences has been used to distinguish between extrusive and intrusive origins of oceanic basalts with a claimed accuracy of 80% (Ellwood (1975)).

The relationship between magnetic lineation and flow direction in igneous rocks is controversial. Bhattacharyya (1965) has discussed mineral lineations in some granites, lavas and deformed metamorphic rocks. In all cases the long axes of the grains are aligned parallel to the "flow" (*sensu lato*). In the case of the deformed and metamorphosed pelitic, psammitic and basic rocks the lineations were parallel to the striations on the axial plane schistosity - which represent the direction of maximum extension during plastic flow, as indicated by the long axes of deformed

ellipsoidal pebbles. This is a good illustration of the alignment process operating during plastic flow of solid rock under deformation (which is probably applicable to post-solidification emplacement of large intrusives), where the mineral lineation is parallel to the flow direction.

Liquid magma behaves as a highly viscous fluid. Thus a plausible model of grain alignment in a flowing magma is afforded by rigid particles in a viscous matrix which is undergoing a homogeneous strain (one in which lines and planes are undistorted), such as pure shear or simple shear. Pure shear is an irrotational strain involving shortening in one direction and extension in another, perpendicular, direction such that the volume always remains constant. Simple shear is a rotational strain, generated by displacing all points parallel to one axis, the amount of displacement being proportional to the distance of the points from the other axis (analogous to the sliding of cards in a pack, distorting a square marked on the side into a rhombus).

Gay (1968) treated the theoretical alignment processes operating in pure shear and simple shear deformation. Under pure shear the long axes of the particles tend to align with the direction of maximum extension. The case of simple shear is more complicated, and has been recently discussed by Owens (1980). The plane of flow is defined as a plane in which the relative velocity of the fluid is zero; the plane of shear is defined as containing the direction of flow and the maximum velocity gradient, and is therefore normal to the plane of flow. The particles undergo an orbital motion which leads to a preferred alignment of long axes, for a uniform initial particle axis distribution, which lies in the plane of shear and oscillates about the flow direction. When the condition that there is a specified initial distribution of axes is relaxed by introducing indeterminacy of phase, the model leads to a steady state distribution of particle axes equivalent to the time average of the previous, periodically varying fabric, with the corresponding principal susceptibility axes parallel to the coordinate axes of the simple shear frame. For an initially isotropic distribution of particle axes, the resultant fabric has maximum

susceptibility along the flow, and minimum susceptibility normal to the flow plane. For extremely elongated (axial ratio ≥ 20) particles or very anisotropic initial distribution of axes directions, the maximum and intermediate susceptibility axes may interchange within the plane of flow (i.e. k_1 now perpendicular to flow). However one would expect for typical grain shapes (slightly prolate and oblate) that the magnetic lineation should be parallel to the flow.

Experiments, such as those carried out by Rees (1979), appear to confirm the conclusions of the previous paragraph, but the field evidence is ambiguous. Khan (1962) reports magnetic lineations from lavas and banded gabbros which are perpendicular to the flow direction. King (1966) and Duff (1975) describe examples of magnetic lineation both parallel to and normal to inferred flow directions in granitic rocks, and attempt to distinguish between plastic (parallel relationship) and fluid (orthogonal relationship) flow on this basis. In the light of Owens' (1980) discussion, however, their conclusions must be considered unconfirmed.

Theory and experiment both predict a magnetic foliation in the plane of flow, and this provides a ready explanation for the frequently observed magnetic foliations parallel to the contact walls of plutons and dykes. However a number of processes may disturb a flow fabric and complicate interpretation. These include distortions of the flow produced by large viscosity gradients associated with even very small temperature gradients as solidification is approached, continued convection after the motion of emplacement has ceased, and churning of solidified material by convection of still liquid magma.

As in sediments, deformation of igneous rocks modifies the primary magnetic fabric. Stress due to thermal contraction or pressure of overburden soon after emplacement has been invoked by Ellwood (1979) to explain the fabric of columnar basalts. Tectonism may partially or completely overprint the emplacement fabric. Henry (1975) reports a tonalite which retains the primary foliation parallel to the contacts, but

has a deformational magnetic lineation parallel to the intersection of the foliation and the plane of maximum stress (perpendicular to the compression axis). There is no visible lineation in the rock, so the magnetic method has detected an important fabric element which would otherwise have been unrevealed. Birch (1979) found a similar pattern in a heterogeneous (gabbroic-granitic) pluton, with the k_1 directions parallel to the fold axes. Norites within an intensely deformed basin (Kligfield et al. (1977)) exhibit an axial planar magnetic foliation parallel to the slaty cleavage in surrounding sediments, and magnetic lineations parallel to mineral elongation lineations in the direction of maximum extension. The magnetic fabric can be traced into zones where there is no visible fabric, and there is a significant change of susceptibility ellipsoid shape, from prolate to oblate with increasing distance from the high grade metamorphic front. Balsey and Buddington (1960) found the magnetic fabric of orthogneisses to coincide with the mesoscopic fabric, where the latter was observable, with lineations along fold axes.

It can be seen from the above examples that the response of the magnetic fabric of igneous rocks is qualitatively similar to that of sedimentary rocks. The general response of magnetic fabric to deformation is an initial increase in lineation, after which it remains constant, while the foliation increases continuously throughout deformation. The susceptibility path lies mostly within the field of flattening ($P < 1$). Anisotropy tends to increase with metamorphism up to phyllites, then remains roughly constant.

The magnetic fabric of ore bodies has not been extensively studied, but would seem to have potential as a tool for structural studies. Ores tend to possess a very marked fabric, due to mesoscopic banding or crystallographic alignment. Hargraves (1959) studied susceptibility anisotropy in the Allard Lake Haemo-ilmenite deposit and found a very pronounced magnetic foliation roughly parallel to the structural contours of the footwall of the ore body. The fabric arises from the parallelism

of titanhaematite lamellae exsolved on the basal planes of ferrian-ilmenite host grains. The anisotropy was large, varying from 1.2 to 3.8, and there was a marked tendency for the NRM directions, which were very scattered, to lie close to the magnetic foliation plane. A graphical technique was used to determine the remanence direction corresponding to the true palaeofield direction - in other words, the directions were corrected for the deflections of remanence vectors towards the plane of maximum susceptibility. Schwarz (1974) described the magnetic fabric of six massive sulphide deposits in Ontario. The fabric arises from pyrrhotite, but it is not certain whether the anisotropy is predominantly textural or magnetocrystalline. Susceptibility axis directions are usually well grouped, suggesting the magnetic fabric is of single origin within each deposit, but the fabric varies from one deposit to another implying a dependence on the geological environment. Magnetic foliations when well-defined, appear to parallel country rock contacts, and lineations are possibly related to folding.

4.6 *Summary*

1. Low-field susceptibility of rocks can usually be well represented by a symmetric 3 x 3 tensor. The eigenvalues of the tensor are the principal susceptibilities, measured along three mutually perpendicular directions corresponding to the eigenvectors, and known as the principal susceptibility axes (major, intermediate, minor). Along the principal susceptibility axes the induced magnetisation is parallel to the applied field.

2. Magnetic anisotropy deflects both induced and remanent magnetisation from the applied field direction towards the easy direction of magnetisation. Thus anisotropy should be considered in interpretation of magnetic surveys and palaeomagnetic data.

3. The susceptibility ellipsoid is defined as having semi-axes equal to the principal susceptibilities, parallel to the principal suscepti-

bility axes. The magnetic foliation plane contains the major and intermediate susceptibility axes. The magnetic lineation lies along the maximum susceptibility direction within the magnetic foliation. Together the foliation and lineation define a magnetic fabric, which may arise from shape anisotropy of inequidimensional strongly magnetic grains, magnetocrystalline anisotropy of non-cubic magnetic minerals, or textural anisotropy of magnetic minerals.

4. The magnetic foliation of undeformed sediments is bedding parallel. The primary magnetic fabric of igneous rocks reflects the emplacement dynamics and in most cases is generated by flow. Deformation and metamorphism modify primary fabrics and ultimately give rise to a purely deformational magnetic fabric in which the susceptibility axes parallel the principal strain axes of the deformation.

Figure 4-1. Magnetic fabric of rocks from the Mt Isa area. Circles represent site mean minimum susceptibility axis directions, squares site mean maximum directions. The lithologies represented are the Eastern Creek Volcanics (magnetite-bearing metabasalts - unlabelled), magnetite-bearing Magazine Shales (MS), and pyrrhotite-bearing Urquhart Shale (US). The mean foliation pole is (92° , $+17^{\circ}$), and is indicated by an asterisk. The corresponding magnetic foliation plane is shown as the dashed great circle arc. Maximum and intermediate (not shown) susceptibility axes are scattered within the foliation, which dips at 73° to the west, parallel to the regional bedding plane. Thus the magnetic fabric of the three different rock types with varying magnetic mineralogy finds a simple interpretation in terms of geological structure.

The stereonet is an equal angle projection. The primitive represents to present horizontal.

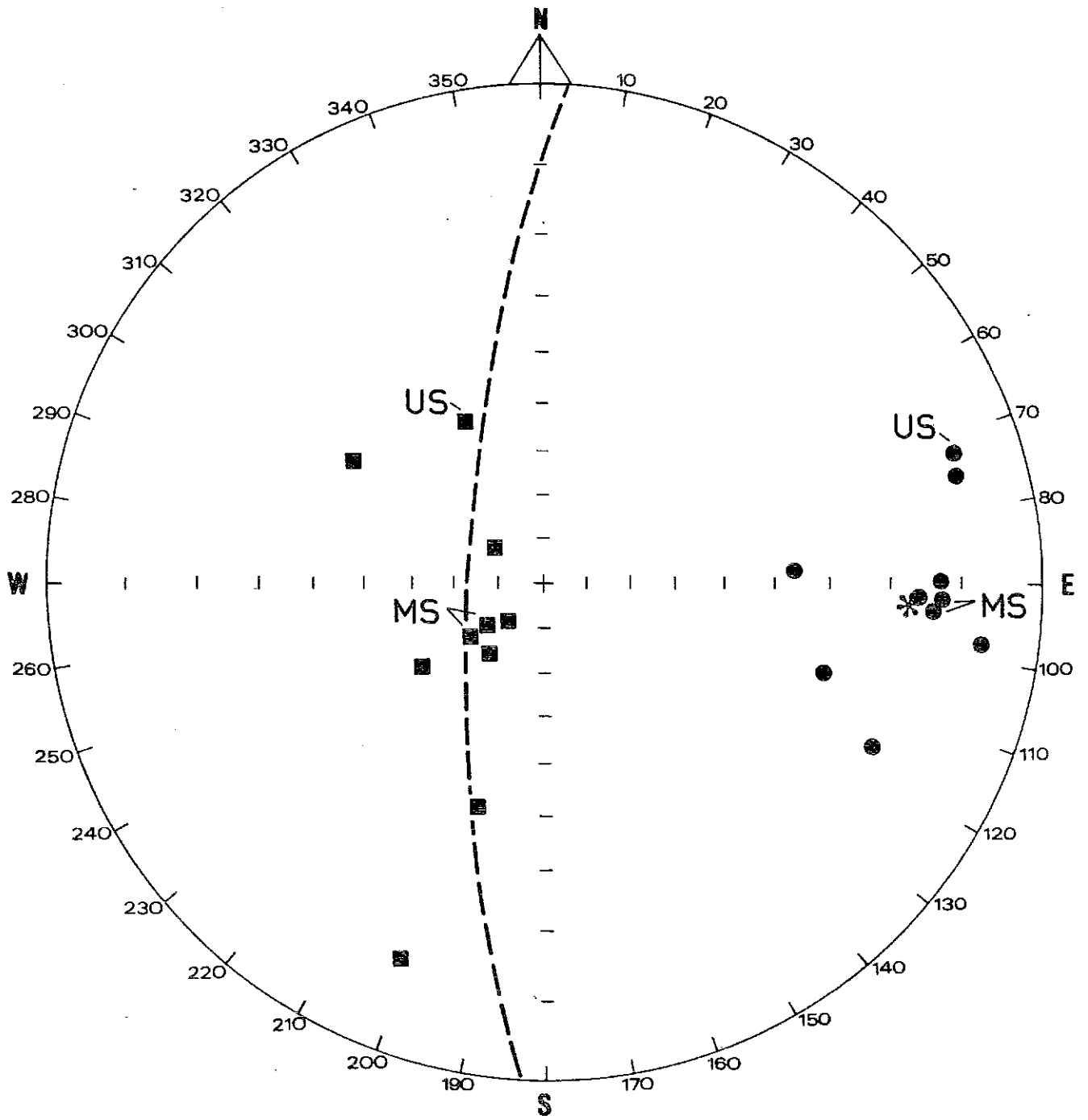


FIG. 4-1

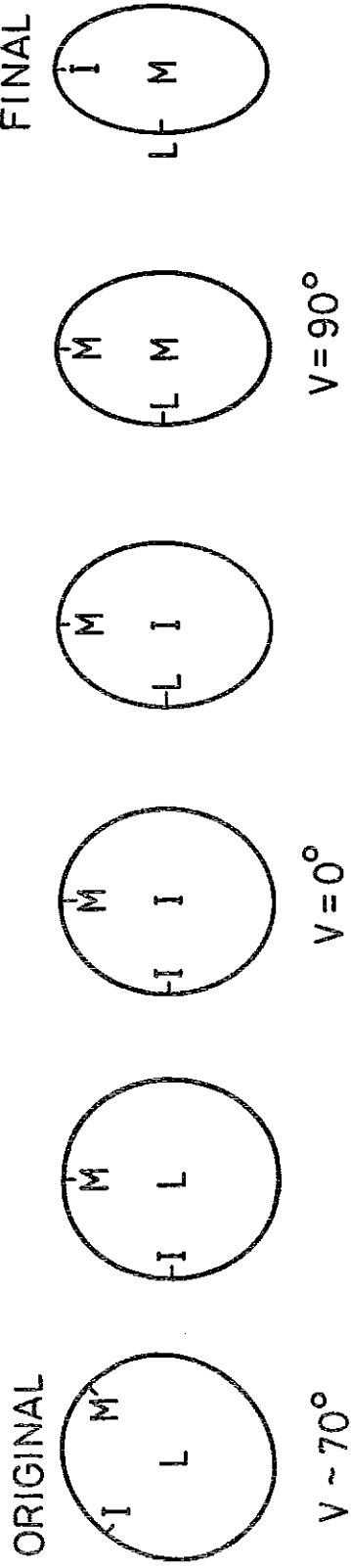
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Figure 4-2. Response of sedimentary magnetic fabric to deformation (after Graham, 1966).

The compression axis is in the bedding plane, parallel to the plane of the page. The flat-lying beds shorten in response to horizontal compressive stress, prior to folding. The direction of maximum extension is perpendicular to the plane of the page, i.e. there is vertical flow. The primary sedimentary fabric is characterised by an oblate susceptibility ellipsoid ($V \sim 70^\circ$) and a bedding-parallel magnetic foliation. The major susceptibility axis alignment reflects palaeocurrent direction. The initial response to compression is to align the major axes perpendicular to the compression, within the bedding plane. As deformation proceeds the intermediate and minimum axes become equal, at which stage the susceptibility ellipsoid is a prolate spheroid ($V=0^\circ$), and then interchange. The magnetic foliation is now perpendicular to the compression axis, and the lineation is parallel to the axis of subsequent folding. If deformation continues the maximum and intermediate axes first become equal, corresponding to $V=90^\circ$ (oblate spheroid), and eventually the vertical flow aligns long axes of grains to produce a vertical lineation. This final stage is often observed in highly deformed slates, for instance, when the susceptibility ellipsoid axes are aligned with the corresponding principal strain ellipsoid axes.

Stage 2 may correspond to development of fracture cleavage, stage 4 to appearance of slaty cleavage, and stage 5 to development of metamorphic foliation, as described by Hrouda (1976). Graham (1966) observed the progression of fabric types shown in Appalachian sedimentary rocks and demonstrated that deformation produced by gravity sliding was more consistent with the results than basement control of folding.

————— INCREASING DEFORMATION —————>



5. THE REMAGNETISATION OF MASSIVE MAGNETITE BY DRILLING

5.1 Aim of the Investigation

Measurements of NRM intensities from drill-core samples of Tennant Creek massive magnetites had produced anomalously high values. Modelling studies by Geopeko had shown that if the measured remanent intensities were representative, the anomalies associated with the magnetite ore bodies should be much greater than those observed. It was also remarked that the remanence directions commonly lay close to the core axis. This suggested that the magnetic material might be substantially remagnetised during drilling, with the drilling-induced component parallel to the field inside the drill barrel. Drill barrels were suspected of becoming highly remanently magnetised after drilling magnetite ore. By symmetry, the effective field inside a rotating, remanently magnetised drill barrel is axial, providing a simple explanation of the orientation of the anomalous magnetisation.

Tests were carried out on a block of massive magnetite to determine the effect of drilling of cores on the measured remanence of the sample.

5.2 Experimental Procedure

The block was mounted in a drill press and cores were drilled out vertically using both Triefus (non-magnetic stainless steel) and Felker (magnetic steel) barrels. The ambient field was near vertical, and therefore roughly along the drill axis.

The block was then rotated through 90° about a horizontal axis, and the procedure repeated. The remanence was then measured for specimens sliced from the cores. The measured remanence directions relative to the sample are shown in Figure 5-1. The coordinate system of the block is chosen, so that the axes of the cores drilled in the first orientation (T1 and F1 for Triefus and Felker bits respectively) plot in the centre of the stereonet, whereas for the second orientation the cores T2 and F2 were drilled from the direction (180° , 0°). All directions have negative inclinations and are plotted on an equal angle upper hemisphere projection.

5.3 Discussion of Results

It is clear from Figure 5-1 that there is a tendency for the measured directions to lie close to the direction from which the core was drilled, i.e. up the barrel and approximately parallel to the ambient field. Therefore drilling does partially remagnetise the magnetite in this case, the anomalous component being directed axially up the barrel.

An initially surprising result is that the magnetic barrels seem to have less effect than the non-magnetic drills. However the measured magnetic field inside Felker barrels is generally lower than the ambient field because of the shielding effect (the barrels are not strongly remanently magnetised). The preferred explanation of the phenomenon is that the magnetisation is due to activation of the soft grains by mechanical vibration in a near-vertical ambient field. The bits are water-cooled and the magnetite is not heated significantly during the drilling process.

The magnetisation is soft with median destructive field for the overprint component of about 20 Oersteds. The fact that the directions are not completely cleaned below about 200 Oersteds means that the original NRM and the drilling-induced overprint have highly overlapped coercivity spectra. It follows that the original NRM intensity cannot be obtained directly by cleaning out the overprint because some, perhaps most, of the original magnetisation will also be destroyed by the AF cleaning.

However, the original NRM direction can be determined in this case by AF demagnetisation to 200 Oersteds, which produces a tight cluster of directions from the specimens which originally had scattered directions (Figure 5-2). We are assuming that the in situ NRM is dominated by a single component, and that this component survives AF cleaning to 200 Oersteds. This assumption is reasonable because the successive cleaned directions lie on great circle arcs joining the drilling axis direction and the stable cleaned direction - suggesting the presence

of only two components (drilling-induced overprint and relatively stable component). Further, it will be shown in 5.4 that the in situ NRM is probably dominated by a viscous component parallel to the Earth's field.

Given that the mean AF cleaned direction for all specimens is (180° , -50°), and assuming the overprint is directed up the drill barrel, we can solve the vector equations to obtain the magnitudes of the overprint and the NRM. The results are

Triefus overprint intensity	Felker overprint intensity	Original NRM intensity
$66,800 \times 10^{-6} \text{ G}$	$49,200 \times 10^{-6} \text{ G}$	$42,400 \times 10^{-6} \text{ G}$

$$\text{Mean emu susceptibility} = 286,000 \times 10^{-6} \quad (\text{isotropic})$$

$$\text{Original Koenigsberger ratio} = \text{NRM}/kH = 0.29 \text{ for } H = 0.51 \text{ Oe}$$

Thus in reality the remanence contributes about 25% of the total in situ magnetisation, whereas measurements of raw remanence on samples magnetically contaminated by drilling would indicate much greater importance of remanence, and would seriously mislead interpretation.

In general low Koenigsberger ratios indicate multidomain behaviour, which is associated with low coercivity. Thus we expect magnetically soft materials to have Koenigsberger ratios less than unity. A typical value for multidomain TRM is $Q_{\text{TRM}} = 0.5$ (Stacey and Banerjee, 1974, p 115). We can therefore expect that induction dominates remanence in rocks which are sufficiently soft to exhibit drilling-induced remagnetisation. Where magnetic contamination from drilling is suspected, the coercivity spectrum of the remanence should be tested. Coercivity of remanence or median destructive field greater than 50 Oersteds would suggest no significant remagnetisation by drilling. This is consistent with the values typical of most rocks, which show little or no sign of remagnetisation by drilling.

If we envisage the drilling-induced overprint as a product of activation of grains by vibration in an ambient field which is less than the intrinsic coercive force of the grains, then the acquisition of drilling-

induced magnetisation is analogous to other magnetisation processes such as production of TRM or anhysteretic remanent magnetisation (ARM). Thermal activation produces TRM, whereas the imposition of a large alternating magnetic field (with a time averaged value of zero) activates the grains in ARM. If the activation takes place in zero ambient field, the processes are thermal and AF cleaning respectively. In the presence of a small DC field, relatively hard TRM or ARM is acquired (the coercivity of remanence is much greater than the DC bias field). Thus vibration-induced magnetisation is envisaged to have a distributed coercivity spectrum, whose overall hardness is controlled by the mechanical energy of vibration, rather than by the strength of the ambient field. The magnitude of the magnetisation will depend on the proportion of magnetic material in the rock with intrinsic coercivities below the mechanical activation threshold. This model explains the very distributed coercivity spectrum of the observed overprint and the fact that the effect is only observed in rocks with predominantly very soft grains.

Because only magnetically soft material is susceptible to drilling remagnetisation, rocks which exhibit a drilling-induced overprint are expected to be magnetically unstable, i.e. significantly viscous. Experiments on the acquisition of viscous remanence by the massive magnetite are described in the next section.

5.4 Magnetic Viscosity of Massive Magnetite

Magnetic material of low coercivity tends to acquire a viscous magnetisation parallel to the ambient field. Therefore rocks which are sufficiently soft to acquire a strong drilling-induced component, may well have reached thermal equilibrium with the Earth's field when in situ. In this case the effect of remanence is merely to enhance the effective susceptibility of the rock, and induction can be assumed in modelling. The remanence is likely to be less than the induced magnetisation ($Q < 1$).

To test the hypothesis that the massive magnetite used in this study carried a dominantly viscous magnetisation before contamination by drilling, a fully demagnetised specimen was exposed to the Earth's field for progressively longer periods. After each measurement of the remanence, the specimen was replaced into the field in the same orientation.

Over the duration of the experiment (30 seconds - 372 days), the viscous magnetisation grew approximately as the cube root of time ($\Delta J = 51.6t^{0.33}$, where ΔJ is in microgauss and t is in seconds). After 372 days the viscous magnetisation was $16,400 \times 10^{-6}$ G, which is almost 40% of the original NRM intensity. This extremely rapid growth of the viscous remanence implies that the specimen is very unstable and that viscous magnetisation should dominate the remanence of similar material exposed to the Earth's field for the last 700,000 years, i.e. since the last reversal of the geomagnetic field. Therefore the in situ remanence of the magnetite ore body should simply parallel the induced magnetisation. This knowledge greatly simplifies interpretation of anomalies due to similar sources.

Viscous magnetisation is usually characterised by a logarithmic time dependence, so we would expect the acquisition of VRM by the specimen to slow down considerably once it is past the initial stage which obeys the power law given above.

The median destructive field of the VRM acquired in one year is 15 Oersteds, but the viscous component is not completely removed by AF cleaning in 150 Oersteds. As the acquisition time increases, the VRM will become harder. Therefore the observed coercivity spectrum of the NRM in this rock seems to be consistent with a VRM acquired over hundreds of thousands of years.

5.5 Conclusions

(i) It has been shown that drilling of this very magnetically soft material in low ambient fields does produce a strong spurious remanent component. It is expected that even greater remagnetisation might occur

in field drilling, and therefore measurements of raw NRM would be misleading, if not meaningless.

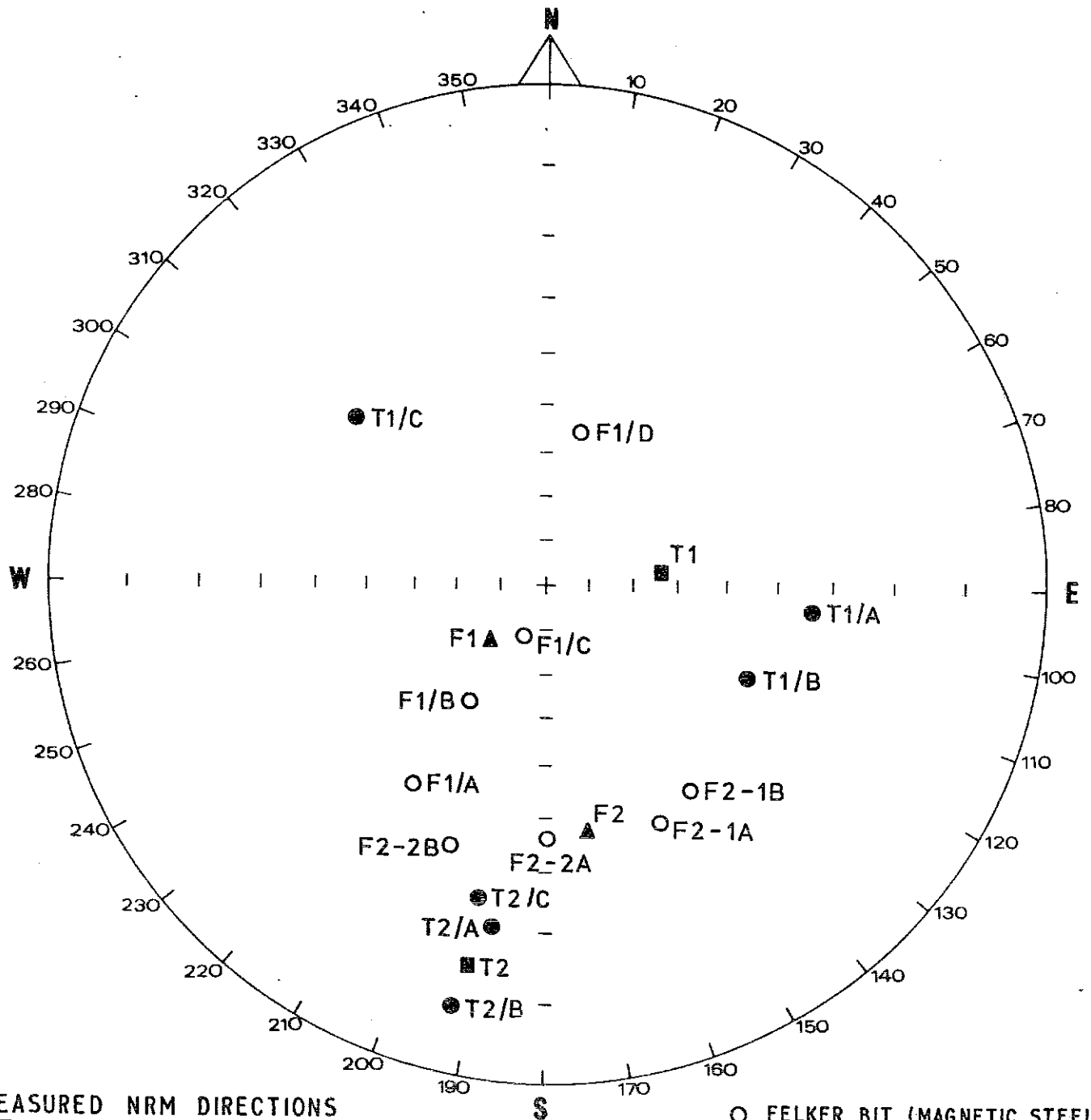
(ii) The drilling remagnetisation effect is negligible for most rocks which have distributed coercivity spectra, dominated by relatively hard grains. In the case of the massive magnetite sample, the predominance of large multidomain grains, which are sufficiently soft to be remagnetised by drilling, is correlated with low Koenigsberger ratio. Therefore modelling can proceed on the assumption of magnetisation by induction, to a first approximation.

(iii) Low coercivity implies magnetic instability, and short viscous relaxation time. We suggest that material which is sufficiently remagnetised by drilling, will possess a remanence dominated by VRM. Therefore the effect of remanence in these massive magnetite deposits should merely be to enhance the effective susceptibility. Magnetisation by induction can be assumed in interpretation, but the apparent susceptibility may be somewhat higher than measured values would indicate (e.g. 50% higher if $Q_{\text{NRM}} = 0.5$).

(iv) AF cleaning preferentially removes the soft drilling-induced overprint in the massive magnetite. Step-wise demagnetisation on oriented drill-core samples may allow determination of the original magnetisation direction and intensity. This is important for modelling the intersected body to determine whether the observed anomaly is accounted for, or whether another magnetic source is indicated. Decisions on further drilling can then be based on this data. The in situ NRM direction can also be tried in modelling anomalies attributed to other unsampled coeval bodies. AF cleaning also has application to isolating the remanence component carried by hard grains, which may only be a very small fraction of the total. A stable ancient magnetisation borne by the hardest grains may be useful for magnetostratigraphic correlation.

Figure 5-1. Remanence directions of massive magnetite specimens partially remagnetised by drilling

Figure 5-2 Remanence directions of same specimens depicted in Fig. 5-1 after AF cleaning to 200 Oersteds.

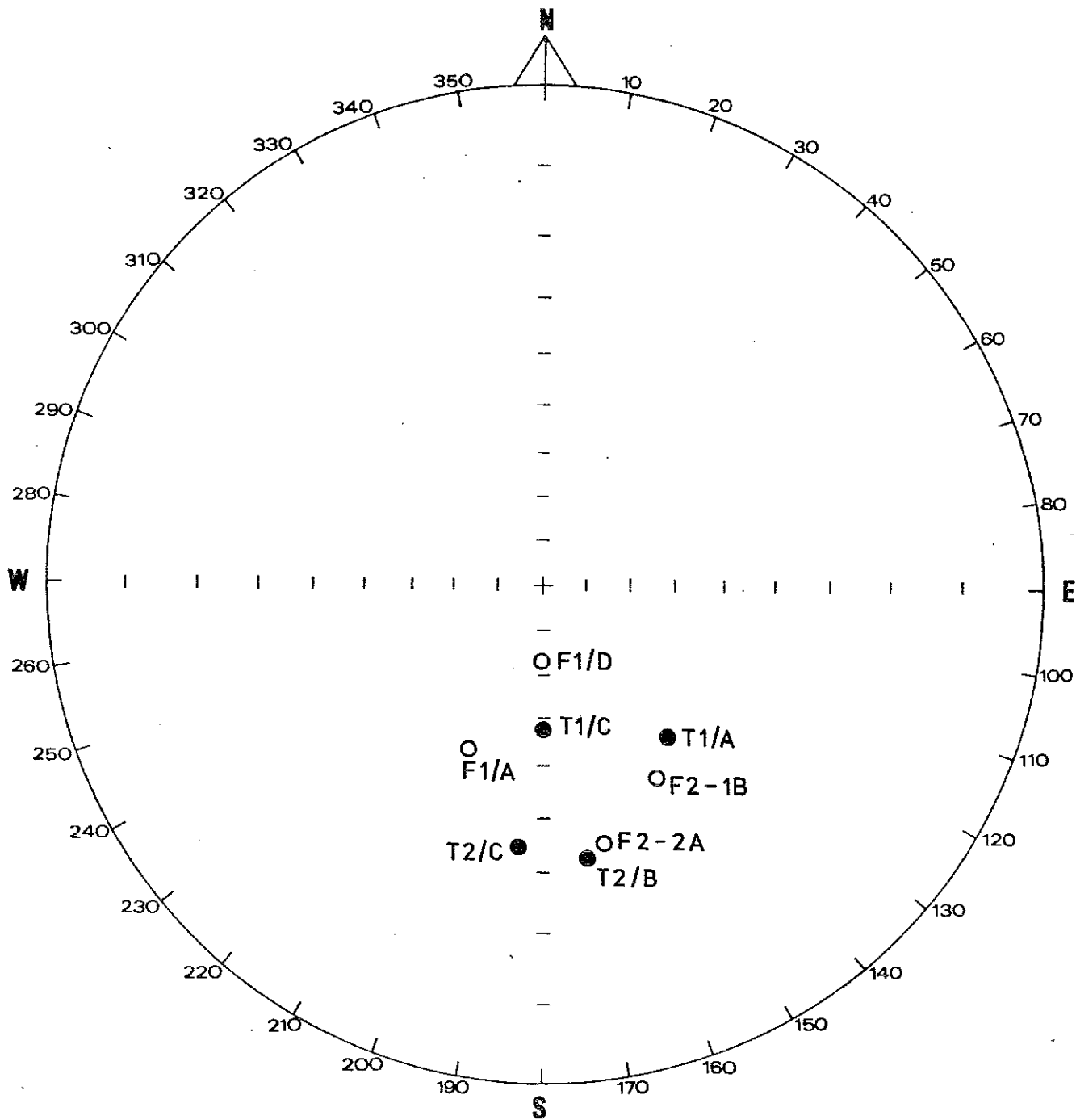


MEASURED NRM DIRECTIONS

T1, F1 DRILLED VERTICALLY
 T2, F2 DRILLED HORIZONTALLY

- FELKER BIT (MAGNETIC STEEL)
- TRIEFUS BIT (STAINLESS STEEL)
- ▲ MEAN DIRECTION F1, F2
- MEAN DIRECTION T1, T2

FIG. 5-1



REMANENCE DIRECTIONS AFTER
AF DEMAGNETISATION TO 200 OE

1R1193 R.

FIG. 5-2

6. USE OF PALAEOMAGNETIC CLEANING TECHNIQUES FOR DETERMINATION OF REPRESENTATIVE REMANENCE DIRECTIONS

6.1 Multicomponent Magnetisations in Rocks

Most rocks contain magnetic grains exhibiting a range of stabilities reflecting variations in grain size, shape and composition. When a rock is formed, it acquires a remanence which is usually parallel to the ambient field at the time of formation (a TRM for most igneous rocks, and a CRM or DRM for sedimentary rocks).

The most stable grains, such as single or pseudo-single domain particles, are capable of retaining this primary magnetisation over geological time, whereas magnetically soft grains are susceptible both to decay of the primary magnetisation and to remagnetisation. These unstable grains may be either large multidomains, or very small single domain particles verging on superparamagnetic size.

The magnetisation of a rock depends on the interaction of its thermal and magnetic history with the stability spectra of its constituent magnetic minerals. The coercivity spectrum of the rock indicates resistance to remagnetisation by exposure to magnetic fields, and the blocking temperature spectrum defines the response to thermal activation.

If a rock is briefly heated and cooled, for instance by contact metamorphism, all grains with blocking temperatures less than the maximum attained temperature are remagnetised. The overprint component is a partial thermoremanent magnetisation (PTRM), is aligned with the ambient field at the time of acquisition, and can be removed by thermal demagnetisation in the laboratory to a temperature approximating that of acquisition.

Thermal activation of magnetic grains is a function of time as well as temperature. For instance, the magnetisation of grains held somewhat below their laboratory blocking temperature will tend to relax towards the ambient field and ultimately equilibrate with it. If the ambient temperature is well below the blocking temperature, the time constant of this relaxation process is very long ($\gg 10^9$ years) and the metastable primary magnetisation may,

for practical purposes, be considered as completely stable. If, however, the ambient temperature is sufficiently close to the laboratory blocking temperature there is a significant tendency for the magnetisation to relax viscously towards the prevailing field direction, whilst any earlier magnetisation decays. Viscous magnetisation is enhanced at elevated temperatures and a substantial viscous PTRM may build up during prolonged burial of a rock formation. During subsequent uplift and cooling the viscous PTRM is "frozen in" and is expressed as an overprint component of intermediate stability, the laboratory blocking temperatures lying between the temperature associated with burial, and the maximum blocking temperature of the residual pre-burial magnetisation, if any.

Viscous magnetisations acquired at surface temperatures in recent geological time are easily removed by thermal cleaning, and are recognisable by their proximity in direction to the present field. AF cleaning is often successful in preferentially removing viscous components in magnetite-bearing rocks, however fine-grained haematite may acquire a VRM which is very resistant to AF demagnetisation (Dunlop and Stirling (1977)).

When a rock is exposed to magnetic fields greater than a few Oersteds, all grains with coercive force less than the applied field acquire an isothermal remanence (IRM). Because the coercivity spectrum in most rocks extends to values of several hundred Oersteds or higher, an IRM is most unlikely to have reprinted the magnetisation of the rock. Even the fields produced by lightning strikes do not usually exceed 100-200 Oersteds, so the primary magnetisation is preserved by the magnetically hard grains, whilst the soft grains bear the lightning induced overprint. Rocks with a significant fraction of low coercivity grains may also acquire secondary components by exposure to the smaller fields inevitably encountered during transport and storage. This may be a significant source of noise in palaeomagnetic work.

IRMs are easily removed by AF cleaning at peak fields similar to the field in which the IRM was acquired. Originally scattered NRM's which group

well after AF cleaning to 5-10 Oersteds suggest that the scatter was due to IRM components acquired during or after collection. The effects of lightning strikes can be recognised by scatter of NRM directions which is essentially removed by AF demagnetisation to 50-200 Oersteds, highly variable and often large NRM intensities, and high but variable Koenigsberger ratios. Thermal demagnetisation is often ineffective in removing IRMs.

Rocks may also acquire a CRM associated with secondary magnetic minerals, during alteration or weathering. The secondary CRM direction normally reflects the field direction at the time of alteration, but Marshall and Cox (1971) report the effects of oxidation on a submarine basalt, finding that the NRM of the primary titanomagnetite is not destroyed by oxidation which occurs below the original Curie temperature of the titanomagnetite. Laterites bear remanence directions associated with the formation of the secondary magnetic minerals. Often the lateritisation process spans several field reversals, and roughly equal numbers of normal and reversed directions are found within the formation. The stability of secondary CRMs may be greater than that of the primary NRM, so cleaning techniques may in fact emphasise a secondary component at the expense of the primary magnetisation.

6.2 Reliability of NRM Measurements

In general the magnetisation of a rock sample will be multicomponent. Chemical and textural inhomogeneities may lead to variability of remanence intensity and direction throughout the rock as the proportion of each magnetisation component present changes. When the stability spectra of different magnetisation components are not completely overlapped, as is commonly the case, cleaning techniques can resolve the individual components, each of which pertains to a particular phase in the history of the rock. This is the basis of cleaning in palaeomagnetism.

Well-grouped NRM directions from a rock unit indicate either the remanence is dominated by a single component, or else the rock is very

homogeneous with regard to grain structure and composition of its magnetic minerals. In either case the in situ remanent magnetisation of the unit should be determined by the NRM measurements. Scattered NRM directions indicate multicomponent magnetisations. If the directions are strung along a great circle arc, two components predominate (for instance a VRM along the present field direction, and an ancient stable magnetisation). More complex magnetisations produce complicated distributions of directions.

When the NRM directions are scattered, more extensive sampling is required to characterise the overall magnetisation of the rock unit, but in principle the gross in situ remanence is best estimated by the vectorial mean of the measured NRMs, provided the sampling is representative of the bulk of the rock. However the sampling is often dictated by accessibility of outcrop and surface effects, particularly weathering and lightning strikes, may significantly bias the results. Similarly spurious components may be acquired during collection (see section 5), transportation or storage of samples.

In attempting to unravel the magnetic history of a sampled rock formation it is therefore advisable to investigate the magnetic mineralogy of the rock and carry out a full palaeomagnetic analysis of the magnetisation components present. This should, plausibly, increase the confidence with which one can discriminate between remanence components which are representative of the rock as a whole, and those which can be considered as noise (IRM and weathering-induced CRM). We may hypothesise that application of palaeomagnetic cleaning techniques may allow determination of more representative remanence directions and, in some cases, magnitudes.

Circumstantial evidence in support of this hypothesis is afforded by three general observations, based on experience with a number of sampling programmes:

- (i) NRM directions from surface samples are frequently scattered

- (ii) NRM directions from under ground or drill-core samples seem often to be less scattered.
- (iii) AF cleaning of surface samples which are suspected of being lightning-affected greatly reduces the scatter of NRM directions.

Stronger evidence is to be found in a number of case histories which will now be discussed, but a definitive testing of the hypothesis requires oriented samples of both surface exposures and virgin rock at depth within the same lithological unit.

6.3 Case Histories

(i) Tennant Creek massive magnetite. In section 5 the effect of drilling in an ambient field on this magnetically soft material was described. An intense, but soft, overprint dominated the measured NRM of core samples, but was not representative of the in situ NRM. AF cleaning successfully removed the drilling-induced overprint and allowed determination of the original NRM.

(ii) Acid volcanics from North Queensland. A prominent negative anomaly is associated with this outcropping rhyo-dacite unit in an area considered possibly favourable for tin mineralisation. Of the five sites sampled one exhibited well-grouped reversed NRMs which were stable to both thermal and AF cleaning, with no evidence of any other components. The other sites were all lightning-affected, with erratically varying NRM intensities and Q values, and scattered directions. Some samples (e.g. SV25D-1 in Figure 6-1) had normal polarity NRM directions, and these would have confused the interpretation had they been considered representative. However lightning-induced IRM is magnetically softer than the primary TRM. Therefore AF cleaning was able to remove the IRM, and the cleaned directions corresponded with directions from the unaffected site. The observed anomaly could then be accounted for using the reversed primary direction and intensity values from the lightning unaffected site

(which is represented by SV25J-1 in Figure 6-1). There was therefore no need to explain the negative anomaly by assuming the presence of a reversely magnetised ore body similar to those elsewhere in the area.

(iii) Mogo Hill basaltic diatreme, Sydney basin. The geology, petrophysics and geophysics of this intrusion have been recently described by Emerson and Wass (1980), and the palaeomagnetism is discussed by Schmidt and Embleton (1980). An 800 gamma negative anomaly is associated with the body, indicating the overall in situ magnetisation of the intrusion is reversed. However the NRM directions are very scattered with normal polarities as common as reversed. The remanence is mostly carried by multidomain titanomagnetite grains which are magnetically quite soft, and which have readily picked up IRM components, probably since collection. The samples were collected in a quarry, so they are presumably not lightning-affected. These randomly directed IRMs are readily removed by AF cleaning, sometimes in fields as low as 5-10 Oerstedes, and the cleaned directions are very well grouped about a mean direction which is near vertical downwards (Figure 6-2). The AF cleaned direction is consistent with the mean magnetisation of the body inferred from magnetic modelling.

(iv) The ultramafic intrusion at Mt Derriwong, NSW. This body was reported on by Emerson, Embleton and Clark (1979). It was found that better agreement between the observed and calculated magnetic anomalies was obtained when the AF cleaned remanence direction was used rather than the mean NRM direction.

The cleaned and raw remanence directions were 35° apart. Although it could be argued that departures from the chosen model geometry could account for the difference, it was considered unlikely because the interpretation was constrained by petrophysical and geological information, and confirmed by gravity modelling. Although a few samples may have been lightning affected, the cleaning data from the majority of samples suggest the presence of two components in the NRM, the softer of which is unrepresentative of the bulk of the intrusion. The explanation is uncertain,

but the more easily removed component may be associated with weathering. If this is so, it is fortuitous that the secondary magnetic minerals produced by the weathering, are predominantly of low coercivity. If the secondary magnetisation is viscous in origin, it should be present throughout the body, contrary to the conclusions based on modelling.

In conclusion, indications are that AF cleaning, in particular, may be useful in determining representative remanence components from a number of rock types so far sampled. Analysis of multicomponent magnetisations through thermal, AF and chemical demagnetisation techniques, together with vector analysis, seems to show promise as an improved method of assigning remanence parameters to sampled rock formations. Provided the sampling is carried out over an originally (i.e. pre-surface effect) representative section, the magnetisation components applicable to the whole rock unit are (i) stable ancient magnetisations and (ii) superimposed viscous components. The palaeomagnetic noise, which it is desirable to remove before using NRM measurements as input to interpretation, is represented by magnetisations carried by secondary magnetic minerals produced by weathering; IRMs (whether lightning-induced or post-sampling); and components associated with vibration or shock, as in drilling or blasting-induced magnetisations.

Figure 6-1. AF cleaning of selected specimens from acid volcanic unit in North Queensland. Stereographic (equal angle) plot of vector directions with open symbols denoting upper hemisphere (negative inclinations), closed symbols lower hemisphere (positive inclinations). Squares denote NRM directions, circles are cleaned directions in progressively higher fields. Note stability of remanence directions for SV25 J-1 (from lightning-unaffected site). SV25 D-1 and SV25 P-1 have multi-component NRMs, but AF demagnetisation removes the soft, but often intense, overprint and isolates a stable direction close to the SV25 J-1 direction. The well-grouped cleaned directions correspond to a primary Carboniferous magnetisation (TRM).

Figure 6-2. AF cleaning of specimens from the Mogo Hill diatreme in the Sydney basin. Vertical and horizontal diamonds represent present dipole field and present field direction respectively; other symbols are as in Figure 6-1. The NRM directions are randomly scattered due to noise components acquired isothermally by the magnetically soft grains. The AF cleaned directions are well-grouped about the mean direction (near vertical downwards), which is consistent with the mean in situ magnetisation direction from ground magnetics. The best overall grouping of cleaned directions is obtained between 5 and 20 mT (50-200 Oersteds), but many specimens are fully cleaned in fields lower than this.

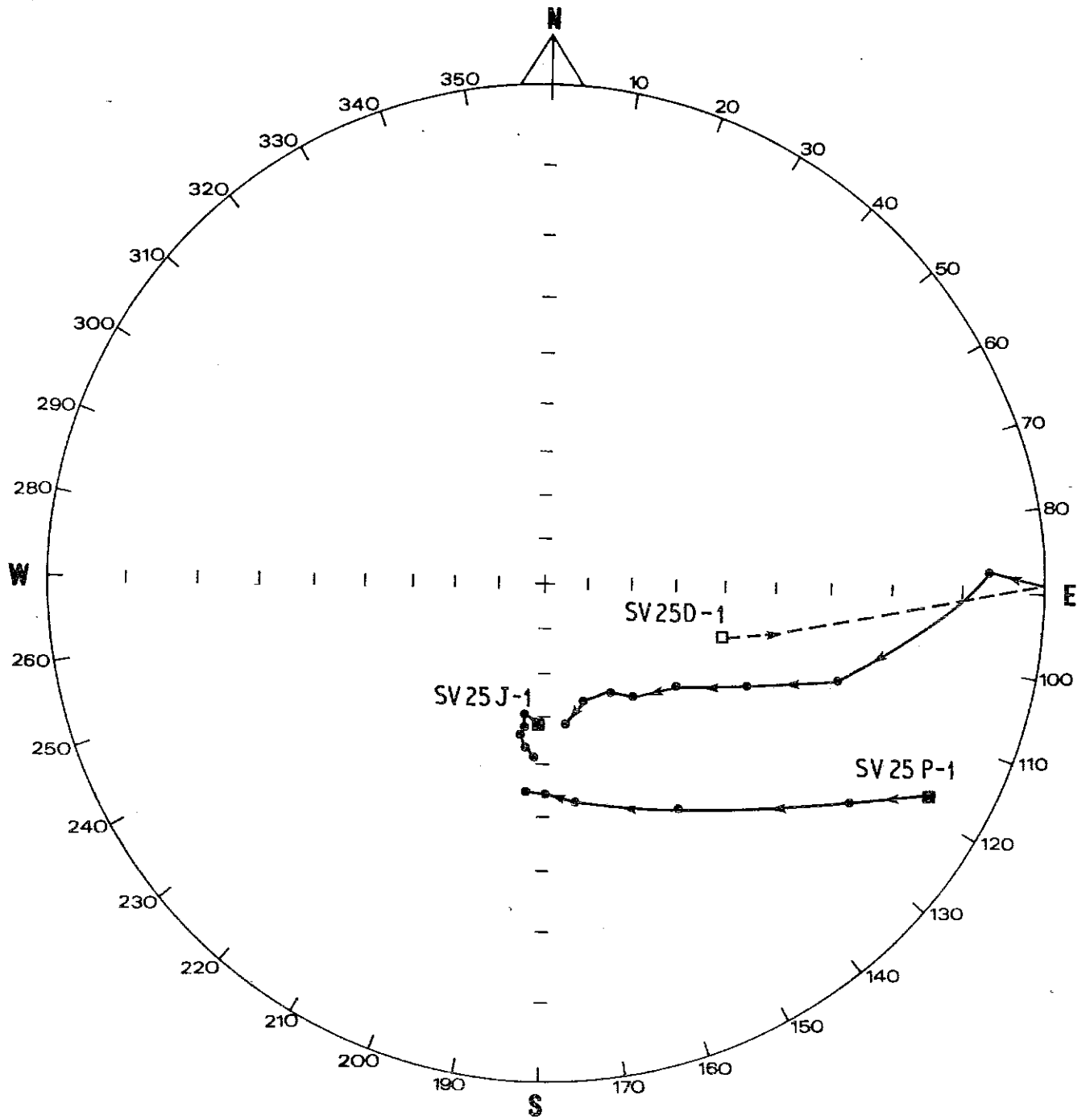
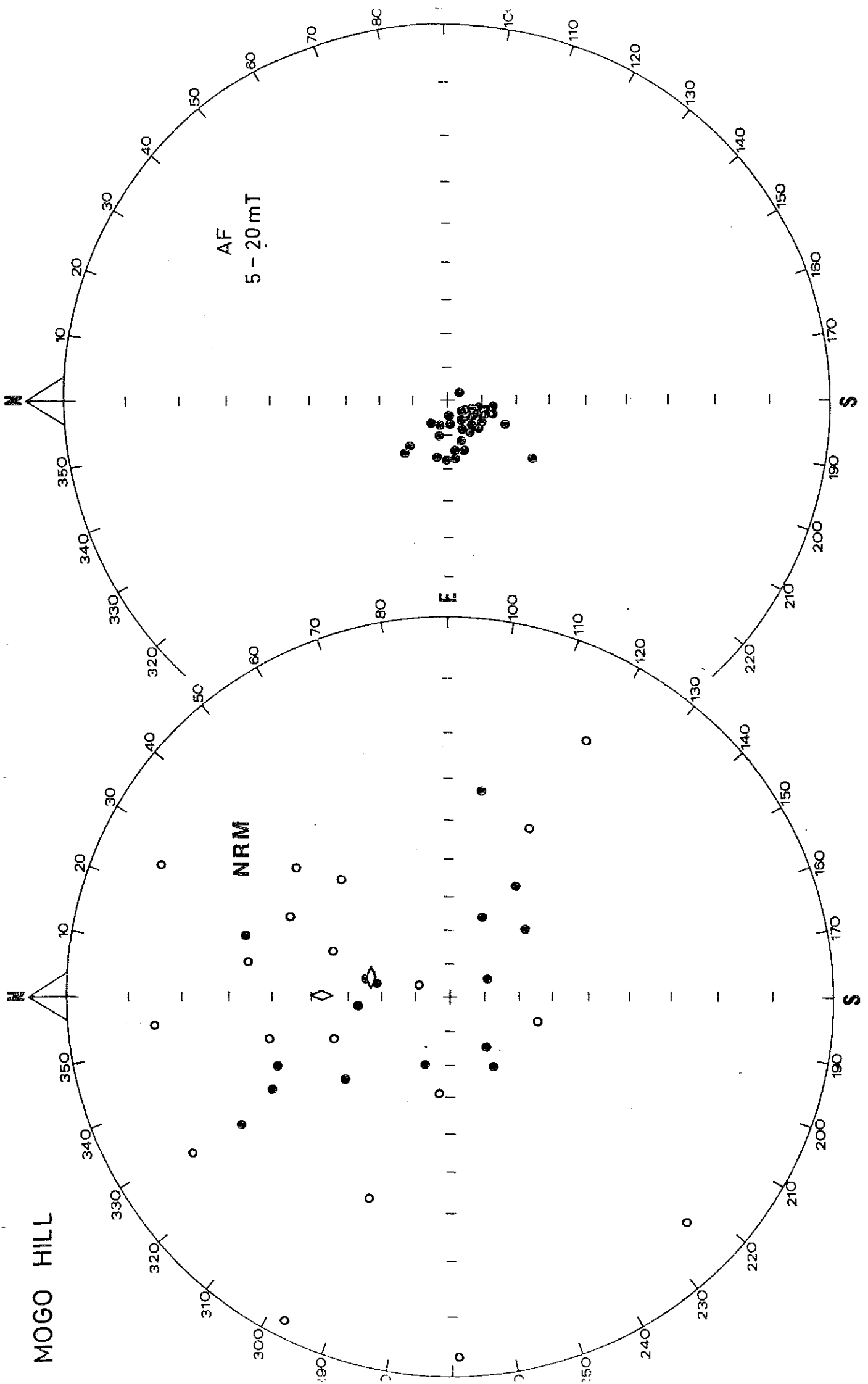


FIG. 6-1

D Clark. 1R1126 R



MOGO HILL

AF
5 - 20 mT

NRM

FIG. 6-2

7. SUPERPARAMAGNETISM OF MAGNETIC MINERALS IN OVERBURDEN AT ELURA

The EM group at North Ryde approached us with a view to analysing "maghaemite"-bearing soils collected around Elura. The motive for this work was to seek an explanation for anomalous tails observed in time-domain SIROTEM responses over Elura at late delay times with coincident loop geometry. The suggestion was that complex, hence frequency dependent, susceptibility of magnetic surface material could influence the TEM response, giving spurious conductivity values for this geometry where the receiving loop is within the magnetic zone of influence around the transmitter loop.

It is well known that the susceptibility of single and multidomain particles is independent of frequency in the range of interest. However extremely fine grains (<0.04 microns) of magnetite or maghaemite are superparamagnetic at room temperature (see section 3). Superparamagnetism arises from lowering energy barriers (which are proportional to particle volume) between stable magnetisation states, enabling thermal agitation to activate transitions between magnetisation directions. Thus superparamagnetic particles are unstable, with relaxation times short compared to the duration of laboratory measurements. They cannot retain a remanence over the laboratory time scale, but because they respond so readily to an applied field, they have high susceptibility.

For each grain there is a critical blocking temperature, below which the grain is a stable, single domain particle, with high remanence and low susceptibility, but above which it is superparamagnetic. Thus as the temperature is increased through the blocking temperature, the susceptibility of the grain suddenly rises. In the vicinity of the blocking temperature the relaxation time of the grain varies sharply with temperature, changing from millions of years in the stable region well below the blocking temperature to 10^{-10} seconds well above it. Therefore at any one temperature a range of grain sizes, corresponding to a spectrum of blocking temperatures will exhibit a spectrum of time constants.

Grains with time constants in the range 1 second to 10^{-4} seconds will exhibit markedly frequency dependent susceptibilities between 1 Hz and 10 kHz. Consider a grain with time constant τ . Upon removal of an applied field its magnetisation will decay exponentially.

$$J = J_0 \exp(-t/\tau) \quad (1)$$

Thus the magnetisation in the absence of an applied field obeys the differential equation

$$\tau dJ/dt + J = 0 \quad (2)$$

If a sinusoidal field $H = H_0 \exp(j\omega t)$ is applied, we then have

$$\tau dJ/dt + J = k_0 H \quad (3)$$

where k_0 is the DC susceptibility. The steady state solution of (3) shows J will lag behind H . The complex susceptibility k is given by

$$k = J/H = k_0 (1 - j\omega\tau) / (1 + \omega^2\tau^2) \quad (4)$$

Thus the real (in-phase) component of susceptibility is frequency dependent and is given by

$$k_r = k_0 / (1 + \omega^2\tau^2) \quad (5)$$

The quadrature component is

$$k_i = k_0 \omega\tau / (1 + \omega^2\tau^2) \quad (6)$$

To determine whether grains which are superparamagnetic at normal ambient temperatures are present in the soil, a thermomagnetic study of a crushed magnetic nodule from the area was made. The presence of grains with blocking temperature near room temperature would have time constants of the right order to exhibit frequency dependent susceptibility.

The thermomagnetic curves shown in the figure give a comparison of the Elura laterite with a typical multidomain magnetite bearing rock. Whereas the susceptibility of the magnetite specimen remains constant until just below the Curie point, the $k(T)$ curve of the laterite climbs steadily and steeply from -196°C to 500°C . This behaviour is diagnostic

of successive unblocking of grains and consequent rise in susceptibility as the temperature increases. The spectrum of blocking temperatures in the sample ranges from liquid nitrogen temperatures up to 500°C corresponding to grains with very short relaxation times to very stable grains. Thus the presence of grains with blocking temperatures in the correct range, approximately 20°C , is clearly demonstrated.

It is difficult to estimate the proportion of viscous magnetic material with time constants in the right range to affect TEM response. If we take the range of time constants over which the superparamagnetism significantly affects the signal as 1 ms - 100 ms, the ratio of the corresponding particle volumes at fixed temperature is 1.33. This corresponds to a ratio of 1.33 between upper and lower limits of the blocking temperature range at constant susceptibility measurement frequency. The blocking temperatures of grains which influence TEM response therefore lie between 257°K and 342°K (-16°C to 69°C). Assuming a uniform distribution of blocking temperatures from -200°C to 500°C , as suggested by the thermomagnetic curve, the proportion of significantly viscous material is 12%. This result is very approximate and only applies to the particular magnetic nodule which was used in the experiment. The superparamagnetic material should be highly diluted in the soil, and the overall proportion therefore reduced.

Figure 7-1. Low-field (k-T) thermomagnetic curve of magnetic nodule from overburden at Elura.

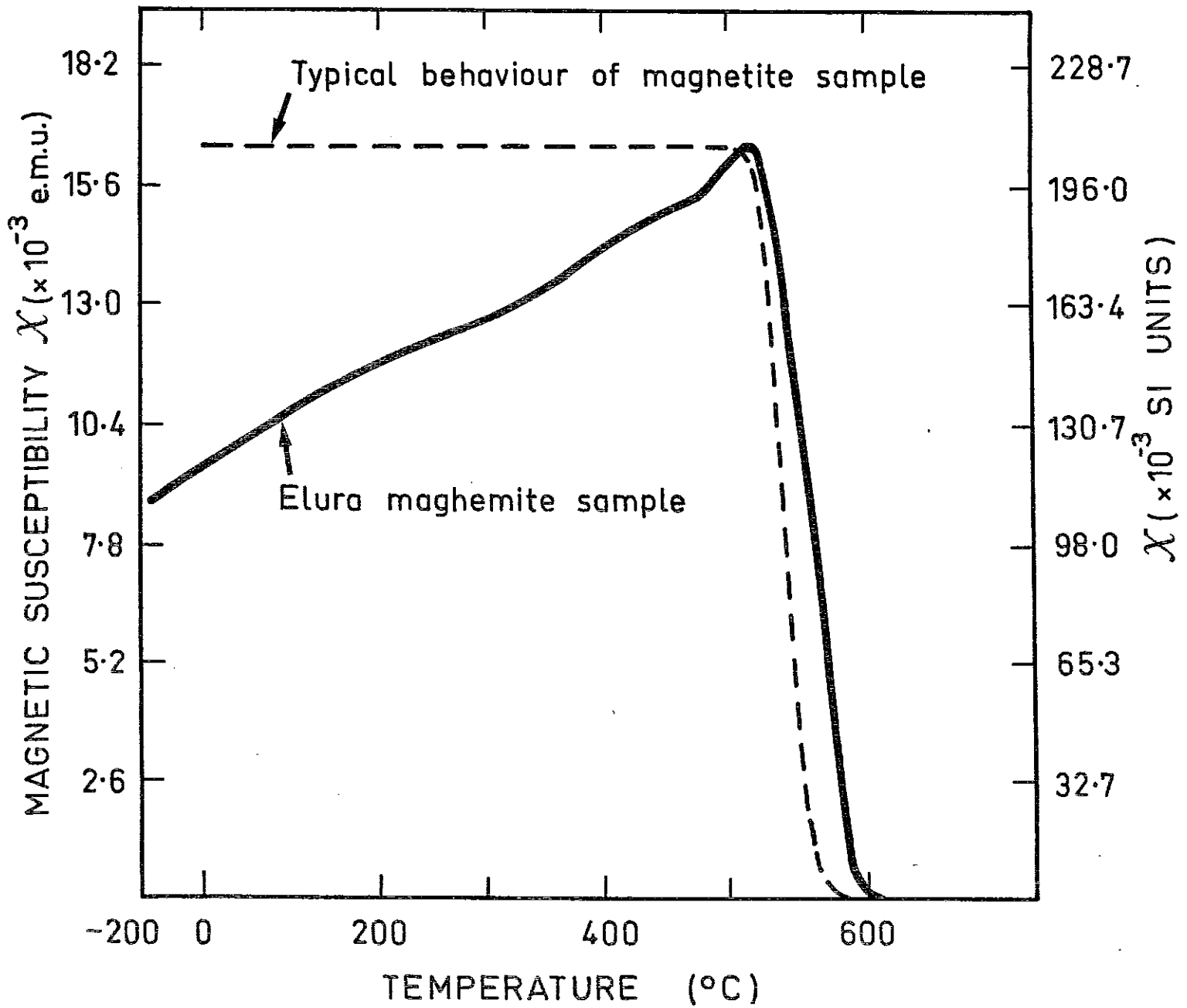


FIG. 7-1

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