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MAGNETIC PETROPHYSICS OF PYRRHOTITE-BEARING ROCKS

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1. MAGNETIC PETROPHYSICS AND MAGNETIC INTERPRETATION

Magnetic surveying is one of the most frequently applied geophysical methods, yet interpretation of magnetic data in terms of geology lags far behind other geophysical techniques, notably seismic methods. The major problem in obtaining useful geological information from magnetic surveys is lack of information about magnetic properties of rocks. Like other geophysical methods, magnetics is afflicted by ambiguity in that models which account for observed anomalies are always non-unique. A simple example is afforded by the commonly applied thin sheet model, for which the magnitude of the anomaly is determined by the magnetisation-thickness product and for which the form of the anomaly depends on both the dip of the sheet and the effective inclination of the magnetisation component normal to strike. Without knowledge of the magnetisation the thickness and dip of the body cannot be determined with any confidence.

The total magnetisation of a rock is made up of induced and remanent components, added vectorially. In the case of an isotropic rock with bulk susceptibility k, the induced magnetisation $\underset{\sim}{J}_I$ is parallel to the Earth's field $\underset{\sim}{H}$ and is equal to $k\underset{\sim}{H}$. The natural remanent magnetisation (NRM) $\underset{\sim}{J}_N$ is the permanent magnetisation of the rock and is independent of a weak applied field. In practice $\underset{\sim}{J}_N$ is usually measured in zero ambient field. The total magnetisation is given by $\underset{\sim}{J} = \underset{\sim}{J}_I + \underset{\sim}{J}_N = k\underset{\sim}{H} + \underset{\sim}{J}_N$. The relative contributions of induced and remanent magnetisation to the total are characterised by the Koenigsberger ratio, $Q = J_N/kH$.

Magnetisation by induction (i.e. $J_N=0$) is commonly assumed in modelling, in the absence of information to the contrary. If $Q \gtrsim 1$, however, this assumption can lead to substantial errors in interpretation, particularly as the remanence may be highly oblique to the present field. In practice remanence is nearly always found to be important. Determination of the magnetic properties of the rock types represented in the area under consideration serves to constrain interpretation by restricting the range of feasible models. Particularly when integrated with other information (geological control, drilling data, other geophysical methods, etc.), knowledge of magnetic properties can often lead to an interpretation which is highly probable or even effectively unique in geological terms.

As well as assisting magnetic interpretation in particular areas, compilation of magnetic petrophysics data is essential for a deeper understanding of the relationship between geology, rock magnetism and magnetic signatures. The complexity of this relationship is evidenced by the dependence of the magnetic response of a rock unit on *inter alia* lithology, structure and geological history (palaeoenvironment, thermal history, alteration).

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 pyrrhotite in barren rock explains the anomaly and that further drilling is not justified. Alternatively, the results may suggest that the target has been missed altogether, or the intersected body only partly accounts for the anomaly. This would encourage further drilling to locate a discrete nearby source which could be an orebody.

Published petrophysical data on pyrrhotite-bearing rocks are rather sparse. Kropacek (1971) and Kropacek and Krs (1971) have made a valuable contribution to knowledge of susceptibilities, remanent intensities and Koenigsberger ratios of pyrrhotites of varying composition and provenance.

Of a total of 27 samples, 32% were determined by thermomagnetic analysis to be monoclinic pyrrhotite, the remaining 68% exhibiting mixed-type thermomagnetic curves which established the presence of varying proportions of intermediate pyrrhotite. Values of saturation magnetisation, J_s, and apparent Curie temperature, T_c, had bimodal distributions. J_s varied approximately from 0-20G with peaks over the intervals 0-5G (40%) and 15-20G (30%). T_c varied roughly from 295^{o}C to 350^{o}C with peaks over the intervals 295-305^{o}C (22%) and 315-325^{o}C (42%). For the samples with mixed-type J_s-T curves, T_γ (the temperature at the peak) ranged from 210° to 310°, with the bulk (60%) of the values lying between 230° and 270°C.

It is probable that most of the massive pyrrhotite samples consisted of relatively coarse grains, not subdivided on a very fine scale by non-magnetic phases, as the coercivity and blocking temperature spectra of all the samples are quite similar. The mean AF coercivity spectrum is exponential in form with ~50% of NRM remaining after demagnetisation to 50 oe peak field, 27% after 100 oe AF and only 2% after 400 oe AF. The bulk of the average unblocking temperature spectrum of NRM (~70%) is above 200°C.

Both the susceptibilities and NRM intensities of the samples are log-normally distributed, to a good approximation. The results of the statistical analysis are summarised in Table 1. Results from samples containing weakly magnetic intermediate pyrrhotite are included in this analysis. Therefore average values (whether arithmetic or geometric means) of k and J_N for monoclinic pyrrhotites are much higher.

As discussed by Clark (1983a), the remanent magnetisation of rocks is often complex with several remanence components present. This particularly applies to pyrrhotite-bearing rocks which readily acquire thermal overprints. At the time of formation the rock acquires a primary remanence, or imprint. During its subsequent history the rock may acquire a thermal or chemical overprint, or even be remagnetised completely, in which case the secondary magnetisation is a reprint. Secondary components of magnetisation may also be NRM acquired parallel to the Earth's field by grains with relaxation times shorter than the latest geomagnetic polarity epoch, may be due to weathering or due to lightning strikes. In addition rock samples may acquire spurious remanence components during or after collection as a result of exposure to magnetic fields.

In general the various components of magnetisation reside in different magnetic grains or zones of grains which have different stabilities to various palaeomagnetic cleaning techniques. Application of cleaning techniques together with modern methods of palaeomagnetic data analysis such as vector diagrams (Zijderveld, 1967), principal component analysis (Kirschvink, 1980), remagnetisation circles (Halls, 1978), Hoffman-Day plots (Hoffman and Day, 1978), etc., allows determination of the various remanence components present in the rock.

The relevance of these palaeomagnetic methods to petrophysical studies intended for input to magnetic interpretation is that NRM measurements on rock samples are often not representative of the bulk of the rock unit. Outcrop samples are often affected by weathering and lightning strikes. Samples collected in mines and quarries are often contaminated by exposure to magnetic fields, or may in some cases be affected by blasting. Drill core samples may, if sufficiently soft magnetically, acquire an axially-directed overprint during drilling using highly magnetic drill barrels.

Provided the sampling is carried out over a section which was originally representative, 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 (rarely) components associated with vibration or shock, as in drilling- or blasting-induced magnetisations.

More than one cleaning technique may be required to investigate the remanence components as the efficacy of each technique is dependent on the nature of the components. For instance, VRM is readily removed by thermal demagnetisation but, generally, not so readily by AF demagnetisation. The reverse applies to IRM.

An example of the application of palaeomagnetic cleaning to a petrophysical study is afforded by the pyrrhotite-bearing sediments at Magnetic Ridge, near Cobar. A number of linear magnetic anomalies in the Cobar area are associated with steeply dipping pyrrhotite-bearing sedimentary horizons. At Magnetic Ridge the susceptibility of the sediments is inadequate to account for the observed anomaly and this raises the question of whether remanent magnetisation of the sediments is responsible, or whether a discrete magnetic source has been missed by the drilling (A. Doe, pers. comm.).

A total of 10 drill core samples, of which 7 were oriented, were supplied by Tony Doe of CRA Exploration Pty. Ltd. The NRM intensities, bulk susceptibilities and Koenigsberger ratios of the samples are given in Table 2 A notable feature of the data is the relative consistency of measured susceptibility values ($k \sim 100 \times 10^{-6}$) throughout the depth range 250m - 431m, contrasting with variable remanent intensities. Koenigsberger ratios are therefore very variable, but generally high, implying that interpretation will need to take remanence into account. However variability in remanence intensity and direction causes difficulty in assigning representative values of these parameters to a modelled causative body and lessens confidence in interpretation. One way of improving estimation of representative remanence vectors is to carry out further sampling, but this is expensive and time-consuming. Alternatively, a deeper understanding of the cause and nature of the variability can improve estimation.

The mean NRM directions of the samples are given in Table 3. Consideration of Tables 2 and 3 together allows classification of the samples into two categories:

(i) Samples with relatively high NRM intensities (>400μG), high Koenigsberger ratios (>10) and well-grouped NRM directions, e.g. 250.0m. With one exception (375.0m) the directions are all of normal polarity, with steep negative inclinations. In the case of sample 375.0m the piece of core may have been inverted in the core tray.

(ii) Samples with relatively low NRM intensities and Q values. Individual specimen directions are streaked roughly along a great circle, suggesting a two-component system, e.g. 270.5 m, 310.4 m.

The variability in the remanence properties of these rocks is due to the multicomponent nature of the magnetisation. The palaeomagnetism of these rocks is discussed by Clark (1983a). Detailed AF and thermal cleaning revealed that all samples carry two well-defined components of magnetisation, a component which is soft to both AF and thermal demagnetisation and a hard component.

Type (i) samples bear soft and hard components of the same polarity which are similar in direction, differing by about 20^{o}, accounting for the relatively tight clustering of NRM directions. Type (ii) samples, on the other hand, possess streaked NRM directions because of the presence of soft normal and hard reversed components in varying proportions. A further two samples from another drill hole were also of this type. Distributions of NRM directions of specimens from the two types of sample are illustrated in Fig. 1.

Knowledge of the multicomponent nature of the NRM considerably simplifies estimation of a representative remanence vector for the formation. Without cleaning it would be necessary to base an estimate on limited sampling, with a highly non-Fisherian distribution of directions and variable intensities, which are strongly correlated with NRM direction.

Taking the palaeomagnetic results into account it is reasonable to assume ubiquity of the soft normal component. This is confirmed by results from other similar rocks in the Cobar area (see Clark 1983a). Both polarities of the hard component are present and reversals occur within narrow stratigraphic intervals (~20m). If we surmise that normal and reversed polarities of the hard component are more or less equally prevalent (4 out of the total of 9 oriented samples from this prospect have reversed hard components) the contribution of the normal and reversed hard components to the observed anomaly will approximately cancel at the surface. Therefore we need only consider the soft component which has a well-defined direction (pointing W and up at ~60^{o}, at this locality). As k is fairly uniform, the average intensity of this component can be roughly estimated from the mean Q values for type (i) and type (ii) samples, respectively assuming approximate parallelism and antiparallism of the hard components. $\bar{Q} \sim 15$ for type (i) samples and $\bar{Q} \sim 3$ for type (ii), giving the appropriate contributions of soft and hard components as $Q \simeq 9$ and $Q \simeq 6$ respectively.

This analysis therefore suggests an effective Q value of ~9 for this formation, with the remanence somewhat oblique (~45^{o}) to the present field, but adding overall to the induced component. Ignoring the effect on anomaly shape, the effect of the remanence is to increase the anomaly magnitude by a factor of ~$9 \cos 45^{o} \simeq 6$. In fact an enhancement of the measured susceptibility values by a factor of ~5 is required to account for the observed anomaly (A. Doe, pers. comm.) which is in good agreement with the value derived above.

2. VARIABILITY OF MAGNETIC PROPERTIES IN THE CLEVELAND TIN MINE

The aim of this study was to provide a case history of the variability of magnetic properties within a pyrrhotitic ore body and to gain an idea of the amount of sampling required to adequately characterise a deposit of this sort. It is important to know, for instance, approximately how many samples are needed to provide useful input to magnetic interpretation. Different sampling programmes might be required for different purposes. For example, if there is a correlation between magnetic susceptibility and ore grade a minimum sampling density is required for reliable geostatistical ore reserve estimation. Another problem of interest is the study of the structure of a deposit (e.g. zoning) through magnetic property measurements for which the optimum sampling pattern may be quite different to that required for other applications. In principle a sampling programme should be tailored to the particular problem at hand although this may be difficult to achieve in practice. The most important variables characterising a sampling programme are the sampling density, total number of samples, sample size (in geostatistical parlance, the "support") and sampling structure (random, stratified random, gridded, etc.).

The geological setting of the Cleveland tin deposit has been described by Ransom and Hunt (1975) and Collins (1981). Because many areas of the mine could not be sampled safely underground sampling was restricted to B Lens at 24 Level and part of 20 Level. Eighteen block samples of pyrrhotite ore and two of barren shale with disseminated pyrrhotite were collected from 24 Level, 4 ore samples were taken from 20 Level, and a further 4 ore samples were collected at the surface in Hall's workings.

On 24 Level sampling was carried out along the full extent of the drive from footwall and hangingwall faces enabling determination of along-strike variations and expression of zoning in the magnetic properties.

The NRM intensities, susceptibilities and Koenigsberger ratios of the 24 Level samples are given in Table 4 and the same quantities for the 20 Level and surface samples are quoted in Table 5.

As expected, the shale samples are only weakly magnetic. The massive ore samples are variably magnetic with emu susceptibilities ranging from 660×10^{-6} to $25,160 \times 10^{-6}$. For the ore samples Koenigsberger ratios are predominantly greater than unity and for 24 Level the unweighted average Q value is 2.4. Therefore we can expect that remanence dominates the induced magnetisation, as found commonly in sulphide ores. The representative Q value for this deposit should be somewhat lower than 2.4 as the more magnetic samples tend to have lower Koenigsberger ratios.

There is no significant difference between J and k values of samples taken from the footwall and hangingwall, so there is no evidence in the magnetic measurements of zoning of the ore body parallel to the lithological layering. Definite trends are apparent along strike, however. As we move inwards from the ends of the drive the k and J values increase, reflecting the trend towards more massive ore.

Susceptibility values, which are mainly determined by the proportion of monoclinic pyrrhotite in the sample, show no clear trend up-dip, as k values from 20 Level and the surface are consistent with those found at 24 Level. The anomalously high NRM intensities of the surface samples are reflected in the very high, but variable, Koenigsberger ratios (some > 100) which suggest these rocks are lightning struck.

The NRMs of the underground samples are directed steeply upwards, sub-parallel to the present field. As discussed by Clark (1983a), the NRM is probably an ancient magnetisation, but the direction is sufficiently close to the present field that induction could be safely assumed in modelling, provided the effective susceptibility of the model were enhanced to account for the contribution of the remanence.

Statistical aspects of the data will now be discussed.

The values of the parameters k, J and Q and their logarithms were grouped in classes of equal width and the frequency distributions calculated. The frequency histograms for k, J and Q are shown in Fig. 2.

Overall it can be seen that J has a symmetric distribution whereas k and, to a lesser extent, Q have skewed distributions with a prominent tail for high values. These histograms are suggestive of normal and log-normal distributions respectively. The fit of the observed distributions to these theoretical distributions was tested by plotting cumulative frequencies against class midpoint on probability paper, both for the parameters and their logarithms. If this procedure produces a straight line the quantity plotted is normally distributed, and statistical estimation problems are reduced to standard procedures.

The results show that J, log k and log Q are approximately normally distributed, i.e. k and Q can be fitted by a log-normal distribution. Estimation from log-normal distributions is more complicated than from normal distributions, but the theory is nevertheless well understood (Aitchison and Brown, 1957). The basic problem is that the arithmetic mean of the sample values, whilst an unbiased estimate of the true mean, is not robust. This is reflected in the well-known fact that with skewed distributions, like that of k here, the sample mean is likely to be unduly influenced by one or two very high values, causing it frequently to overestimate the true mean. The effect is negligible for very large samples, but for the number of measurements here the minimum variance unbiased estimator of the mean should be used.

To calculate the best estimate of the true mean susceptibility of the ore body, based on the 26 ore samples, the following procedure is necessary:

(i) For each sample ln k is taken and the mean m and variance V of the logarithms calculated.

(ii) The best estimate of the true mean is $\exp(m)\ \gamma(V)$ where $\gamma(V)$ is Sichel's t-estimator, which is tabulated by David (1977, pp. 20-21).

Applying this:

$N = 26$, Arithmetic mean $k = 5{,}954$ s.d. $= 5{,}463$

$m = 8.317$, $V = 0.8254$

$\therefore \quad e^m \gamma(V) = 4{,}093 \times 1.5008 = 6{,}143$

Since the standard error $= 5{,}463/\sqrt{26} = 1{,}072$ the sample arithmetic mean and the best estimate of the true mean differ by only 18% of the standard error and there is little to choose between the estimators in this case.

Note also the sample median value is 4,130 which is close to the value estimated by the geometric mean $= e^m = 4{,}093$.

No rigorous statistical procedure is known for estimating the effective remanence vector for a rock unit with, say, a Fisherian distribution of NRM directions and normally or log-normally distributed NRM intensities. For the general case an intuitively plausible estimator of a representative value of $\tilde{J}$ is the vector sum of NRMs from all samples, divided by the number of samples.

Since the remanence direction for the undisturbed underground samples is virtually constant, the representative remanent intensity can be calculated from the individual sample intensities, with a correction factor R/N to account for scatter of directions (Strangway, 1965). Because the intensities can be taken as belonging to a normal population, the appropriate estimate of the mean value is simply the arithmetic mean of the sample values.

For the 22 underground ore samples we have:

$\bar{J} = 7{,}070 \pm 1{,}440$ (s.d. $= 6{,}774$)

The effective remanent intensity is $J_{eff} = 7{,}070 \times 21.72/24 = 6{,}400$, where we have considered all 24 NRM directions (see Clark 1983a).

The effective Koenigsberger ratio can then be estimated from the mean remanent intensity and susceptibility values:

$$Q = \bar{J}_{eff} / (\bar{k} \times 0.625) = 1.67 \pm 0.45$$

where the error is calculated assuming relative error equals the square root of the sum of the squares of the relative errors in $\bar{J}$ and $\bar{k}$.

Because in this case remanent and induced magnetisations are essentially parallel it is valid to assume induction in modelling taking the effective susceptibility $k' = \bar{k}\ (1 + Q) = 2.67\ \bar{k}$. Because no magnetic survey data collected before mining of the ore body are available, it is not possible to compare expected and observed anomalies over the deposit.

In recent times an advanced theory of regionalised variables has been developed for purposes of geostatistical ore reserve estimation. Techniques are available which give best estimates of average ore grades, total tonnages, risks and profitability etc. (David, 1977). In the case of estimation of average grade the technique is known as kriging.

Petrophysical parameters such as specific gravity, magnetic susceptibility and NRM intensity can also be regarded as regionalised variables and geostatistical methods can be applied. The key concept in geostatistics is that of the variogram, which is an inverse measure of the correlation between sample values as a function of the separation of the samples. In the one-dimensional case the variogram is defined by:

$$2\ \gamma(h) = [1/N(h)]\ \Sigma\ [Z(x_i) - Z(x_i + h)]^2$$

where the $Z(x)$ are sample values, $N(h)$ is the number of samples separated by h, and the summation is from $i = 1$ to $i = N(h)$.

Because correlation between samples generally decreases with separation, $\gamma(h)$ generally increases with h. The range of a variogram is the distance over which $\gamma(h)$ increases before reaching a plateau and therefore measures the zone of influence of a sample. Samples separated by more than the range are uncorrelated.

If $\gamma(0)$ is non-zero, the variogram is said to exhibit a nugget effect. Nugget effects reflect a component of random variation in the variable at the scale of sampling. If the variogram is simply a plateau it is called pure nugget effect type, and samples are uncorrelated whatever their separation. On the other hand, continuity in the deposit is reflected in gradual increase of $\gamma(h)$. The plateau value beyond the range of influence is known as the sill.

In Figure 3 the variograms for k and J are shown. There is some scatter but the data can be quite well fitted by a spherical model (David, 1977, p. 122) for k and a linear model for J.

The susceptibility variogram has negligible nugget effect and a range of 15 metres. The equation fitted to the data points by eye is:

$$\gamma(h) = 17.5\ [1.5\ (^{h}/15) - 0.5\ (^{h}/15)^{3}],\ h<15$$

$$\gamma(h) = 17.5,\ h>15$$

For J there is a small nugget effect and no apparent zone of influence. The variogram can be fitted by:

$\gamma(h) = 0.75h + 5.25$

From these variograms the best linear unbiased estimator of the average values can be calculated by kriging. In practice a computer is required, using one of the now freely available programmes for this purpose (e.g. David, 1977). As the geostatistical approach should now be used for routine ore reserve calculations, it is highly desirable that mine managers have access to geostatistical packages. These programmes could then be usefully applied to petrophysical studies.

The fact that the variograms shown in Figure 3 can be constructed implies that the sampling on 24 Level was sufficient to define the gross structure of the magnetic parameters of this lens. This is also borne out by the comparison of various estimates of mean values, which suggest that approximately 20 samples, of volume approximately $100cm^3$, distributed over a strike length of 70m are sufficient to estimate mean values to within 20% (which is the approximate standard error for both k and J). Values of k for 8 further samples distributed over a dip distance of about 500 metres (24 Level to Hall's workings) are consistent with the distribution of values found on 24 Level, which confirms the assumption that this lens, at least, has been well characterised by the sampling. Had only one quarter of the number of samples been taken, the relative error would double to approximately 40%, which is probably unacceptable. If only 10 samples had been collected from

24 Level, it is probable that well-defined variograms could not have been calculated.

In conclusion, the distributions of susceptibility and NRM intensity values within B lens of the Cleveland ore body appear to have been fairly well characterised by the level of sampling carried out (total of 28 small block samples over a strike length of 70 metres, up-dip distance of 500m, lens thickness 10 metres). Calculation of variograms for k and J on 24 Level suggest the applicability of modern geostatistical methods to estimation of average susceptibility and remanence.

The magnetisation of this body is dominated by remanence which is directed sub-parallel to the Earth's present field. Induction could be assumed in modelling, provided the model susceptibility is enhanced to account for the contribution of remanence.

3. MAGNETIC PROPERTIES OF SOME AUSTRALIAN PYRRHOTITE-BEARING ROCKS

A substantial collection of rock samples from all over Australia has been built up by the Rock Magnetism Group of the CSIRO Division of Mineral Physics. Because of the prominence of pyrrhotite as a contributor to magnetic anomalies in mineralised terrains, a large number of pyrrhotite-bearing samples have been submitted by mining and exploration companies. The magnetic properties of samples from a number of localities are summarised here.

k - cgs (emu) bulk susceptibility x 10^6

J - NRM intensity in microgauss

Q - Koenigsberger ratio = J/kH, where H is the Earth's field in oersteds

A - susceptibility anisotropy

The results are listed by locality with the 1:250,000 sheet in parentheses.

No particular order is followed, apart from grouping of results by State. Each set of results is an abbreviated case history of an orebody or rock unit and consideration of all the studies together allows some general conclusions to be drawn about the magnetic petrophysics of representative pyrrhotite-bearing rocks.

<u>Mt. Bischoff</u> (Burnie, Tas.)

k	J	Q	A
12,600	21,300	2.6	1.8
(5,900-23,100)	(5,400-41,200)	(1.7-3.2)	(1.3-2.3)

Sampling: Outcrop (exposed by excavation). 3 sites, 10 oriented samples collected with portable drill.

Remarks: Massive monoclinic pyrrhotite in cassiterite ore hosted by Upper Proterozoic or Cambrian sediments. Mineralisation possibly associated with Devonian granites and quartz-feldspar porphyries. Magnetic foliation plane appears to be bedding parallel. Near porphyry dykes mean AF cleaned direction (dec = 25°, inc = -55°) ~20° from present field. At margin of deposit AF cleaned direction (dec = 249°, - 13°) is highly oblique to present field. Directions are stable up to 300 - 400oe AF after removal of soft IRM components in 10 - 50oe AF.

Mt. Cleveland (Burnie, Tas.)

k	J	Q	A
6,100±1,100	7,100±1,400	1.9±0.7	1.34±0.05
(650-32,100)	(470-25,200)	(0.6-4.9)	(1.11-1.74)

Sampling: 26 magnetically oriented block samples from mine drives and quarry.

Remarks: Monoclinic pyrrhotite in semi-massive cassiterite-bearing ore hosted by Upper Proterozoic or Cambrian sediments. Mineralisation probably associated with nearby Devonian granite. Magnetic foliation plane sub-parallel to bedding and cleavage, and is probably a mimetic fabric. Mean NRM and (AF and thermal) cleaned directions (dec = 32°, inc = -75°) close to, but not identical with, present field. NRM is magnetically soft (mdf~20oe) but blocking temperatures >200°C predominate, with directioned stability to ~310°C.

Mt. Lindsay (Burnie, Tas.)

k	J	Q	A
280	290	1.1	-
(130-430)	(10-560)	(0.15-20)	

Sampling: 6 oriented outcrop samples from 2 sites, collected with portable drill from mine adit and river bed.

Remarks: Massive intermediate pyrrhotite with peak-type thermomagnetic curve. Remanence directions close to present field. NRM is magnetically hard (mdf 150-800 oe). Magnetic foliation plane parallel to regional bedding plane, consistent with magnetite-bearing rocks from the same area.

Balfour Area (Burnie, Tas.)

k	J	Q	A
560	7,700	22	
(520-600)	(7,300-8,000)	(20-24)	

Sampling: 2 unoriented drill core samples

Remarks: Disseminated (~5%) pyrrhotite in Proterozoic sediments.

Locality unspecified (Burnie, Tas.)

k	J	Q	A
370	2,200	12	1.5
(100-700)	(250-6,040)	(1-32)	(1.3-1.8)

Sampling: 3 oriented drill core samples

Remarks: Cambrian pyrrhotite-bearing skarn. NRM directions scattered. AF and thermal cleaning remove very soft randomly directed components, isolating more stable components which are S-SE or N-NW directed with very shallow inclinations. Zijderveld plots are often noisy. Mean direction of NRM, without regard to polarity, is dec = 166°, inc = + 3°, $\alpha_{95} = 23^{\circ}$. The reversed polarity predominates. Cleaned remanence directions are clearly ancient and are consistent with those from associated magnetite-bearing skarn samples.

Magnetic foliation plane dips shallowly to west with lineation plunging shallowly to NW.

Elura Orebody (Cobar, N.S.W.)

k	J	Q	A
4,300±400	67,000	27	1.44
(2,530-7,050)	(2,800-234,000)	(1-78)	

Sampling: 4 oriented block samples from mine drive plus 4 unoriented drill core samples from 3 holes with different attitudes.

Remarks: Elura pyrrhotite ore is semi-massive to massive (70%-80%) sulphide mineralisation containing ~20% pyrrhotite with pyrite, sphalerite, galena, minor chalcopyrite and arsenopyrite in gangue dominated by siderite. The pyrrhotite consists of intergrowths of monoclinic and intermediate pyrrhotite with monoclinic dominating. The host rock is C.S.A. Siltstone. The magnetic foliation (F≃1.44) is near-vertical, striking E-W, roughly orthogonal to bedding and mineralogical banding (which are sub-vertical with N-S strike). The magnetic fabric reflects deformation of the orebody which caused the ductile sulphides to be forcibly intruded into and through the overlying strata, forming the present vertical pipe-like structure which lies in the core of an anticline (Adams and Schmidt, 1980). The weak magnetic lineation is vertical, parallel to the direction of maximum extension. The pronounced magnetic foliation and the weak lineation may arise from fine-scale crenulation of the original bedding-parallel pyrrhotite foliation. The magnetic foliation on this interpretation is transposed.

The NRM direction is dec = 56°, inc = -76°, α_{95} = 13°, which is close to, but different from the present field. The mdf of NRM is 100-200 oe, with directional stability of NRM up to ~250 oe AF.

The associated pyrite and siliceous ore types are very weakly magnetic. The geophysics of this deposit has been extensively studied (Emerson, 1980).

Bathurst Area (Bathurst, N.S.W.)

k	J	Q	A
(1,560-58,550)	(260-78,600)	(0.3-2.3)	-

Sampling: 2 unoriented drill core samples

Remarks: 1 sample contains disseminated pyrrhotite, the other semi-massive pyrrhotite in Palaeozoic metasediments. The samples appear to contain a relatively intense, soft (mdf ~40 oe) component with steep negative inclination, superimposed on a weaker, probably ancient, component with shallow inclination (stable to 300 oe AF).

Magnetic Ridge (Cobar, N.S.W.)

k	J	Q	A
100±10	580	10	1.45±0.02
(50-180)	(100-1,950)	(2-24)	

Sampling: 9 oriented and 3 unoriented drill core samples

Remarks: Disseminated monoclinic pyrrhotite in C.S.A. Siltstone (see Clark 1983a and 1983b).

Coronation (Cobar, N.S.W.)

k	J	Q	A
115±9	1600±350	24±4	-
(100-140)	(860-2,360)	(13-32)	

Sampling: 4 oriented drill core samples.

Remarks: Disseminated pyrrhotite in C.S.A. Siltstone. NRM consists of ancient soft normal component overprinting more stable ancient normal component (see Clark (1983a)).

Hill View (Cobar, N.S.W.)

k	J	Q	A
75	375	8.5	-
(70-80)	(280-470)	(6.9-10.1)	

Sampling: 2 oriented drill core samples.

Remarks: Disseminated pyrrhotite in C.S.A. Siltstone. NRM consists of soft normal plus hard normal components (see Clark (1983a)).

Red Tank (Cobar, N.S.W.)

k	J	Q	A
300	30	0.18	-
(140-415)	(10-40)	(0.16-0.20)	

Sampling: 3 oriented drill core samples.

Remarks: Disseminated pyrrhotite in C.S.A. Siltstone. NRM consists of soft normal plus hard normal components (see Clark (1983a)).

Elsinore (Cobar, N.S.W.)

k	J	Q	A
100±20	210±60	3.6±0.8	1.19±0.06
(80-150)	(90-330)	(2.1-5.8)	

Sampling: 2 oriented and 2 unoriented drill core samples.

Remarks: Disseminated pyrrhotite in C.S.A. Siltstone. Mean NRM direction dec = 114°, inc = -49°, is oblique to present field but directions from individual specimens are rather scattered. Zijderveld plots of demagnetisation data are noisy and palaeomagnetic significance of magnetisation is unclear. Magnetic foliation plane dips very steeply to SE, similar to that at Magnetic Ridge, and is probably parallel to cleavage.

Dugald River Orebody (Cloncurry, Qld.)

k	J	Q	A
13,800	47,500	13	-
(90-110,000)	(30-259,000)	(0.6-67)	

Sampling: 12 unoriented drill core samples.

Remarks: Samples consist of semi-massive to massive sulphide (pyrrhotite-sphalerite-pyrite-galena) assemblage with quartz and carbonate in Lower Proterozoic graphitic shale. Pyrrhotite content ranges from very low to 20% in different ore types. Pyrrhotite grain size is typically ~20μm.

Mt. Isa Silver-Lead-Zinc Orebody (Mt. Isa, Qld.)

k	J	Q	A
1380±310	710±210	1.1±0.1	1.42±0.07
(730-2,100)	(260-1,400)	(0.7-1.3)	(1.28-1.66)

Sampling: 5 magnetically oriented blocks from mine drive.

Remarks: Semi-massive sulphides (pyrite-pyrrhotite-galena-sphalerite) in dolomitic shale (Mid-Proterozoic Urquhart Shale). The pyrrhotite is monoclinic. NRM directions scattered but predominantly reversed. Mdf of NRM 50-150 oe. Magnetic foliation plane dips steeply to the west parallel to bedding and to the nearby major Mt. Isa fault. Magnetic lineation plunges steeply to the NW, parallel to regional fold axis plunges. Overall the magnetic fabric is consistent with that of neighbouring magnetite-bearing rocks.

Herberton Tinfield (Atherton, Qld.)

k	J	Q	A
30,000	400,000	27	-

Sampling: Unoriented drill core sample.

Remarks: Pyrrhotite vein in Devonian sandstone. Mineralisation associated with Carboniferous granite.

Herberton Tinfield (Atherton, Qld.)

k	J	Q	A
1,380	960	1.2	-

Sampling: Unoriented drill core sample.

Remarks: Brecciated hornfelsed Devonian sediment containing disseminated pyrrhotite.

Frieda River (May River, P.N.G.)

k	J	Q	A
21,400	10,900	1.5	1.13
(17,100-25,700)	(2,400-19,300)	(0.2-2.8)	

Sampling: 2 unoriented drill core samples.

Remarks: Pyrrhotite skarn containing semi-massive sulphides (chalcopyrite mineralisation). The skarn formed from limestones of Upper Cretaceous to Eocene Salumei Formation. The alteration and mineralisation is associated with late intrusive phases of the Miocene Frieda Igneous Complex (an andesitic volcanic complex with comagmatic intrusions). The magnetic foliation is parallel to the sulphide banding.

Pine Creek Geosyncline (Pine Creek, N.T.)

General Remarks: Results from 8 mineralised zones of the Pine Creek Geosyncline are given. The mineralisation occurs within the Lower Proterozoic Golden Dyke Formation. Long curvilinear magnetic anomalies of amplitude $>500\gamma$ are associated with this formation which typically contains ~5% monoclinic pyrrhotite, probably produced by metamorphic breakdown of pyrite (Tucker et al., 1979).

1

k	J	Q	A
26,800	121,000	9.5	-
(14,600-48,300)	(75,500-196,000)	(7.7-12.6)	

Sampling: 3 oriented drill core samples plus 4 unoriented block samples from cross-cut.

Remarks: See Clark (1983c) for petrographic description. Mean NRM direction dec = 190^{o}, inc = -45^{o} (~100^{o} from present field). Mdf of NRM ~40 oe, direction stable up to 600 oe AF. Measured NRMs consistent with magnetic modelling.

2

k	J	Q	A
11,700	65,600	11.1	-
(4,000-17,000)	(23,300-118,000)	(7.7-13.9)	

Sampling: 3 oriented drill core samples.

Remarks: Semi-massive sulphides. NRM directions almost vertically upwards, ~50^{o} from present field. Magnetisation direction inferred from measurements is consistent with magnetic modelling. Mdf of NRM ~40 oe, direction stable to ~200 oe.

3

k	J	Q	A
3,030	12,600	10	1.6
(1,720-5,360)	(2,100-18,200)	(2-21)	(1.3-1.9)

Sampling: 3 oriented drill core samples.

Remarks: Disseminated pyrrhotite. NRM consists of a very soft randomly directed component (presumably IRM noise) of variable intensity superimposed on a more stable component. The stable component represents ~80% of NRM in the 2 samples with high Q (>6) and has mean direction dec = 141^{o}, inc = -72^{o}, $\alpha_{95} = 16^{o}$, which is highly oblique to the present field. The soft component is destroyed by ~40 oe AF. The magnetic foliation plane is sub-vertical, striking N-S, and contains a moderate-to-steep N plunging lineation.

4

k	J	Q	A
51,400	169,000	14.6	-

Sampling: Unoriented drill core sample.

Remarks: Semi-massive sulphides. NRM oblique to present field and is directionally stable from 50 - 200 oe AF. Mdf of NRM ~60 oe.

5

k	J	Q	A
4,270	877,000	411	-

Sampling: Unoriented drill core sample.

Remarks: Disseminated pyrrhotite. NRM oblique to present field and is directionally stable from 100 - 200 oe AF. Mdf of NRM ~140 oe.

6

k	J	Q	A
1,550	16,300	22	-

Sampling: Oriented drill core sample.

Remarks: Disseminated pyrrhotite. NRM direction dec = 71°, inc = -23°, oblique to present field.

7

k	J	Q	A
1,840	14,500	17	-

Sampling: Oriented drill core sample.

Remarks: Disseminated pyrrhotite. NRM direction dec = 58°, inc = $+38^{\circ}$, oblique to present field.

8

k	J	Q	A
1,630	65,600	86	-

Sampling: Oriented drill core sample.

Remarks: Disseminated pyrrhotite. NRM direction dec = 135°, inc = -61°, oblique to present field.

<u>Bowes River</u> (Geraldton, W.A.)

k	J	Q	A
1,900±300	7,300	7	1.19±0.02
(1,360-3,200)	(2,340-19,200)	(3-24)	

Sampling: 6 unoriented drill core samples.

Remarks: Disseminated (1-5%) pyrrhotite in Upper Proterozoic pelitic granulite. The pyrrhotite is probably a product of breakdown of pyrite in a carbonaceous shale during metamorphism to ~750-800°C. The pyrrhotite is found in a zone ~100 m wide within steeply dipping horizons striking N-S. Depth to the top of the magnetic zone is ~90 m. A 160γ positive anomaly with full width at half maximum ~250 m is found over the rocks. NRM is soft (mdf ~10-40 oe).

Stuart Shelf (Port Augusta, S.A.)

k	J	Q	A
2,960	2,670	1.6	-

Sampling: Sample from vertical drill hole. Azimuthal orientation unknown.

Remarks: Semi-massive sulphides with pyrrhotite in Upper Proterozoic sediments. Inclination of NRM similar to present field inclination.

4. DISCUSSION

The most striking feature of the magnetic properties summarised in Section 3 is the predominance of high Koenigsberger ratios. Coupled with the tendency for NRM directions to be systematically distributed, this implies that remanence is a dominant contributor to magnetic anomalies associated with most pyrrhotite-bearing rocks. Values of Q are almost always greater than unity, are commonly in the range 10-30, and go as high as ~400. For massive coarse-grained pyrrhotitic ores Q tends to be in the range 1-10 but takes larger values for less massive, finer-grained pyrrhotite.

Although the NRM of coarse-grained monoclinic pyrrhotite tends to be magnetically soft (median destructive fields of <100 oe predominate, and are commonly ≤ 50 oe) viscous remagnetisation (reprinting) of pyrrhotite is rare and in most cases viscous overprinting is minimal. Many of the pyrrhotite-bearing rocks are carrying a stable ancient magnetisation, suggesting their suitability for palaeomagnetic study, either for purposes of indirect dating or for defining thermal histories.

Specific NRM intensities and susceptibilities cannot be accurately calculated for these rocks as the pyrrhotite content is not well known. However the results from the massive pyrrhotite samples establish that the volume susceptibility of coarse-grained monoclinic pyrrhotite ranges up to at least 0.11. In cases where pyrrhotite contents are estimated the calculated susceptibilities of the pyrrhotite are in the range 0.02-0.1. We can therefore expect the susceptibility of monoclinic pyrrhotite to range from 0.004 for SD grains to ~ 0.1 for large soft grains. Kropacek (1971) found susceptibilities of up to 0.06 for 27 samples of coarse-grained pyrrhotite. Koenigsberger ratios for the same samples fell mainly in the range $1<Q<5$ ($\sim 50\%$), with $\sim 80\%$ in the range $1<Q<20$. Taking $Q = 5$, $k = 0.1$, $H = 0.5$ oe we get $J = 0.25$ G as a typical NRM intensity of coarse-grained pyrrhotite. Syono et al. (1962)

determined the TRM acquired in 0.5 oe within the basal plane of a large (5 x 5 x 1 mm) monoclinic pyrrhotite crystal to be ~0.8 G, which corresponds to ~0.6 G for an assemblage of randomly oriented crystals.

Because the calculated intensities of TRM and CRM for SD pyrrhotite are also high (up to ~0.4 G) we can expect the NRM intensities of even relatively dilute pyrrhotite assemblages to be strong and to dominate induced magnetisation.

The results also indicate that pyrrhotite-bearing rocks are generally quite anisotropic. The mean value of A for the 10 rock units or ore bodies for which the susceptibility anisotropy was determined is 1.41 (s.d. = 0.21). In most cases the anisotropy will not greatly affect interpretation as the total magnetisation is dominated by the remanence. However anisotropy of this magnitude significantly affects interpretation of palaeomagnetic results.

In most cases the magnetic fabric bears a simple relationship to geological structure. The magnetic foliation plane tends to be parallel to bedding and to mineralogical layering in stratiform orebodies. This relationship breaks down when the orebody has been extensively deformed and bears a discordant relationship with the country rocks (e.g. Elura). For disseminated pyrrhotite the magnetic foliation tends to be parallel to cleavage, as discussed in Clark (1983b).

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TABLE 1 STATISTICAL PARAMETERS FOR SUSCEPTIBILITY AND NRM INTENSITY

(After Kropacek, 1971)

	Arithmetic mean	Mode	Median	Geometric mean	Standard deviation of logarithms	Total range
Susceptibility (G/oe)	1.74×10^{-2}	4.2×10^{-3}	5.38×10^{-3}	5.56×10^{-3}	0.509	10^{-3}-6×10^{-2}
NRM Intensity (G)	6.78×10^{-2}	7.0×10^{-3}	9.62×10^{-3}	1.15×10^{-2}	0.772	3×10^{-4}-2×10^{-1}

TABLE 2 MAGNETIC PARAMETERS OF MAGNETIC RIDGE SAMPLES

Sample	No. of specimens	$\overline{J}$ (Range, or ±SE)	$\overline{k}$ (Range, or ±SE)	$\overline{Q}$ (Range, or ±SE)
250.0m	5	850 (490-1,810)	90±20 (60-170)	16±1
270.5m	4	100 (30-210)	90±20	1.9±0.3
291.8m	7	480±120 (230-920)	70±10	11±1
310.4m	7	370±60 (120-600)	180±30 (60-250)	3.6±0.2
340.3m	6	1,950±410 (1,050-3,710)	135±20 (80-220)	24±2
344.5m	7	850±60 (610-1,070)	96±6	15.3±0.5
375.0m	4	670±50 (540-770)	120±10	10.0±0.3
390.2m*	5	390±60 (230-470)	90±10	7±1
413.0*	4	490±100 (250-750)	80±10	10.5±1
431.4m*	7	310±50 (170-520)	67±5	8±1

*unoriented

$\overline{J}$ = mean NRM intensity in microgauss (mAm^{-1})

$\overline{k}$ = mean emu susceptibility x 10^6

$\overline{Q}$ = mean Koenigsberger ratio ($Q = J/kH$, where $H = 0.58$ Oersteds)

The standard error is quoted if considered meaningful. For very inhomogeneous samples the range of values is given.

TABLE 3. NRM DIRECTIONS OF MAGNETIC RIDGE SAMPLES

Sample	Mean NRM direction (α_{95})	Components present
250.0m	$(257^\circ, -66^\circ)$ (3°)	SN + HN
270.5m	$(286^\circ, 23^\circ)$ Streaked between $(269^\circ, -3^\circ)$ and $(289^\circ, 55^\circ)$	SN + HR
291.8m	$(252^\circ, -55^\circ)$ (5°)	SN + HN
310.4m	$(269^\circ, 9^\circ)$ Streaked between $(271^\circ, -27^\circ)$ and $(297^\circ, 77^\circ)$	SN + HR
340.3m	$(239^\circ, -51^\circ)$ (6°)	SN + HN
344.5m	$(237^\circ, -56^\circ)$ (6°)	SN + HN
375.0m*	$(103^\circ, 72^\circ)$ (12°)	SR + HR

SN = soft normal
SR = soft reversed
HN = hard normal
HR = hard reversed

α_{95} = radius of 95% circle of confidence about the mean direction

*core possibly inverted

TABLE 4 SUSCEPTIBILITY AND NRM INTENSITY (24 LEVEL, B LENS)

Sample	N	NRM intensity (microgauss)	Emu susceptibility (x 10^6)	Koenigsberger ratio (H=0.625 Oersteds)
1 (shale)	9	11	60	0.29
2	6	2,010	660	4.90
3	10	8,470	7,310	1.85
4	17	9,590	7,190	2.13
5	8	6,760	4,040	2.68
6	8	7,680	2,990	4.11
7	5	9,830	6,590	2.39
8	6	15,950	13,330	1.91
9	24	10,670	8,670	1.97
10	18	3,530	3,060	1.85
11	25	6,014	25,160	0.57
12	8	6,340	3,480	2.91
13	23	6,010	2,540	3.79
14	7	5,690	2,700	3.37
15	4	6,920	4,530	2.44
16	14	3,040	4,220	1.15
17 (shale)	7	12	53	0.36
18	8	470	650	1.14
19	10	2,560	1,400	2.91
20	22	1,170	1,780	1.05

N = no. of speciments drilled from block sample

For the 18 ore samples the following relationships hold:

(i) Susceptibilities are approximately log-normally distributed (i.e. log k is normal) with arithmetic mean 5,570, geometric mean 3,740, median 3,760, mode 2,750, standard deviation 5,840, standard error 1,380.

(ii) NRM intensities are approximately normally distributed with arithmetic mean 6,420, standard deviation 3,920 and standard error 920.

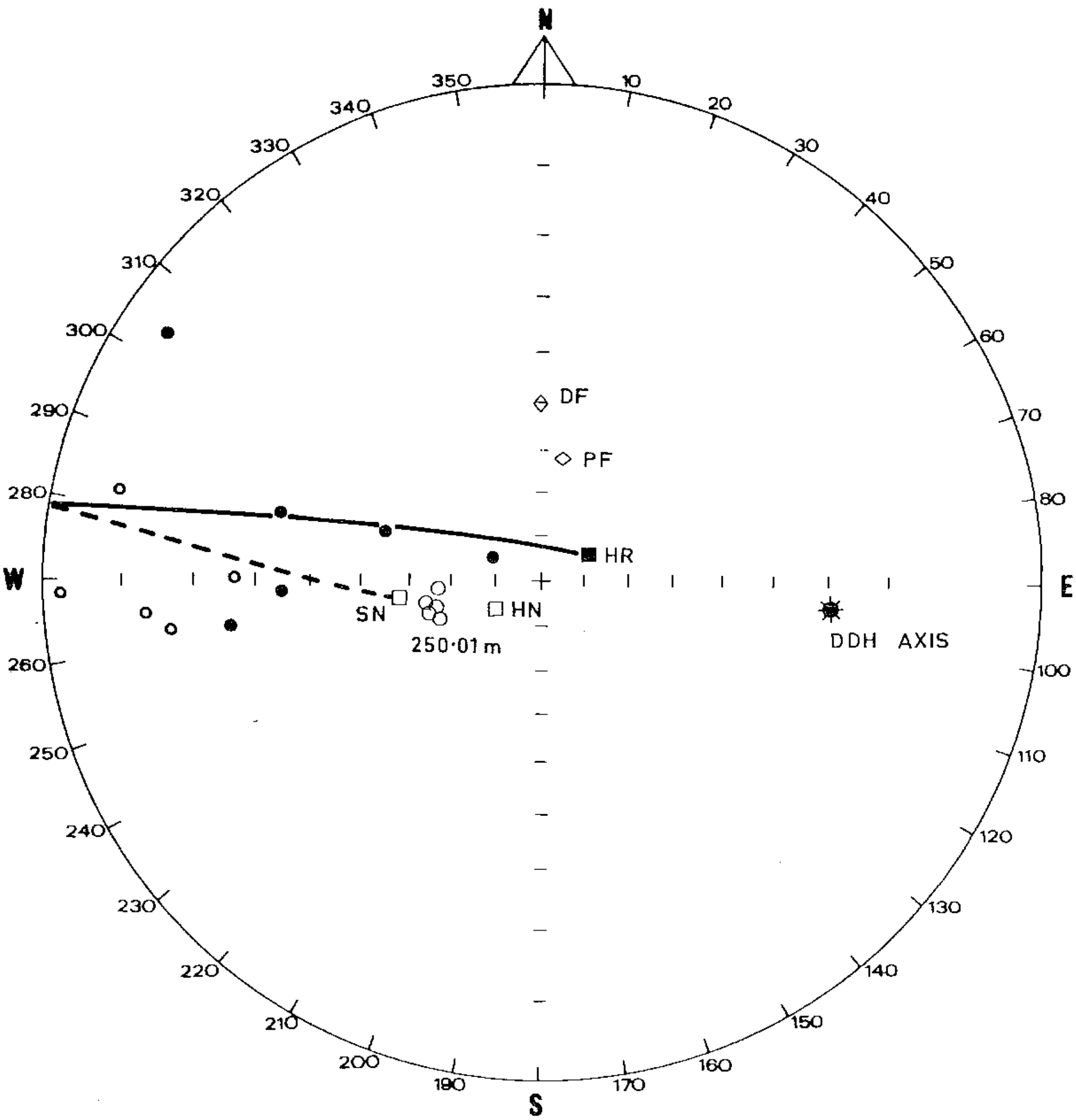
(iii) Koenigsberger ratios are approximately log-normally distributed with arithmetic mean 2.40, standard deviation 1.14, standard error 0.27, geometric mean 2.12, median 2.17, mode 1.75.

TABLE 5 SUSCEPTIBILITY AND NRM INTENSITY (20 LEVEL AND SURFACE)

Sample	N	NRM Intensity (microgauss)	Emu susceptibility ($\times 10^6$)	Koenigsberger ratio (H = 0.625 Oersteds)
20 Level, B Lens				
1	4	610	1,050	0.93
2	4	4,410	3,240	2.18
3	2	2,710	2,000	2.17
4	5	32,120	15,400	3.34
Hall's open-cut				
1	5	464,600	6,170	120
2	4	566,200	9,070	100
3	15	33,670	9,480	5.7
4	15	63,290	8,100	12.5

Fig. 1 NRM directions of specimens from selected Magnetic Ridge samples. The sample from 250.01m depth exhibits well-grouped NRM directions (indicated by the larger circles). This sample contains a soft normal remanence component superimposed on a hard normal component. Samples from 270.5m and 310.4m, on the other hand, possess soft normal + hard reversed components and have NRM directions (smaller circles) streaked approximately along the great circle path shown. SN, HN and HR respectively denote site mean directions for soft components, hard components converted to normal polarity and hard components converted to reversed polarity.

Stereographic projection. Filled symbols are on the lower hemisphere, open symbols are on the upper hemisphere. The primitive represents the present horizontal.


N
S
W
E
350
340
330
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170
160
150
140
130
120
110
100
80
70
60
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40
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20
10
DF
PF
HR
SN
HN
250·01 m
DDH AXIS

FIG. 1

Fig. 2 Frequency histograms for susceptibility (k), NRM intensity (J) and Koenigsberger ratio (Q) of Cleveland ore samples.

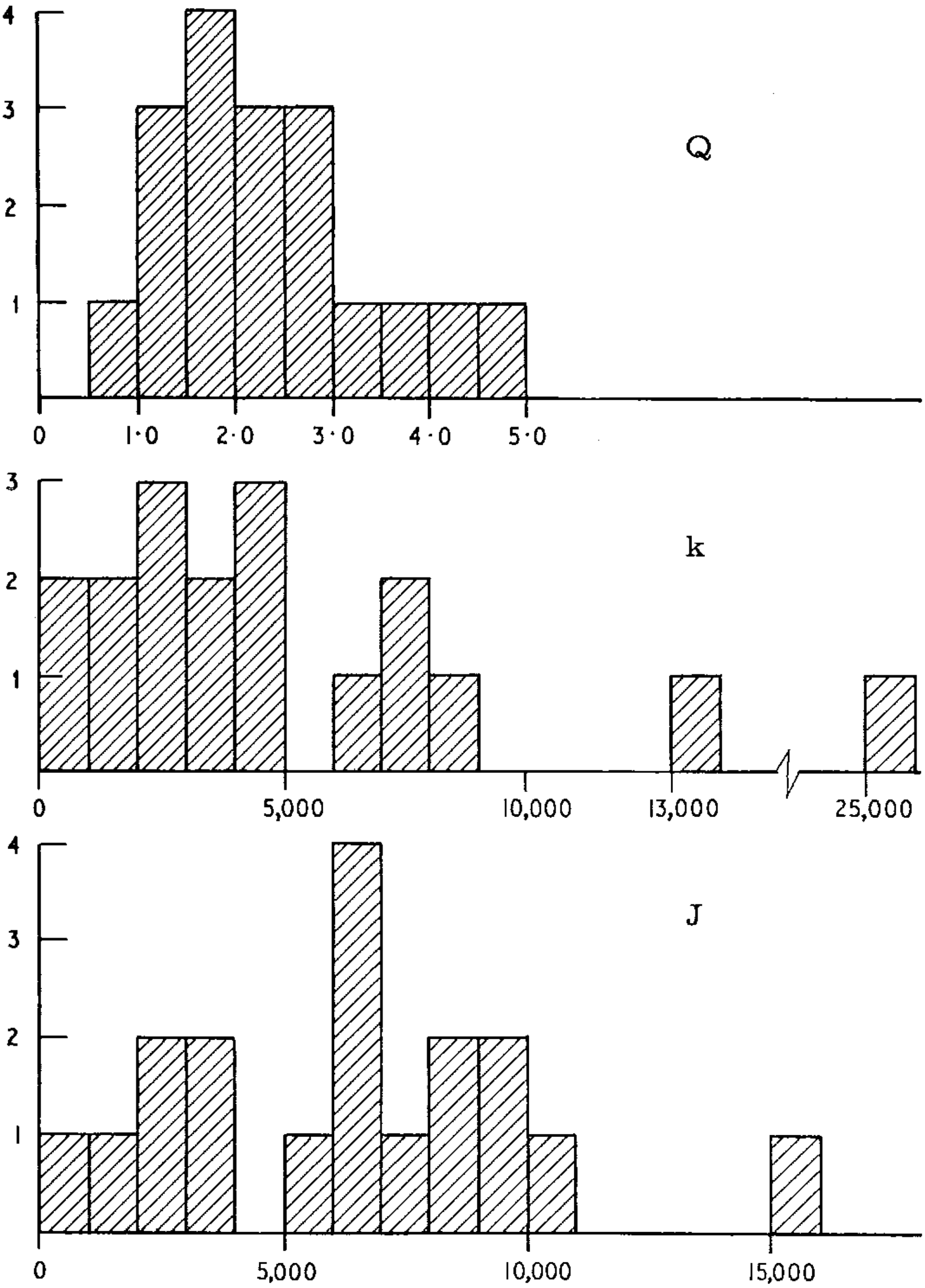

FIG. 2

Fig. 3 Variograms for k and J in the Cleveland orebody. h is measured along strike.

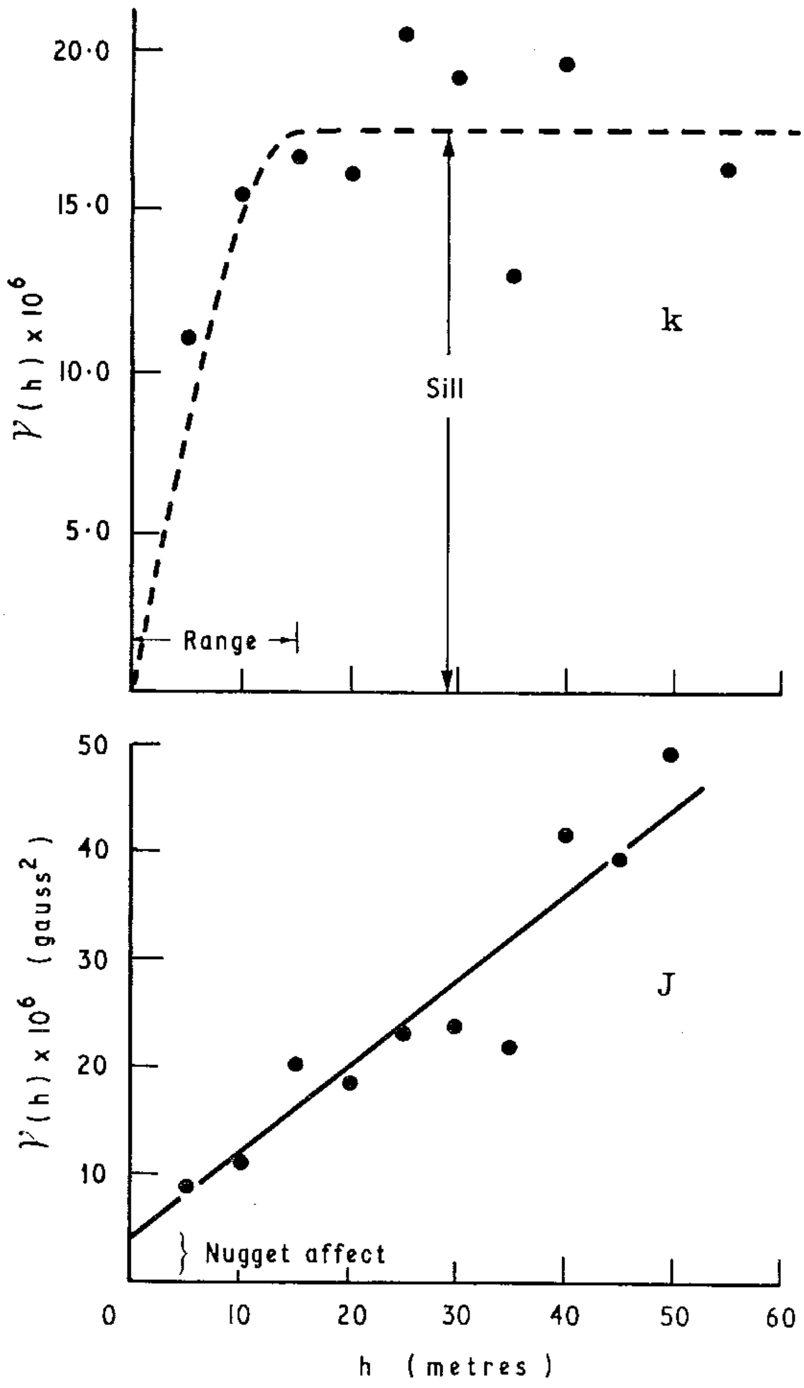
20·0
15·0
10·0
5·0
γ(h) x 10^6
Sill
Range
k
50
40
30
20
10
γ(h) x 10^6 (gauss^2)
J
Nugget affect
0
10
20
30
40
50
60
h (metres)

FIG. 3