RESTRICTED INVESTIGATION REPORT 1438R

CSIRO

INSTITUTE OF ENERGY AND EARTH RESOURCES

Division of Mineral Physics

PALAEOMAGNETISM OF PYRRHOTITE-BEARING ROCKS

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AUGUST 1983

TABLE OF CONTENTS

		Page
1.	INTRODUCTION	1
2.	PALAEOMAGNETIC STABILITY OF PYRRHOTITE	4
3.	PREVIOUS PALAEOMAGNETIC STUDIES	7
4.	PALAEOMAGNETIC RESULTS FROM THE C.S.A. SILTSTONE	10
5.	THE CLEVELAND TIN MINE, N.W. TASMANIA	17
6.	BAKED SEDIMENT ADJACENT TO THE CYGNET ALKALINE COMPLEX	20
7.	CONCLUSIONS	24
8.	REFERENCES	26

LIST OF TABLES

Table 1 Survival Potential of Primary NRM

Table 2 Soft Component Mean Directions (C.S.A. Siltstone)

Table 3 Hard Component Mean Directions (C.S.A. Siltstone)

LIST OF FIGURES

Figure 1 Thermal activation nomogram for monoclinic pyrrhotite

Figure 2 Zijderveld plots for Magnetic Ridge specimens

Figure 3 Zijderveld plots for Magnetic Ridge specimens

Figure 4 Sample mean NRM directions for Cleveland orebody

Figure 5 Zijderveld plots for specimens of pyrrhotite-bearing baked sediment

1. INTRODUCTION

The vast majority of palaeomagnetic results have been obtained from (titano) magnetite-bearing and haematite-bearing rocks, typified by common lithologies such as basalts and red sediments respectively. Rock magnetism has been primarily motivated by the need, initially, to validate palaeomagnetism and, subsequently, to aid interpretation of palaeomagnetic information carried by rocks. The neglect of pyrrhotite by rock magnetists is therefore not surprising.

Palaeomagnetists have shied away from pyrrhotite-bearing rocks for a number of reasons:

(i) Palaeomagnetism has hitherto been mainly concerned with the definition of apparent polar wander based on isolation of primary magnetisations. Pyrrhotite has a low Curie temperature and is easily thermally reset. As discussed in the next section, primary NRM borne by pyrrhotite cannot survive regional metamorphism of higher grade than lower pumpellyite facies, which severely restricts the set of ancient pyrrhotite-bearing rocks which may have retained a primary remanence.

(ii) Interpretation of palaeomagnetic data is hampered by the presence of magnetic anisotropy. Pyrrhotite grains in rocks commonly exhibit pronounced preferred orientation, and this, coupled with the strong intrinsic anisotropy of pyrrhotite, leads to high overall anisotropy of the rock.

(iii) Mineralisation processes are not as well understood as igneous and sedimentary processes. Consequently palaeomagnetic data from pyrrhotite-bearing rocks may be difficult to interpret in terms of magnetisation age.

(iv) There is evidence for self-reversal of TRM in some pyrrhotite-bearing rocks (e.g. Everitt, 1962). Therefore remanence carried by pyrrhotite cannot be confidently interpreted in terms of palaeofield polarity.

With regard to point (i), in recent years there has been increasing interest in detection of overprint magnetisations and their interpretation in terms of tectonic and thermal histories. Palaeomagnetic studies on pyrrhotite-bearing rocks offer the potential for detection and characterisation of low grade thermal events, to which other techniques are insensitive. Magnetic palaeothermometry of pyrrhotite may therefore prove to be a useful technique for elucidating geological histories.

Concerning point (ii), magnetic anisotropy is not as great a problem for pyrrhotite-rich rocks as for magnetite-bearing rocks as it can, in principle, be corrected for. Magnetic fabric in magnetite-bearing rocks is due to shape anisotropy of inequidimensional grains and is dependent on intrinsic susceptibility, which is a strong function of temperature in the vicinity of the blocking temperature, and domain structure, which varies in a complex manner at high temperatures. The anisotropy of TRM acquisition then differs considerably from anisotropy of induced magnetisation in low fields at room temperature. Anisotropy of pyrrhotite-bearing rocks, on the other hand, reflects the fact that magnetisation of pyrrhotite crystals is confined to the basal plane and the anisotropy of an assemblage in this case is effectively independent of temperature below the Curie point. Provided the dilution of susceptibility anisotropy by paramagnetic matrix minerals is negligible, which is the case if the rock susceptibility is greater than ~10^{-3} (Fuller, 1963), the susceptibility anisotropy also defines the anisotropy of remanence acquisition. For weakly magnetic rocks, however, measurements of anisotropy of IRM or TRM acquisition are more appropriate.

Consider the simple, but commonly applicable, case of a rock with an approximately isotropic plane of high susceptibility. The magnetisation is deflected away from the inducing field towards the magnetic foliation plane such that the azimuthal angle is unchanged but the inclination with respect to the foliation plane is decreased from I to I′ where $\tan I = (1/A)\tan I'$ and $A = k_{max}/k_{min}$ (or IRM_{max}/IRM_{min}). Knowing A and I′ then allows the inclination of the inducing field to be determined.

With regard to point (iii), palaeomagnetism can make a significant contribution to investigations of ore genesis, alteration and thermal history. In favourable circumstances, for instance, palaeomagnetism may determine whether a pyrrhotite ore is syngenetic or epigenetic.

Self-reversal of magnetisation does not affect palaeopole determination and is not a hindrance to use of palaeomagnetic directions from pyrrhotite-bearing rocks, however partial self-reversal in the laboratory may complicate analysis of thermal demagnetisation data to obtain these directions. Interpretation of magnetisation polarity in terms of palaeofield polarity will be dubious.

2. PALAEOMAGNETIC STABILITY OF PYRRHOTITE - THEORY

The hysteresis properties of dispersed monoclinic pyrrhotite grains have been discussed in a previous report by Clark (1983). Because of the relatively large coercive forces of pyrrhotite grains smaller than 100μm we expect remanence carried by these grains to be very stable at ambient temperatures. In the absence of an applied field the remanence of an assemblage of identical grains approaches zero exponentially with time constant τ given by (e.g. Dunlop, 1976)

$$\tau = (1/2f_o) \exp (E/kT) \qquad (1)$$

where f_o is a frequency factor of the order of 10^{10} Hz and E is the energy barrier between stable states. Eq. (1) is dominated by the exponential factor and f_o, which is a weakly varying function of volume, temperature and coercive force, can be regarded as effectively constant.

For SD grains E is the energy barrier between easy directions of magnetisation. For SD pyrrhotite grains of volume v, $E = (K_1+K_2)v \approx 3.8 \times 10^5 v$. The SPM threshold size at 300K for spherical grains can be calculated by setting $\tau = 1s$ in (1). Solving for v gives $2.6 \times 10^{-18} cm^3$, corresponding to $d_{spm} = 1.7 \times 10^{-6}$ cm (0.017μm).
Precise knowledge of f_o is unnecessary as choosing $f_o = 10^{12}$Hz, for example, gives $d_{spm} = 1.8 \times 10^{-6}$cm, which is only slightly different from the value above. Similarly changing τ somewhat makes little difference to the calculated d_{spm}.

However grains only slightly larger than the SPM threshold size are very stable. For instance for 0.04μm grains $\tau \sim 10^{200}$s.

For the case of MD grains $E = v_{act}J_sH_c/2$, where v_{act} is the volume affected by a single thermal activation event (Dunlop, 1976). Theoretical calculations to be given in a subsequent report give $v_{act} \sim 3 \times 10^{-12}$ cm^3 for a 2μm grain. Taking J_s = 93G, H_c = 800 oe and substituting into (1) gives a huge value for τ. Massive coarse grained pyrrhotite is much softer with, typically, $H_c \sim 10$ oe. However, even assuming v_{act} is no larger for this material than for small MD grains, (1) shows the remanence is unaffected by thermal agitation at ambient temperatures over geological time.

This conclusion must be drastically modified at higher temperatures. Because of the relatively low Curie temperature (~325°C) of pyrrhotite and the rapid decrease in J_s, K_1, K_2 and H_c as the Curie point is approached, pyrrhotite is easily reset by low grade thermal events. Considering again spherical 0.04μm grains which are very stable at 300K, $K_1 + K_2$ is ~0.9×10^5 erg/cm^3 at T = 523K (250°C) (Besnus, 1966), giving $\tau \sim 7 \times 10^7$s, or about 2 years. Clearly regional metamorphism attaining ~250°C would completely reset any palaeomagnetic signal carried by these grains.

The survival potential of primary NRM as a function of regional metamorphic grade is summarised in Table 1. The table shows, for example, that for a primary remanence to have survived prehnite facies metamorphism at 200°C for 10^6 years the laboratory unblocking temperature must be greater than 260°C.

Blocking contours for remanence carried by pyrrhotite are shown in the thermal activation nomogram (Fig. 1). This diagram is analogous to those of Dunlop and Buchan (1977) for magnetite and haematite. The contours are derived for SD grains by assuming a grain volume and calculating values of τ corresponding to chosen values of T, using eq. (1). Each contour corresponds to a different grain size. The temperature variation of J_s, K_1 and K_2 for monoclinic pyrrhotite are taken from Besnus (1966).

The left of the diagram where the contours have shallow slope (the B field) corresponds to grains which are easily reset at temperatures well below the original blocking temperature. Time is the dominant resetting factor in the B region, which is therefore characterised by viscous remanence.

By contrast, the A region (where the contours are steep) corresponds to thermally stable magnetisation. Temperature, not time, is most effective in resetting magnetisations in this region of the diagram. In the A region the laboratory unblocking temperature of magnetisation is a good indicator of the acquisition blocking temperature, whereas in the B region the laboratory unblocking temperature is much higher than the temperature at which the magnetisation was acquired (assuming a prolonged acquisition period).

However monoclinic pyrrhotite is chemically unstable above ~250^{o} and natural remanence acquired on cooling will generally be thermochemical in nature. Thus the greater portion of the A region in Fig. 4.2 is not applicable to remanence carried by monoclinic pyrrhotite. Furthermore primary remanence cannot survive regional metamorphism above lower pumpellyite facies (T<250^{o}C).

3. PREVIOUS PALAEOMAGNETIC STUDIES

Hanus and Krs (1968) discussed the palaeomagnetism of fine-grained pyrrhotitic ore of hydrothermal origin from Central Bohemia. A soft viscous component is removed by AF cleaning in 50 oersteds, revealing a stable magnetisation consistent with the Upper Palaeozoic age of the ore. Thermal demagnetisation gives similar results.

A stable magnetisation carried by primary pyrrhotite in a Devonian diabase from Northern Bavaria has been discussed by Soffel (1977). Directions obtained after AF and thermal cleaning are consistent with a primary magnetisation. A soft component, possibly of viscous origin, was removed below 100 oe, leaving a very hard, directionally stable component with 16% of NRM still remaining at 1000 oe. Pyrrhotite grains in this rock range from ~150μm to sub-micron in size.

Morris and Pay (1981) and Morris (1980, 1982) studied the palaeomagnetism of pyrrhotite-rich sulphides associated with the main Sudbury irruptive and its offsets (Canada), relating the results to those obtained from igneous phases.

It was concluded that there are at least three episodes of sulphide formation, one representing magmatic sulphide deposition and the other two representing remobilisation of pre-existing sulphides or secondary hydrothermal introduction of new sulphides. The latter events are recorded by slowly acquired chemical or thermochemical remanence which considerably postdates the magmatic episode. Consistency with results from associated igneous rocks and a baked contact test from a dike intruding sulphides provide strong evidence for retention of stable Proterozoic magnetisations by pyrrhotite. The utility of these results for genetic interpretation is evident.

At the other extreme very fine-grained pyrrhotite and some massive pyrrhotite ores appear to have been completely remagnetised in geologically recent times. Kligfield and Channell (1981) report on the magnetisation carried by ultrafine pyrrhotite within pyrite in Mesozoic limestones of the Helvetic nappes. The NRM appears to be a viscous magnetisation built up during the Brunhes polarity epoch. Similarly the NRM of some massive pyrrhotite ores from Sudbury are dominated by a present field component (Schwarz, 1973).

In some cases highly unstable behaviour is found for pyrrhotite-bearing rocks which are therefore unsuitable for palaeomagnetism (e.g. Sherriff and Shive, 1982). Thus the full spectrum of palaeomagnetic behaviour has been observed, but it has been established that in suitable circumstances meaningful palaeomagnetic information can be carried by pyrrhotite.

Further evidence of stable palaeomagnetic directions retained by pyrrhotite is furnished by the field examples of inferred self-reversal (Almond et al., 1956; Everitt, 1962; Robertson, 1963) as these constitute a form of consistency test with surrounding, oppositely magnetised, rocks.

Schwarz (1974) has discussed problems with use of conventional palaeomagnetic cleaning techniques on pyrrhotite-bearing rocks. He concluded that AF demagnetisation was inapplicable to massive pyrrhotite due to screening caused by high conductivity. However his calculation of the skin depth is incorrect (he gives 0.3cm instead of 0.3m) and attenuation of the alternating applied field inside the specimen is negligible.

Heating of pyrrhotite may cause chemical changes and it is therefore advisable to monitor changes in magnetic susceptibility, or some other diagnostic property, for representative specimens during step-wise thermal demagnetisation. Experience has shown that difficulties are rarely encountered, except perhaps in the case of intermediate pyrrhotite intergrown with monoclinic pyrrhotite.

4. PALAEOMAGNETIC RESULTS FROM THE C.S.A. SILTSTONE

C.R.A. Exploration Pty. Ltd. supplied a total of 20 oriented drill core samples of C.S.A. Siltstone from the Cobar area, N.S.W. (31.5^{o}S, 145.5^{o}E). The samples came from drill holes at two unspecified prospects and a further two holes at each of the Magnetic Ridge and Coronation prospects. The magnetic petrophysics of these samples will be discussed in a subsequent report.

The C.S.A. Siltstone member of the Lower Devonian Amphitheatre Group consists of a thin-bedded sequence of turbiditic siltstone and mudstone (Glen, 1982), and hosts the C.S.A. and Elura ore deposits. The rocks have been deformed and metamorphosed to lower greenschist grade, probably in the Carboniferous (R. Glen, pers. comm.). The samples contain disseminated (<1%) pyrrhotite. Thermomagnetic analysis reveals monoclinic pyrrhotite as the only detectable magnetic phase in the rock.

In all cases the holes were drilled perpendicular to the strike of the regional geology and the linear aeromagnetic anomalies associated with these rocks. The orientation of the samples was determined from the intersection of bedding laminations (of known attitude) with the cores and from the surveys of the drill holes. The absolute errors in orientation may be as large as 10^{o} but relative orientation of the samples within each hole is more precisely defined. Samples are usually separated by a considerable stratigraphic interval (e.g. 7 samples from one hole span a stratigraphic thickness of ~150m).

NRM directions of individual specimens from a number of Magnetic Ridge samples were streaked between a steeply upward-pointing direction in the SW quadrant and a westerly-pointing direction with moderate positive inclination, suggesting a two-component magnetisation. All other samples exhibit fairly well-grouped NRM directions, mostly in the SW quadrant, with steep negative inclinations.

AF and thermal cleaning revealed the presence of two components in all samples - a soft component of normal polarity (i.e. upward-pointing) directed SW with steep negative inclination, and a hard component directed SSW with very steep negative inclination or NNE with very steep positive inclination. Samples containing the soft normal component and a hard reversed component exhibit streaking of NRM directions along a great circle, whereas samples containing normal soft and hard components (which are similar in direction) have well-grouped NRMs.

Representative Zijderveld (1967) plots for AF and thermal demagnetisation are shown in Fig. 2 and Fig. 3. Fig. 2 illustrates very clearly the presence of a soft normal magnetisation superimposed on a hard reversed component. In Fig. 3 both components have normal polarity. The soft normal and hard normal components are similar in direction, but the breakpoint in the vector diagrams is nevertheless quite distinct and recognition of the two component system is facilitated by analogy with the samples which have a hard reversed component.

During AF cleaning (Figs. 2 (a) and 3 (a)) the soft component is usually removed below about 40 oe, although in some cases it is not completely removed until >100 oe. Often a small amount of IRM noise is removed during the initial demagnetisation step (5-10 oe). The soft component is unblocked by thermal demagnetisation to ~150°C. The hard component is consistently removed above about ~100-150 oe and ~150-180°C defining a linear segment in the Zijderveld plots which passes through the origin, indicating that this component is well-resolved and that it is the most stable component present in these samples.

The demagnetisation data for individual specimens were analysed by Principal Component Analysis (Kirschvink, 1980) which resolves magnetisation components by searching for linear segments in the Zijderveld diagrams and calculating least-squares-best-fit straight lines for each segment. In all cases the data were consistent with a two-component magnetisation.

Mean directions were calculated (separately and together) for soft components revealed by AF and thermal demagnetisation, and similarly for the hard components. In each case the directions were assumed to have a Fisher (1953) distribution and the statistics R, k and α_{95} were calculated. There was no significant difference between components resolved by AF and thermal cleaning and all corresponding components could be combined for calculation of a mean direction. Similarly the hard normal and reversed components found in the Magnetic Ridge samples appeared to be truly antiparallel and could therefore be combined, after conversion to a single polarity.

All fully resolved components from each drill hole were combined, with unit weight to specimens, to give "site" mean directions. Mean directions for soft and hard components are given in Tables 2 and 3 respectively. Within-site precision is much higher than between-site precision.

Combining these "site" directions to give formation means:

Soft component

Mean = $(238^{\circ}, -72^{\circ})$, N = 6, k = 17.3, $\alpha_{95} = 16.5^{\circ}$

Palaeomagnetic pole = 11°S, 173°E; dp = 26°, dm = 29°

Hard component

Mean = $(220^{\circ}, -80^{\circ})$, N = 6, k = 46.2, $\alpha_{95} = 9.9^{\circ}$

Palaeomagnetic pole = 16°S, 158°E; dp = 18°, dm = 19°

The relatively large errors arising from between-site scatter presumably reflect the approximate method of orientation. The magnetisations may have been deflected somewhat from the true palaeofield direction by anisotropy. The Magnetic Ridge samples have a well-defined magnetic foliation plane parallel to the regional cleavage. The average susceptibility anisotropy of the rock is 1.45. Correcting for dilution of the anisotropy by the weak susceptibility of the matrix, which can be estimated from barren siltstone samples, the anisotropy of the pyrrhotite assemblage is about 1.6. The soft and hard components lie close to, and on either side of, the magnetic foliation plane which strikes just east of north and is sub-vertical, dipping steeply to the east.

In these circumstances the theoretically calculated deflection of the magnetisation is small, only a few degrees. Although the proximity of the magnetisation vectors to the foliation plane may seem suspicious, it is to be expected as palaeofield directions in SE Australia have been consistently steep since the Carboniferous.

Preferential alignment of pyrrhotite grains in the cleavage plane suggests that the pyrrhotite predates, or is contemporaneous with, the cleavage-forming event. The pyrrhotite may be syn-sedimentary or it may be of metamorphic origin. Remanence carried by the pyrrhotite cannot have survived the greenschist facies metamorphism in the ?Carboniferous, and the oldest magnetisation which can have survived to the present is a TRM acquired during post-metamorphic (and post-deformational) cooling through the

~ $250^{o}C$ isotherm. Thus tectonic correction of the directions is inappropriate. The only plausible candidate for the soft component is also a thermally activated component (a viscous PTRM) which was blocked during cooling accompanying final uplift and removal of overburden in this area. Consideration of the maximum laboratory unblocking temperature ($<200^{o}C$) of the soft component and the blocking contours of Fig. 1 suggests that the soft component reflects a very low grade event ($<100^{o}C$). If this is so the sensitivity to thermal events of pyrrhotite with a distributed blocking temperature spectrum is clear and palaeomagnetic study of pyrrhotite-bearing rocks may yield information on events which are only weakly reflected in apatite fission tracks, for instance, as well as medium grade thermal events.

On this interpretation the soft component must be younger than the more stable component. The hard component represents a genuine palaeomagnetic direction and is not merely an artefact of partial self-reversal during heating of the specimens. This follows because the hard reversed component is not antiparallel to the soft component, and because the reversed magnetisation is consistent with the hard normal magnetisation in other specimens. Of course the dual polarity of the hard component may have resulted from irreproducible self-reversal at the time of acquisition, but this does not affect the palaeomagnetic interpretation. The discrete blocking temperature spectra of the soft and hard components, reflecting very different temperatures of acquisition, suggest that the magnetisations were acquired at quite different times although the directions are not greatly divergent. Comparison of the pole positions with the post-Devonian apparent polar wander track for Australia (see Embleton, 1981) suggests two possible ages for the magnetisations: Permo-Triassic or Early Cretaceous. The preferred interpretation is that the hard component represents cooling through the ~250°C isotherm either as a result of post-orogenic lowering of the geothermal gradient or during an initial episode of uplift in the Late Permian or Early Triassic. Prior to the deformation the C.S.A. Siltstone was overlain by several kilometres (possibly up to 10km) of Winduck Group and Mulga Downs Group sediments (R. Glen, pers. comm.) which would have been stripped during uplift and may have been a source for some of the Permo-Triassic sedimentation in Eastern Australia. It is inferred that stabilisation occurred until the Early Cretaceous when further, and final, uplift took place, thereby blocking the soft component.

This interpretation rests on a number of assumptions, which must be tested before acceptance of the inferred history. However, irrespective of the details of the interpretation, the following important features have emerged from this study:

(i) Pyrrhotite in these rocks has preserved a palaeomagnetic record of two distinct and clearly ancient events.

(ii) A stable ancient magnetisation has been preserved in spite of the fact that it is very soft to AF and thermal demagnetisation.

(iii) Palaeomagnetic study of pyrrhotite-bearing rocks offers potential for geothermometry from ~250°C to less than 100°C.

5. THE CLEVELAND TIN MINE, N.W. TASMANIA

The Cleveland cassiterite-sulphide deposit occurs at Luina, N.W. Tasmania (41.5°S, 145.4°E) and is one of a number of inferred replacement cassiterite-pyrrhotite bodies of Upper Proterozoic and Lower Cambrian dolomitic horizons in the region (e.g. Renison Bell, Mt. Bischoff and Mt. Lindsay). The geological setting has been described by Collins (1981). The ore is a metasomatic replacement of calcareous shales and shaley limestone by mineralising solutions, probably associated with intrusion of the Devonian Meredith Granite, which is a late igneous phase of the Tabberabberan orogeny.

Because many areas of the mine could not be sampled safely, underground sampling was restricted to B Lens in 24 Level and part of 20 Level. Eighteen block samples of ore and two of 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.

All samples were oriented using magnetic compass only and in the case of the underground samples the strike directions were confirmed by sighting along the drive. It was felt that the strikes were accurate to $\pm 10^{\circ}$. The magnetisation of the rocks underground is not so intense that very large declination anomalies are expected (the average NRM intensity is ~7000 microgauss and the direction is steep), but some cultural noise from trolley tracks etc. was undoubtedly present. Efforts were made to sample well away from mine equipment and as far as practicable from rock bolts.

On the surface, however, the intense NRMs make the orientation highly suspect and the sample mean NRM directions are very scattered, whereas those of the underground samples are well-grouped. The susceptibilities of the surface samples are typical of the rest of the deposit but the NRM intensities are variable and much higher, with Koenigsberger ratios ranging from 6-120, compared to values typically of 2-3 for the underground samples. This suggests the surface samples have been struck by lightning and accordingly they will not be considered further.

The NRM directions of the shale samples are consistent with the directions from the ore samples (Fig. 4). All 24 underground sample-mean directions may therefore be combined to give a formation mean direction. The mean NRM direction is dec $=32^{\circ}$, inc $=-72^{\circ}$ with $N = 24$, $R = 21.72$, $k = 10.0$, $\alpha_{95} = 9.8^{\circ}$. This is only 7° from the present field (12°, -71°) but is considerably steeper than the dipole field at this locality (0°, -61°). Similar NRM directions were found for a smaller number of samples by Falvey (1966).

It appears at first sight that the observed magnetisation may represent a VRM acquired very recently and thus have no palaeomagnetic significance. It will be argued, however, that the magnetisation is ancient.

AF and thermal cleaning of pilot specimens from the samples reveal only the presence of a single component of magnetisation. The magnetisation is very soft to AF demagnetisation, with the median destructive field $\sim$ 20 oe. As discussed in Section 2, this is not inconsistent with the capacity of MD grains to retain ancient remanence. The thermal demagnetisation curves are rather square-shouldered with the bulk of the blocking temperature spectrum lying above 200°C. The directions remain essentially unchanged up to ~310°C. Much of the magnetisation therefore lies in the A field of the thermal activation nomogram (Fig. 1), whereas a VRM acquired over less than 10^6 years should be unblocked in the laboratory below ~150°C. In fact if the NRM is viscous in origin it must have been acquired over less than 10^4 years to have completely failed to average secular variation and therefore reflect only the anomalously steep field of the very recent past at this locality.

Examination of Fig. 4 suggests a slight streaking of the sample mean directions along a NW-SE trend. When the directions are classified according to the side of the mine drive from which the samples were taken, they fall into two groups on either side of the overall mean direction - suggesting there is a small but systematic orientation error due to the local declination anomaly within the drive. Consistent errors in measurements of strike will be systematically reflected in the field-corrected directions of the samples as the block faces which were oriented were nearly all sub-vertical. A possible cause of change in declination across the drive, which runs NW-SE, is the iron tracks along the floor, which will tend to rotate magnetic strikes in the opposite sense on either side.

A mean direction can be calculated for each group and the two means (which are significantly different) combined to give a resultant which is indistinguishable from the overall mean direction given above. This suggests a better estimate of the formation mean direction could be obtained by rotating each group such that the group mean coincides with the overall mean and then recalculating a combined sample mean. This improves the precision ($\alpha_{95} = 6.8^{o}$). This is consistent with the Late Devonian pole for Australia (Embleton, 1981). Thus the magnetisation could have been acquired during post-metamorphic cooling following the mid-Devonian Tabberabberan orogeny.

However recent palaeomagnetic studies on igneous and sedimentary rocks in coastal areas of SE Australia have revealed widespread, severe overprinting at c.90 m.y. associated with uplift and erosion of the continental margin during initial opening of the Tasman sea (Schmidt and Embleton, 1981). The palaeomagnetic pole from Cleveland is consistent with a magnetisation age of c.50 m.y. The magnetisation may be associated with initiation of rapid sea-floor spreading between Australia and Antartica at c.45 m.y., following the commencement of very slow spreading at c.100 m.y. (Cande and Mutter, 1982). The remanence of the Cleveland pyrrhotite would then represent the first evidence of a magnetic overprint recording the initiation of spreading of the Southern Ocean, and would serve to collaborate the prediction of Schmidt and Embleton (1981) that magnetic overprinting may generally accompany development of passive Atlantic-type continental margins.

6. BAKED SEDIMENT ADJACENT TO THE CYGNET ALKALINE COMPLEX

The Cygnet Alkaline Complex is a predominantly alkali-syenite stock-like intrusion about 50km south of Hobart, covering an area of approximately 60 km^2. A series of petrologically similar dykes is associated with the syenite. The complex, which has been dated at 100 m.y. by the K-Ar method (Evernden and Richards, 1962), intrudes Permian sediments and Jurassic Tasmanian Dolerite. Palaeomagnetic results from the syenite, the associated dykes and baked contacts have been reported by Robertson and Hastie (1962). The results are in good agreement with poles from other c.100 m.y. rock units in Australia (Embleton, 1981).

Robertson and Hastie collected samples from two sites within baked sediments, but the magnetic mineralogy of these rocks was not specified. The remanence directions were consistent with those from the Complex itself. In 1981 Dr. B. J. J. Embleton collected 6 samples of baked shale adjacent to the intrusive as well as several sites in the syenite. The country rock is pyritic shale. In the contact aureole of the intrusive the pyrite has been converted to pyrrhotite which would therefore have acquired a thermal or thermochemical remanence at the time of intrusion. The remanence of these contact rocks is discussed here.

The NRMs are rather scattered but after removal of a very soft component during initial AF or thermal demagnetisation the directions cluster about a mean which is NW with very steep negative inclination. Representative Zijderveld diagrams for AF and thermal demagnetisation are shown in Fig. 5 (a) and 5 (b) respectively. It is intriguing that the response of specimens from a single sample which bears a multicomponent magnetisation to AF and thermal cleaning is very similar - analagous to the case of the C.S.A. Siltstone. This contrasts with the case of magnetite- and haematite-bearing rocks for which the response of magnetisation components to different cleaning methods is usually very different - in fact the relative stability of two magnetisation component systems to AF and thermal demagnetisation is often reversed.

After thermal demagnetisation to ~325°C many specimens were completely demagnetised indicating that pyrrhotite was the only significant magnetic carrier in the sample. However some specimens, generally the more weakly magnetised, retained a residual remanence above 325°C. In these cases the magnetisation directions remained unchanged until the specimens were completely demagnetised at 550-570°C. Thus it appears the magnetisation was borne by pyrrhotite and magnetite in some samples, and by pyrrhotite only in others. The palaeomagnetic information for declination and inclination in either case was similar.

The soft components of magnetisation which are removed during AF demagnetisation to 20-50 oe and thermal demagnetisation to 75-150°C are rather scattered but overall are directed southwards with shallow negative inclinations. This component does not represent a palaeofield direction and its origin is uncertain. A possible explanation is that the samples, which were collected in a ~15 m radius, are in the peripheral zone of influence of a lightning strike. The softness of the component and its approximate consistency of direction across the site indicate the lightning strike must have been quite distant.

Estimates of the stable component of magnetisation for each specimen were obtained by Principal Component Analysis. Including only the specimens for which the magnetic mineralogy is dominated by pyrrhotite the mean direction is (317°, -83°) with N = 5, R = 4.972, k = 145, $\alpha_{95} = 6.3°$. This is in very good agreement with the mean direction (313°, -81°) obtained from the syenite stock by Robertson and Hastie (1962). They found the overall mean of directions from the stock, associated dykes, dolerite hybrids and sediment contacts to be (327°, -84°) with $\alpha_{95} = 5°$.

Thus the evidence is clearly in favour of retention of a stable remanence by pyrrhotite in these shales since initial acquisition c.100 m.y. ago. Further work may determine whether this area, which adjoins the eastern continental margin, has also been subjected to the overprinting episode at c.90 m.y. If 100 m.y. primary and 90 m.y. overprint components are present in the intrusion they are both of normal polarity and, being so close in age, are sub-parallel. Therefore the two components will be very difficult to resolve. Similarly it may prove impossible to unambiguously determine the degree of overprinting in the pyrrhotite.

7. CONCLUSIONS

Palaeomagnetic studies of pyrrhotite-bearing rocks have potential applications to determination of apparent polar wander, investigation of ore genesis and elucidation of the thermal history of mineralised terrains.

Theoretical considerations show that monoclinic pyrrhotite grains larger than the superparamagnetic threshold size ($\sim$0.02μm) are capable of retaining stable ancient remanence components for geologically long times at low temperatures. Grains with laboratory blocking temperatures below about 200^{o}C are sensitive recorders of very low grade ($<$100^{o}C) thermal events, suggesting the applicability of magnetic palaeothermometry to unravelling the tectonic history of pyrrhotite-bearing rocks. Primary remanence carried by pyrrhotite can survive metamorphism up to, but not above, 250^{o}C.

The theoretical conclusions are supported by palaeomagnetic studies which demonstrate retention of probable primary magnetisation by pyrrhotite in rocks as old as Proterozoic. Three palaeomagnetic case histories of pyrrhotite-bearing rocks from Australia were discussed in some detail. In each case a stable ancient remanence component has been preserved.

In addition the C.S.A. siltstone bears a complex magnetisation with a soft normal component overprinting a hard component, which may have either normal or reversed polarity. The evidence suggests that the soft component represents a record of a very low-grade thermal event, faithfully preserved for at least 120 m.y., with no evidence of recent viscous overprinting. This spectacularly illustrates the potential of pyrrhotite-bearing rocks for magnetic palaeothermometry.

In summary, the neglect of pyrrhotite-bearing rocks by palaeomagnetists is clearly unjustified, given the useful information which can often be extracted from analysis of remanence components in these lithologies.

8. REFERENCES

Almond, M., Clegg, J.A. and Jaeger, J.C., 1956. Remanent magnetism of some dolerites, basalts and volcanic tuffs from Tasmania. Phil. Mag., 1: 771-782.

Besnus, M.J., 1966. Propriétés magnétiques de la pyrrhotine naturelle. Thèse, Universite de Strasbourg.

Cande, S.C. and Mutter, J.C., 1982. A revised identification of the oldest sea-floor spreading anomalies between Australia and Antarctica. Earth Planet. Sci. Lett., 58: 151-160.

Clark, D.A., 1983. Hysteresis Properties of Sized Dispersed Monoclinic Pyrrhotite Grains. CSIRO Restricted Investigation Report 14 11R.

Collins, P.L.F., 1981. The geology and genesis of the Cleveland tin deposit, Western Tasmania: fluid inclusion and stable isotope studies. Econ. Geol., 76: 365-392.

Dunlop, D.J., 1976. Thermal fluctuation analysis: a new technique in rock magnetism. J. Geophys. Res., 81: 3511-3517.

Dunlop, D.J. and Buchan, K.L., 1977. Thermal remagnetization and the paleointensity record of metamorphic rocks. Phys. Earth Planet. Inter., 13: 325-331.

Embleton, B.J.J., 1981. A review of the paleomagnetism of Australia and Antarctica. In: M.W. McElhinny and D.A. Valencio (Editors), Paleoreconstruction of the Continents. American Geophysical Union and Geological Society of America, Geodynamics Series, 2: 77-92.

Everitt, C.W.F., 1962. Self-reversal of magnetization in a shale containing pyrrhotite. Philos. Mag., 7: 831-842.

Evernden, J.F. and Richards, J.R., 1962. Potassium-argon ages in eastern Australia. J. Geol. Soc. Australia, 9: 1-49.

Falvey, D., 1966. The interpretation of geophysical surveys at the Cleveland Mine, Tasmania. B.Sc. (Hons) thesis, University of Sydney.

Fisher, R.A., 1953. Dispersion on a sphere. Proc. Roy. Soc. Lond. A, 217, 295-305.

Fuller, M.D., 1963. Magnetic anisotropy and paleomagnetism. J. Geophys. Res., 68: 293-309.

Glen, R.A., 1982. The Amphitheatre Group, Cobar, New South Wales: preliminary results of new mapping and implications for ore search. N.S.W. Geol. Surv. Quarterly Notes, 49: 1-14.

Hanus, V. and Krs. M., 1968. Applicability of palaeomagnetism of pyrrhotite to ore-genetic studies. Mineralium Deposita, 3: 242-248.

Kirschvink, J.L., 1980. The least-squares line and plane and the analysis of palaeomagnetic data. Geophys. J.R. astron. Soc., 62: 699-718.

Kligfield, R. and Channell, J.E.T., 1981. Widespread remagnetisation of Helvetic Limestones. J. Geophys. Res., 86: 1888-1900.

Morris, W.A., 1980. Tectonic and metamorphic history of the Sudbury Norite: the evidence from paleomagnetism. Econ. Geol., 75: 260-277.

Morris, W.A., 1982. A paleomagnetic investigation of the Sudbury Basin offsets, Ontario, Canada. Tectonophysics, 85: 291-312.

Morris, W.A. and Pay, R., 1981. Genesis of the Foy(?) Offset and its sulfide ores: the paleomagnetic evidence from a study in Hess Township, Sudbury, Ontario, Econ. Geol., 76: 1895-1905.

Robertson, W.A., 1963. Paleomagnetism of some Mesozoic intrusives and tuffs from Eastern Australia. J. Geophys. Res., 68: 2299-2312.

Robertson, W.A. and Hastie, L., 1962. A palaeomagnetic study of the Cygnet alkaline complex of Australia. J. Geol. Soc. Australia, 8: 259-268.

Schmidt, P.W. and Embleton, B.J.J., 1981. Magnetic overprinting in southeastern Australia and the thermal history of its rifted margin. J. Geophys. Res., 86: 3998-4008.

Schwarz, E.J., 1973. Magnetic characteristics of massive sulphide ore bodies near Sudbury, Canada. Can. J. Earth Sci., 10: 1735-1743.

Schwarz, E.J., 1974. Magnetic properties of pyrrhotite and their use in applied geology and geophysics. Geol. Surv. Canada Paper, 74-59.

Sheriff, S.D. and Shive, P.N., 1982. Unreliable paleo-magnetic results from the Wilkins Peak Member of the Eocene Green River Formation, Wyoming. Geophys. Res. Lett., 9: 723-726.

Soffel, H., 1977. Pseudo-single-domain effects and single-domain multidomain transition in natural pyrrhotite deduced from domain structure observations. J. Geophys., 42: 351-359.

Zijderveld, J.D.A., 1967. A.C. demagnetization of rocks: analysis of results. In: D.W. Collinson, K.M. Creer and S.K. Runcorn (Editors), Methods in Palaeomagnetism. Elsevier, Amsterdam, pp. 254-286.

TABLE 1 SURVIVAL POTENTIAL OF PRIMARY NRM

Heating temperature* (^{o}C)	Metamorphic grade	$(T_B)_{min}$ (^{o}C)
100	Zeolite	195
150	Zeolite	225
200	Prehnite	260

*Temperature attained during metamorphic heating for 10^6 years.

$(T_B)_{min}$ = minimum laboratory unblocking temperature of primary NRM.

TABLE 2 SOFT COMPONENT MEAN DIRECTIONS (C.S.A. SILTSTONE)

Drill hole	Mean direction	N	k	α_{95}
MR1	(257°, -54°)	14	49.2	5.7°
MR6	(263°, -63°)	4	27.9	17.6°
CR1	(211°, -70°)	4	154	7.4°
CR2	(91°, -73°)	4	194	6.6°
HV1	(224°, -61°)	4	15.7	23.8°
RT1	(247°, -76°)	2	-	-

N = no. of specimens

k = estimate of Fisherian precision parameter

α_{95} = half-angle of 95% cone of confidence

Mean directions are calculated giving unit weight to specimens.

TABLE 3 HARD COMPONENT MEAN DIRECTIONS (C.S.A. SILTSTONE)

Drill hole	Mean direction	N	k	α_{95}
MR1	(232°, -71°)	14	28.1	7.6°
MR6	(306°, -83°)	4	29.1	17.2°
CV1	(196°, -80°)	4	235	6.0°
CV2	(111°, -77°)	4	137	7.8°
HV1	(223°, -71°)	4	19.4	21.3°
RT1	(236°, -75°)	2	-	-

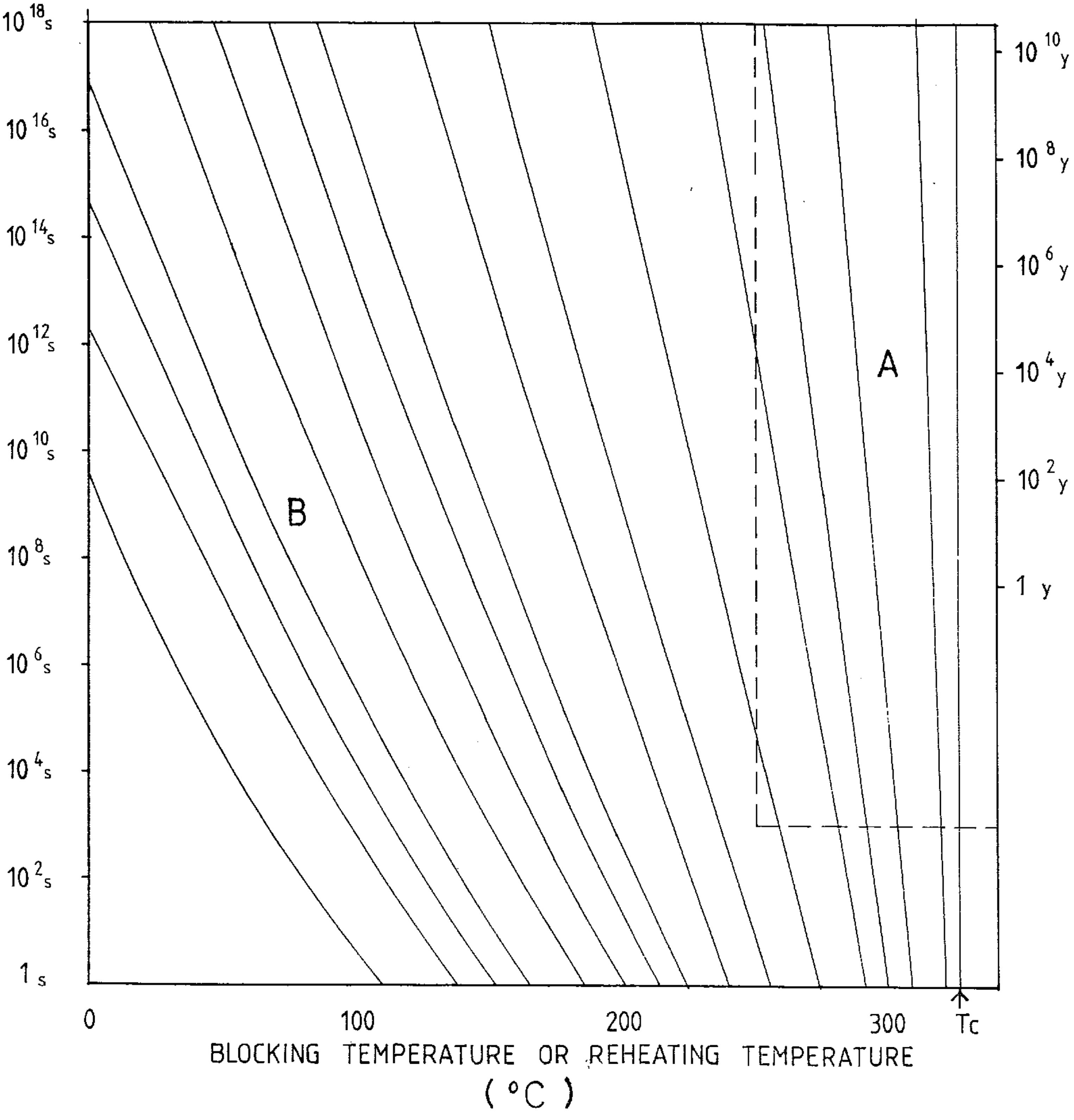
N = no. of specimens

k = estimate of Fisherian precision parameter

α_{95} = half-angle of 95% cone of confidence

Mean directions are calculated giving unit weight to specimens.

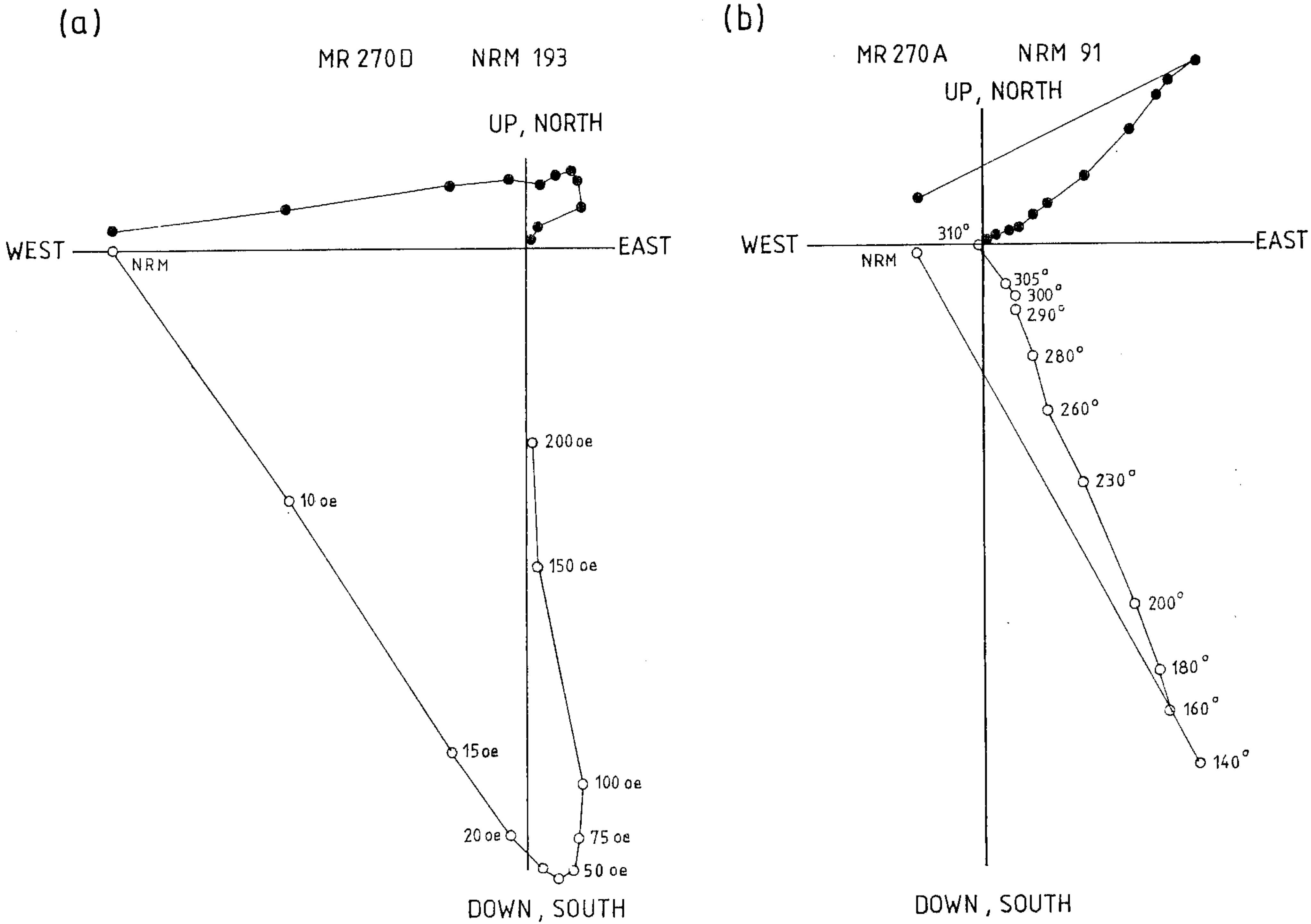
Fig. 1 Thermal activation nomogram for monclinic pyrrhotite. The contours join time-temperature conditions of equal probability of thermally activating a magnetic grain. The B field represents the region where time is relatively effective in resetting a rapidly acquired remanent magnetisation acquired at considerably higher temperature, whereas in the A field a magnetisation is unblocked only at temperatures approaching those in which the remanence was acquired. Conversely a remanent magnetisation corresponding to the B field which was acquired over a geologically long time (a viscous PTRM) will only be unblocked in the laboratory at a temperature well above the temperature of acquisition. In the A region the temperature of acquisition and the laboratory unblocking temperature are similar, irrespective of the duration of acquisition.
The dashed lines enclose the region within which monoclinic 4C pyrrhotite is unstable with respect to 1C pyrrhotite + pyrite, precluding acquisition of remanence.



THERMAL ACTIVATION NOMOGRAM FOR MONOCLINIC PYRRHOTITE

FIG. 1

Fig. 2 Zijderveld plots for Magnetic Ridge specimens bearing a soft normal remanence component superimposed on a hard reversed component. The diagrams are projections of remanence vector end-points onto two orthogonal planes. The dots represent projection onto the horizontal plane, the circles onto a vertical plane (in this case the E-W vertical plane). Successive points represent remanence vectors after successive demagnetisation steps. Linear segments indicate removal of a single component of magnetisation over the corresponding demagnetisation range. In this case the soft component is in the SW quadrant with moderate negative inclination (upward-pointing) and the hard component is in the NE quadrant with steep positive inclination (downward-pointing). 2 (a) is a typical result obtained for AF demagnetisation and 2 (b) depicts the equivalent response to thermal demagnetisation.



(a)
MR 270D
NRM 193
UP, NORTH
WEST
EAST
NRM
10 oe
15 oe
20 oe
50 oe
75 oe
100 oe
150 oe
200 oe
DOWN , SOUTH
(b)
MR 270A
NRM 91
UP, NORTH
WEST
EAST
NRM
310°
305°
300°
290°
280°
260°
230°
200°
180°
160°
140°
DOWN , SOUTH

FIG.2

Fig. 3 (a) Zijderveld plot for AF demagnetisation of a Magnetic Ridge specimen bearing a soft normal component in the SW quadrant with moderate negative inclination superimposed on a hard normal component, also in the SW quadrant but with steeper negative inclination.

3 (b) Zijderveld plot for thermal demagnetisation of a Magnetic Ridge specimen bearing soft normal + hard normal components.

Symbols as for Fig. 2.

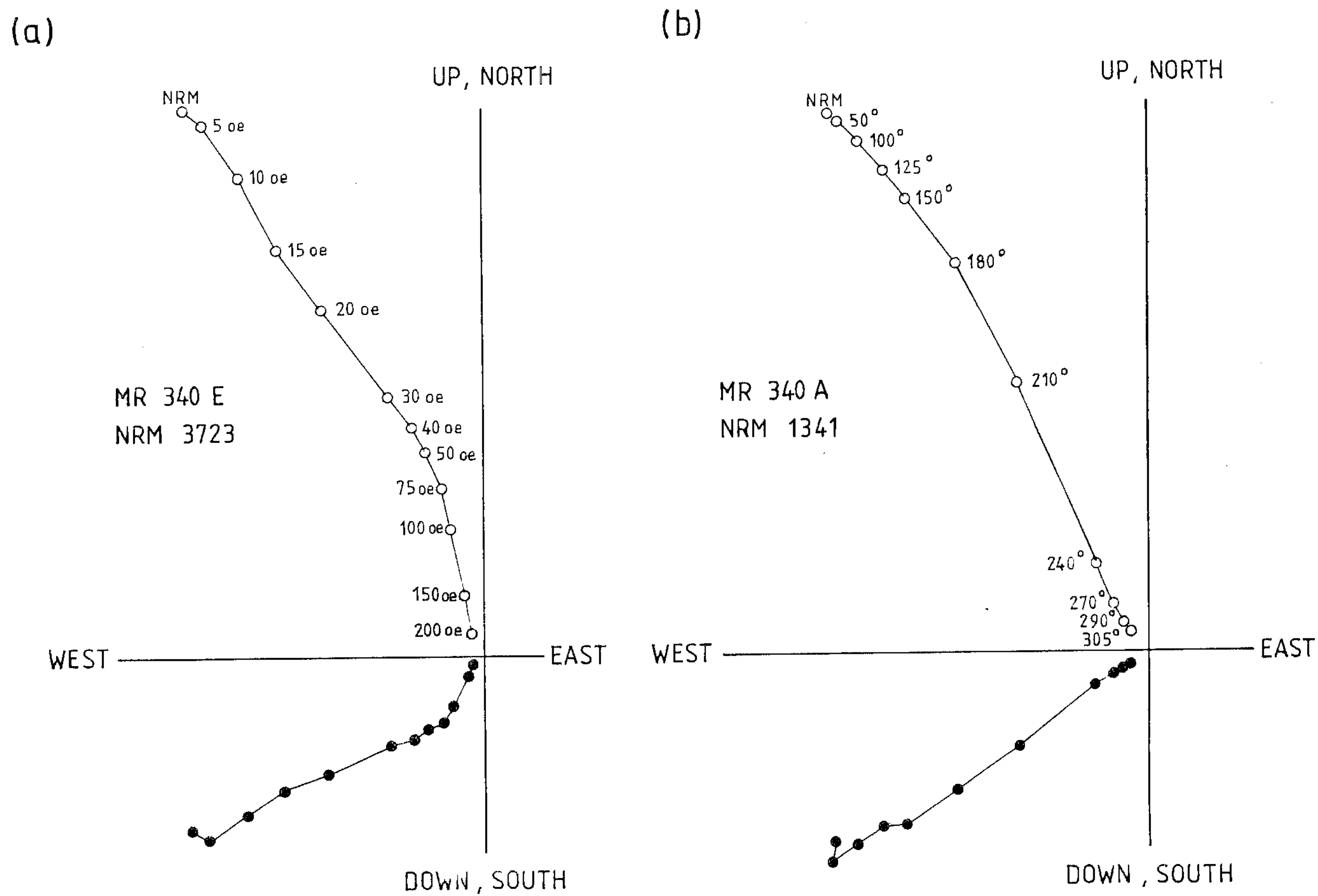
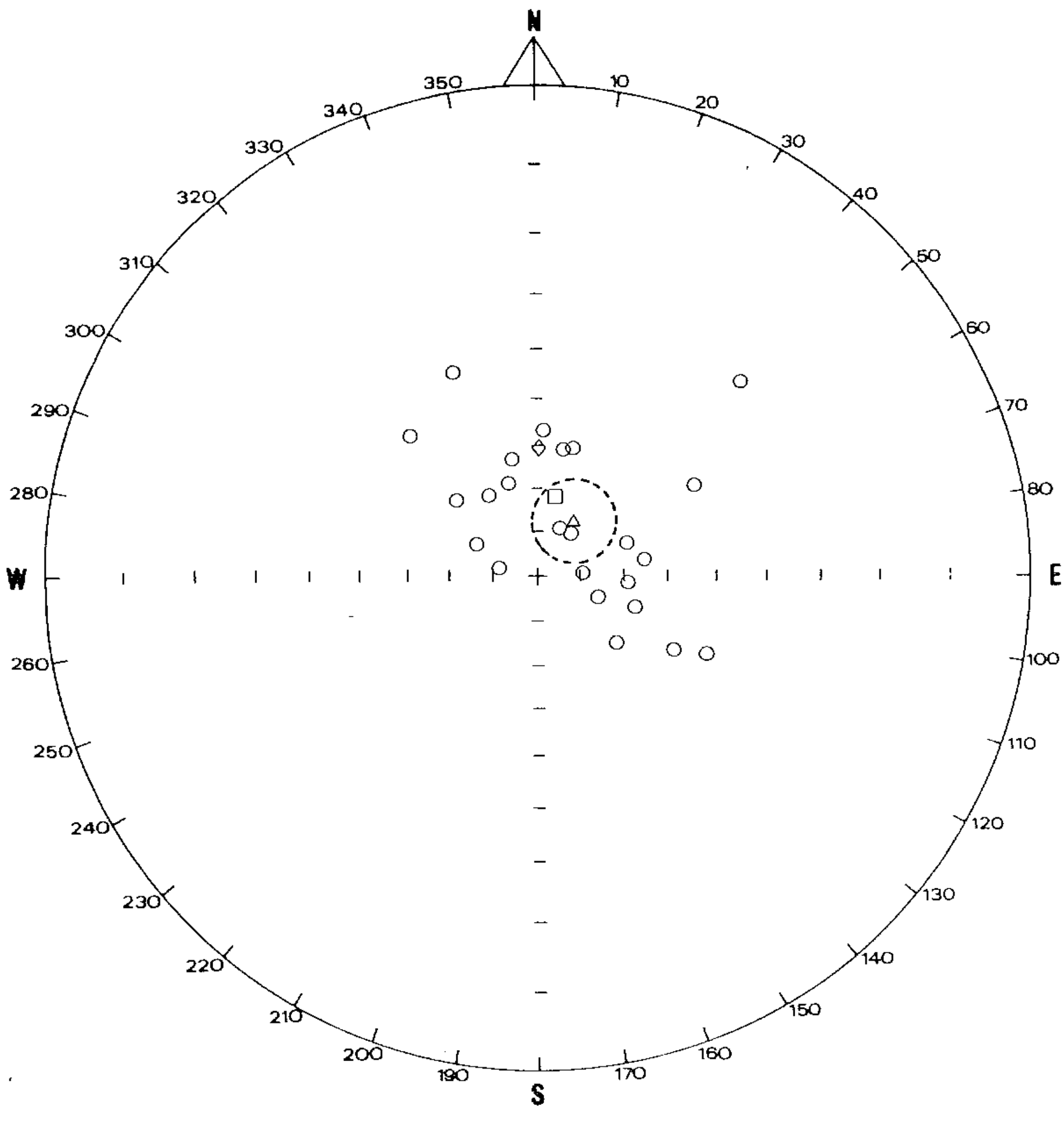

(a)
UP, NORTH
NRM
5 oe
10 oe
15 oe
20 oe
30 oe
40 oe
50 oe
75 oe
100 oe
150 oe
200 oe
MR 340 E
NRM 3723
WEST
EAST
DOWN , SOUTH
(b)
UP, NORTH
NRM
50°
100°
125°
150°
180°
210°
240°
270°
290°
305°
MR 340 A
NRM 1341
WEST
EAST
DOWN , SOUTH

FIG.3

Fig. 4 Sample mean NRM directions for Cleveland orebody. Stereographic upper hemisphere projection. The primitive represents the present horizontal.



○ Sample mean NRM directions

△ Mean NRM direction and cone of confidence

□ Present field direction

◇ Dipole field direction

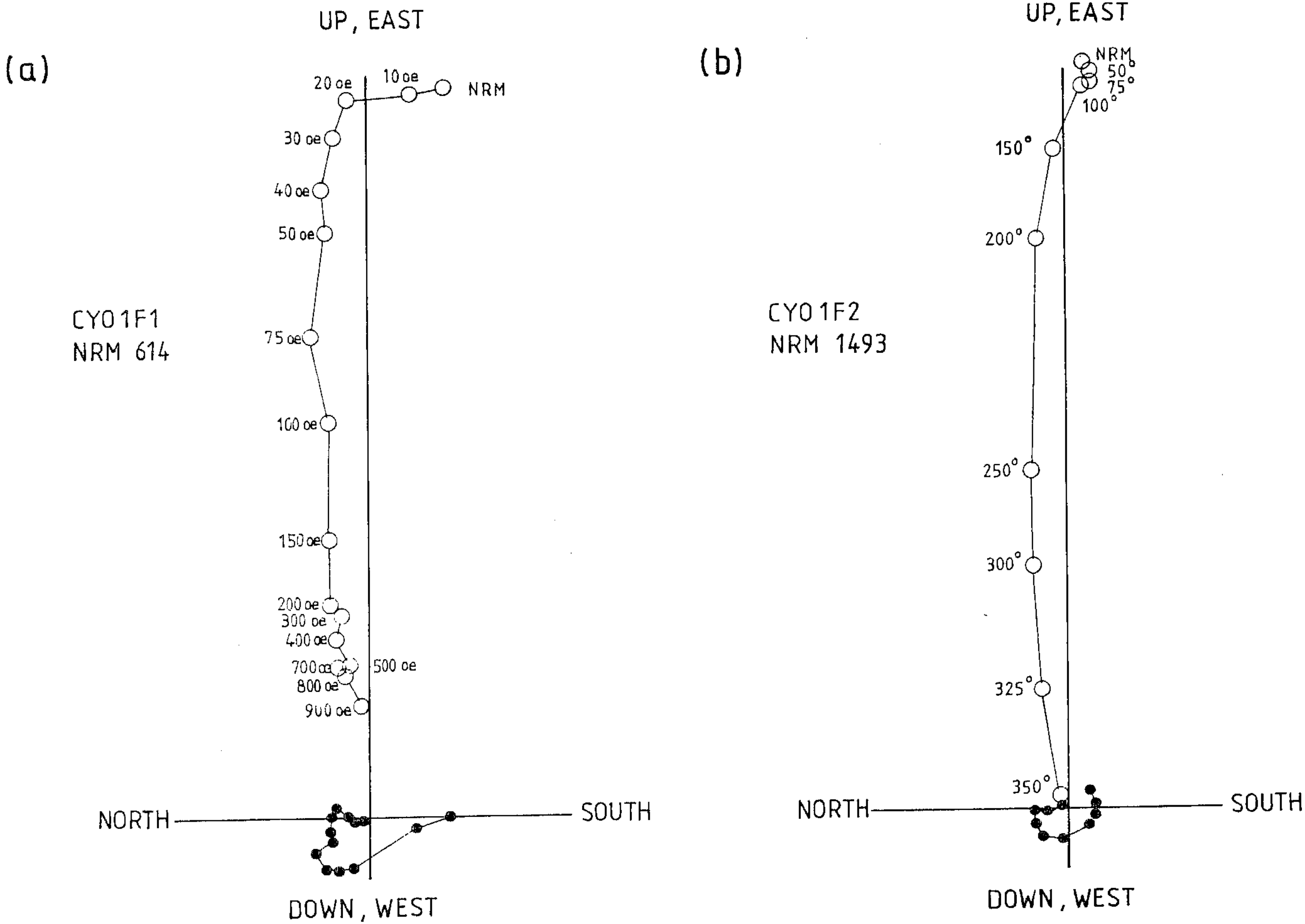
FIG.4

Fig. 5 Zijderveld plots for specimens of pyrrhotite-bearing baked sediment adjacent to the Cygnet Alkaline Complex.

5 (a) depicts AF demagnetisation data.

5 (b) depicts thermal demagnetisation data.

The dots represent projection onto the horizontal plane, circles projection onto the N-S vertical plane. The curved segments represent removal of two (or more) magnetisation components with overlapped stability spectra. In this case the soft component(s) represent palaeomagnetic noise. Following cleaning to above 500 oe or 250^{o}C a single stable component of magnetisation directed N with steep negative inclination is indicated by the linear segments extrapolating to the origin.



(a)
UP, EAST
NRM
10 oe
20 oe
30 oe
40 oe
50 oe
75 oe
100 oe
150 oe
200 oe
300 oe
400 oe
500 oe
700 oe
800 oe
900 oe
CY01F1
NRM 614
NORTH
SOUTH
DOWN, WEST
(b)
UP, EAST
NRM
50°
75°
100°
150°
200°
250°
300°
325°
350°
CY01F2
NRM 1493
NORTH
SOUTH
DOWN, WEST

FIG.5