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Prefolding and Overprint Magnetic Signatures in Precambrian (~2.9–2.7 Ga) Igneous Rocks From the Pilbara Craton and Hamersley Basin, NW Australia

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A total of 446 oriented samples have been collected from an Archaean intrusion and the Fortescue Group volcanics and intrusions in the Pilbara and Hamersley regions of northwestern Australia. The paleomagnetism and rock magnetism of these samples have been investigated using susceptibility and hysteresis properties and both alternating field (af) and thermal demagnetization. The most consistent paleomagnetic results were achieved by first applying af demagnetization and then stepwise thermal demagnetization. Evidence of the effects of lightning are widespread which accounts for the efficacy of this particular demagnetization strategy. Application of the fold test has resulted in placing significant constraints on the acquisition ages of some of the magnetizations and their corresponding pole positions. A prefolding pole position from the "Millindinna Complex," is latitude = 11.9°S, longitude = 161.3°E (dp = 6.8°, dm = 8.4°) and is correlated with a radiometric age of 2.86 ± 0.02 Ga. Folding in the "Millindinna Complex" occurred prior to the deposition of the Fortescue Group. New geochronological data indicate that the extrusion of the flood basalts commenced about 2.8 Ga. This provides a minimum age for the magnetization of the "Millindinna Complex." Deformation responsible for the formation of the mobile belt separating the Pilbara and Yilgarn blocks during the Ophthalmian Orogeny has affected the Fortescue Group and produced a moderate degree of folding in the southern part of the Hamersley Basin. In the region of "Millindinna Complex" outcrop, the Fortescue Group is generally flat lying. Prefolding pole positions from the Fortescue Group are for the Mount Roe Basalt, latitude = 52.4°S, longitude = 178.0°E (dp = 6.4°, dm = 9.1°) and for the Mount Jope Volcanics, latitude = 40.5°S, longitude = 128.7°E (dp = 19.9°, dm = 20.8°). The overprint magnetization in the Mount Jope Volcanics yields a pole position, latitude = 35.0°S, longitude = 211.5°E (dp = 2.8°, dm = 5.5°) and is interpreted as having been acquired during folding relating to the formation of the Ophthalmian Fold Belt.

INTRODUCTION

It is widely acknowledged that paleomagnetic investigations of Precambrian rocks are fraught with traps and pitfalls, and consequently interpretations concerning Precambrian landmass distributions have been called into question. "It now seems to us that ... contradictions arise because of the attempts by ourselves and others ... to compare long segments of APW paths which represent motion over hundreds of millions of years" [*Irving and McGlynn*, 1981]. "Many of the proposed hypotheses, based on a scanty and poorly defined data base have been premature" [*Roy*, 1983]. Some of the obstacles that have plagued researchers who have attempted to analyze Precambrian paleomagnetic data are (1) the problem of resolving complex magnetizations and determining which (if any) corresponds to the age of the rock, (2) the fragmentary nature of the Precambrian record, and (3) the uncertainties regarding structural attitudes of many Precambrian rock units.

The above views represent a denunciation of the general consensus expressed as recently as the late 1970's when many authors agreed that the Precambrian paleomagnetic data from the major continents were best interpreted in terms of constituent cratons having maintained their relative spatial relationships since the Proterozoic [*Piper et al.*, 1973; *McElhinny and Embleton*, 1976; *McElhinny and McWilliams*, 1977; *Roy and Lapointe*, 1976; *McGlynn and Irving*, 1978; *Irving and McGlynn*, 1979]. Generally, workers were careful to qualify their interpretations, indicating that although they were the simplest, alternative and more complex solutions could not be unequivocally ruled out, e.g., small-scale or east-west motions between cratons would remain undetected in apparent polar wander paths (APWP). Nevertheless, the established opinion precluded large-scale motion between cratons. It is apparent that before further profitable research in this field is possible, many anomalies and unsubstantiated assertions will have to be identified and excised, and future paleomagnetic investigations will have to satisfy more stringent acceptance criteria with greater control over the resolution and ages of magnetization. In this study, particular emphasis has been placed upon the fold test [*Graham*, 1949] as a means of establishing the timing of magnetizations. We note that while baked contact tests are potentially capable of relating magnetizations to original cooling and are often reported as such, definitive accounts of the full contact test described by *Graham* [1949], are rare because the test is intrinsically difficult to implement. Although the fold test is less powerful than the contact test, it is often easy to implement, unless of course sequences are everywhere flat lying or the directions of magnetization and fold axes are parallel.

Previous paleomagnetic studies of the Pilbara region (northwestern Australia, Figure 1) encompass the early work of *Irving and Green* [1958], the work on the iron formations by *Porath* [1967] and *Porath and Chamalaun* [1968], and some of the major dykes by *Embleton* [1978]. *Embleton et al.* [1979] reported magnetic measurements on a range of rock types, including banded-iron formations, volcanics, and a number of intrusions. As a continuation of that project, we present here details of results from an Archaean intrusive complex and some lower Proterozoic volcanics and intrusions.

GEOLOGY AND GEOCHRONOLOGY

The subhorizontal to moderately folded Fortescue and Hamersley groups rest unconformably on a deformed 3.5–2.85

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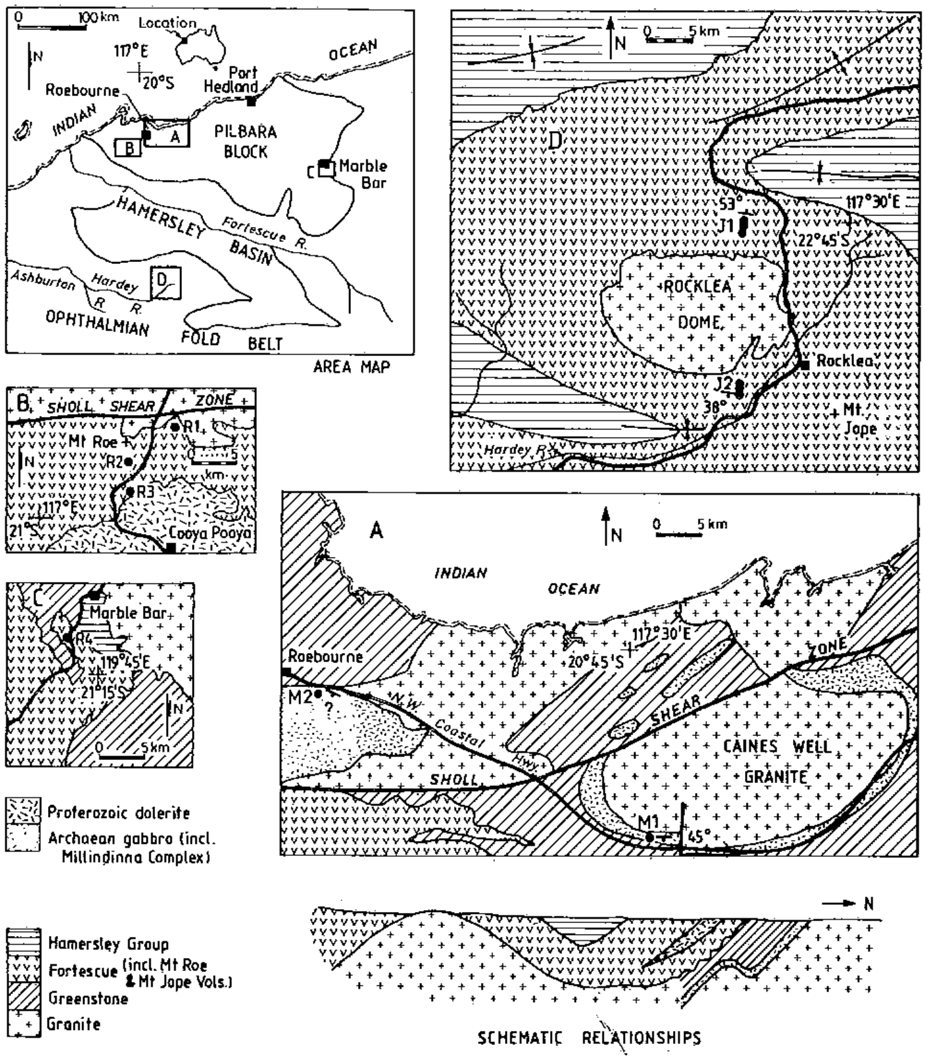

Fig. 1. Geological sketch map of the Pilbara and Hamersley Basin regions of northwestern Australia, showing sampling localities.

Ga granite and greenstone terrain, the Pilbara Craton. Together, the groups comprise the major units of the Mount Bruce Supergroup (Figure 1). The Fortescue Group is dominated by flood basalts which include the Mount Roe Basalt and the Mount Jope Volcanics, with subordinate beds of pyroclastic and other clastic rocks in the lower part of the group and nonclastic and fine-grained rocks at the top. The sequence commonly exceeds 2000 m thickness. The younger Hamersley Group is an evenly stratified succession of banded-iron formation, chert, shale, and dolomite, with acid lavas and tuff near the top. This group is up to 1500 m thick. *Hickman* [1983] has described the stratigraphic and tectonic development of the Pilbara region.

The oldest rock unit sampled is the "Millindinna Complex." It is considered to be a large differentiated sill, intruded preferentially along an unconformity and folded during the late Archaean [*Fitton et al.*, 1975]. The "Millindinna Complex" is a controversial unit, of uncertain regional extent and relationship [*Hickman*, 1983]. Samples collected for paleomagnetic work yield a combined age of 2.86 ± 0.02 Ga from Sm-Nd (2.85 ± 0.02 Ga) and Pb-Pb (2.85 ± 0.02 Ga) isotope geochronology [*Gulson and Korsch*, 1983].

The timing of igneous events during the period $\sim$2.9–2.7 Ga is not well understood at present. Hence the relationship of the Black Range Dyke, one of a major north-northeast trending swarm, with the basal unit of the Fortescue Group, the Mount Roe Basalt, remains uncertain. Paleomagnetic data were reported for the Black Range Dyke by *Embleton* [1978]. The earlier geochronological studies of the Black Range Dyke [*Lewis et al.*, 1975] using the Rb-Sr technique, yielded an age now regarded as too young. The isochron included data from the dolerite as well as remelted wall rock material. Recent Rb-Sr work on whole rock samples of the Black Range Dyke indicates that it may have an isotopic age greater than about 2.7 Ga (J. R. de Laeter, personal communication, 1984). The ages of the mafic dykes in the Pilbara Craton and the overlying Fortescue Group are further constrained by the results of isotope studies on a posttectonic granitoid and the Spinaway Porphyry in the Lower Fortescue Group. Readers are referred to *Hickman* [1983], *Blake* [1984], and *Blake and McNaughton* [1984] for a description of the geochronology of the Pilbara region.

The Spinaway Porphyry, which occurs in the lower Fortescue Group and was originally considered to be intrusive [*Hickman*, 1978] although now is interpreted as having an erosive upper contact [*Blake*, 1984], is reported [*Pigdeon*, 1984; *Blake and McNaughton*, 1984) to have an age about 2.77 Ga. The lower part of the Fortescue Group is also intruded by dolerite sills and rare dykes, collectively known as the Cooya Pooya Dolerite. In stratigraphic order the units sampled for the present study are the "Millindinna Complex," the Mount Roe Basalt, the Spinaway Porphyry, the Mount Jope Volcanics, and the Cooya Pooya Dolerite.

METHODS

The majority of samples collected were drilled using portable rock drills and oriented using both magnetic and sun compasses [*Embleton*, 1979]. The cores were later sliced into specimens of nominal dimensions 2.5 cm diameter × 2.2 cm height, usually yielding two to four specimens per core. Magnetizations of specimens were measured using an ScT Squid magnetometer or Digico flux gate magnetometers. The latter instruments were only used for magnetic moments greater than approximately 10^{-5} emu (10^{-8} A m^{-1}).

Demagnetization of specimens was performed with a three-axis tumbling alternating field (af) device (similar to that described by *Roy et al.* [1972]) or less frequently with Schonstedt GSD-1 af equipment. Most specimens were demagnetized using a furnace and zero-field coils similar to those described by *McElhinny et al.* [1971]. Demagnetization trends from all demagnetized specimens have been examined with the aid of both stereo nets and orthogonal plots [*Zijderveld*, 1967]. Principal component analysis [*Kirschvink*, 1980] as adapted to linearity spectrum analysis (LSA) [*Schmidt*, 1982] has been utilized extensively.

All directions of magnetization were derived from LSA only accepting directions defined with better than a 5° maximum angular deviation (MAD) except for the Mount Jope Volcanics where the cutoff was relaxed to 10° since intensities of magnetization of these volcanics were very low.

Anisotropies of susceptibility were measured using Digico equipment, and ARUN Electronics equipment similar to that described by *Likhite et al.* [1965] was used for measuring bulk hysteresis parameters. The Digico anisotropy delineator has been calibrated against a susceptibility bridge thus avoiding problems recently brought to light by *Hrouda et al.* [1983] and *Veitch et al.* [1983]. The susceptibility bridge (described by *Ridley and Brown* [1980]) was used to determine the low field susceptibility versus temperature (χ/T) characteristics discussed.

PALEOMAGNETIC RESULTS

"*Millindinna Complex*"

The "Millindinna Complex" was sampled at two localities (M1 and M2, Figure 1*a*). Ten sites, each of five or six cores, were collected from south dipping exposures, M1, of medium- to fine-grained gabbro west of Little Sherlock River. The magnitude of the dip as determined from layering of plagioclase crystals has been estimated to be 45° (R. Horwitz, personal communication, 1984). The second locality, M2, approximately 40 km to the west-northwest of M1, was sampled at 11 sites, in medium- to fine-grained gabbro, also each of five or six cores. The structure at this locality, while different from that of the first, was difficult to ascertain since layering was not well developed and outcrop pattern gave no clear indication of attitude. The outcrops at locality M1 were in the form of an east-west series of elongated hills, clearly defining the strike of the unit. Since no similar patterns were observed at locality M2 it would appear that dips here were low. A single measurement of a rare planar feature suggested that the sequence at this place dipped 16° in a direction 215°. Measurements of anisotropy of susceptibility (often greater than 5%) failed to provide better attitude information, with large variations between sites occurring at both localities. At the first locality the anisotropy ellipsoids, while often strongly oblate and with good within-site agreement, appeared to vary along strike (Figure 2), suggesting that rather than gravitational settling, perhaps some flow mechanism prior to solidification of the magma controlled the anisotropy. The susceptibility ellipsoids did not reflect the visible tabular alignment of the plagioclase crystals. Similar conclusions are applicable to the second locality. The cause of the anisotropy remains enigmatic.

Natural remanent magnetization (NRM) measurements showed considerable scatter of directions and high intensities of remanence (often >0.05 emu cm^{-3}, 50 A m^{-1}), which coupled with the prominent topography of the outcrops and monsoonal climate strongly suggested that the cause was lightning. Specimens from sites 04 and 10 exhibited intensities of between 0.1 to 0.2 emu cm^{-3} (100 and 200 A m^{-1}) and an average ratio of NRM to saturation remanent intensities of 0.6 and 0.25, respectively. These supposed lightning-induced isothermal remanent magnetizations (IRM) of specimens from these two sites could not be effectively preferentially removed with af demagnetization. These samples were consequently used for radiometric dating using Sm-Nd and Pb-Pb techniques [*Gulson and Korsch*, 1983]. Most other specimens showed at least some effects of lightning, e.g., there was generally systematic decrease (rarely increase) of intensity within samples and a decrease in angular dispersion of the initial direction relative to the final cleaned direction with distance from the present rock surface. This is most naturally explained as the result of lightning-induced IRM.

At least two specimens from each site were stepwise af demagnetized to 1000 Oe (100 mT). Typically, by 400 Oe (40 mT), directions converged and began demagnetizing toward the origin (Figures 3*a* and 3*b*). It was apparent that the majority of specimens required af intensities of the order of 400 Oe (40 mT) to eliminate the lower coercivity IRM responsible for the scattering of the NRM directions. Before applying thermal demagnetization all specimens were pretreated at af demagnetization intensities of 400 Oe (40 mT). This procedure minimized the effects of lightning-induced IRM components. Orthogonal plots of thermal demagnetization following this af partial demagnetization are displayed in Figures 3*c*–3*f*. The af pretreatment proved more effective at the first locality than at the second. While 400 Oe (40 mT) would appear to be a harsh pretreatment for many igneous rock types, the remarkable stability of the magnetic remanence of the gabbroic phase of the Millindinna Complex permits such tactics. To investigate this facet of the character of the gabbro, further rock magnetic properties that are diagnostic of domain state have been measured on two specimens from each locality. The ratios of coercivity of remanence (H_{cr}) to bulk coercivity (H_c), saturation remanence (J_{rs}) to saturation magnetization (J_s), and χ to J_s are given in Table 1. The high values of J_{rs}/J_s of 0.4–0.5 accompanied by low values of H_{cr}/H_c of 1.2–1.7 and χ/J_s of less than 10^{-3} Oe^{-1} ($4\pi \times 10^{-6}$ m A^{-1}) are compatible with pseudo-single domain (PSD) properties or single domain (SD) properties slightly diluted by superparamagnetic (SPM) or multidomain (MD) properties. The contribution by SPM, however, must be low since the hysteresis parameter ratios fall well within the SD-PSD range of values [*Dunlop*, 1981, Figures 8–10, pp. 10–11]. Also, observations of viscous change of

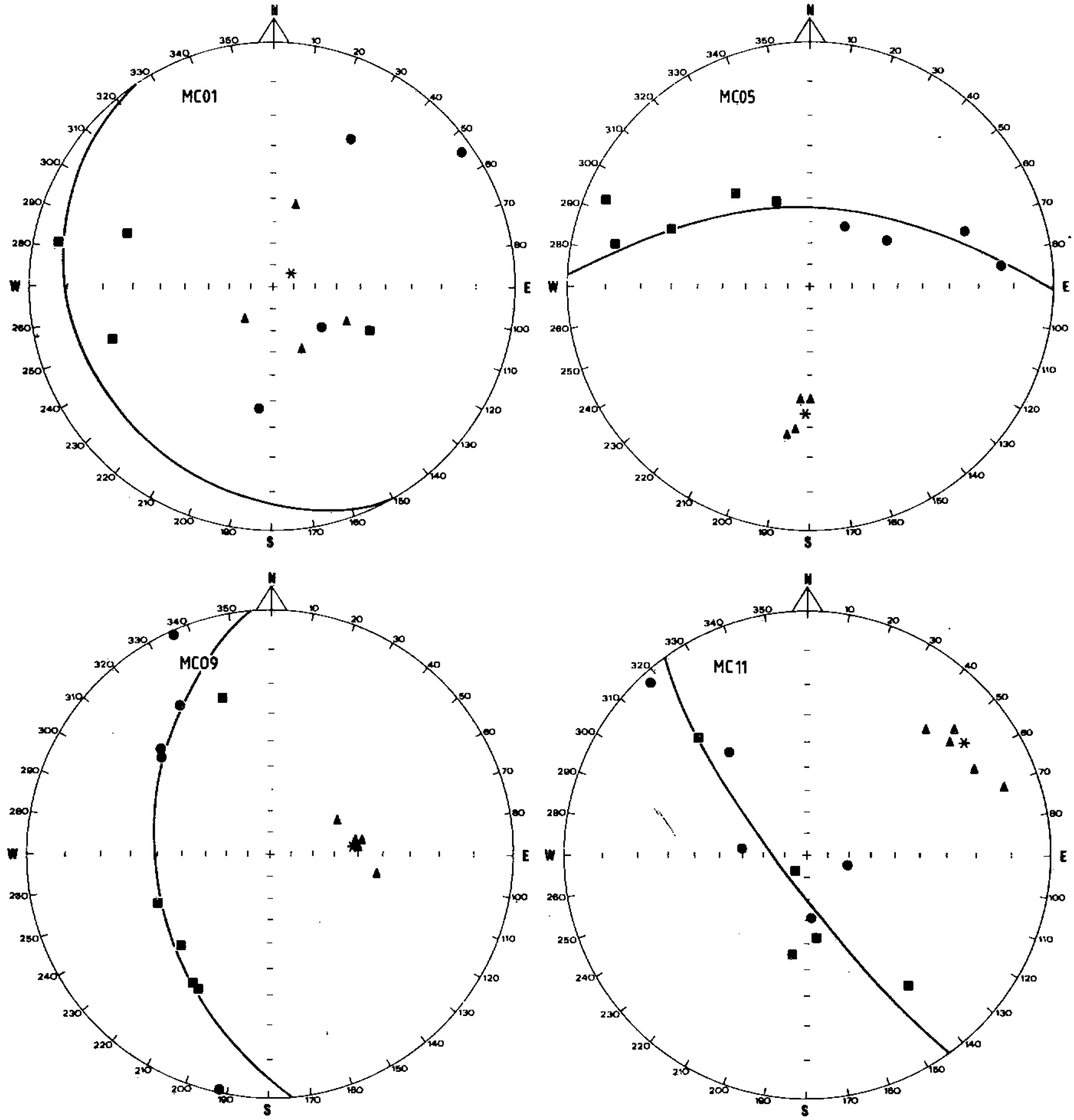

Fig. 2. Directions of principal axes of anisotropy of susceptibility ellipsoids of samples from locality M1 of the Millindinna Complex gabbro. The asterisks represent the mean of the minimum susceptibility axes. The squares represent maximum, while the circles represent the intermediate susceptibility axes. Lower hemisphere equal-angle projection.

remanence over a period of months indicate an insignificant coefficient of viscosity. The high values of H_{cr} (up to more than 800 Oe, 80 mT (Figure 4)) also suggest the dominance of SD particles (Figure 4*b*). However, the χ/T curve (Figure 4*a*) reveals the presence of at least some multidomain (MD) grains with a small isotropic peak at approximately $-150°C$. The af demagnetization and other rock magnetic characteristics would seem to indicate that any MD contribution is minor. The χ/T curve also reveals two Curie temperatures at 550°C and 580°C, which presumably reflects two distinct compositions, one pure magnetite and one slightly impure magnetite. The reversibility of the curve is evidence against chemical change during heating, showing that the two compositions are original and that one or the other has not been produced by laboratory heating.

Electron microprobe analysis confirms these findings, in particular, the presence of two spinel phases and a bimodal grain size distribution. An electron micrograph (Figure 5) shows very fine (~ 1 μm) magnetite within a pyroxene host and a larger (~ 10 μm) grain of an impure magnetite. An average of four analyses of the latter grains yielded a composition of approximately $Fe_{2.3}Cr_{0.4}Ti_{0.2}Al_{0.1}O_4$, which implies

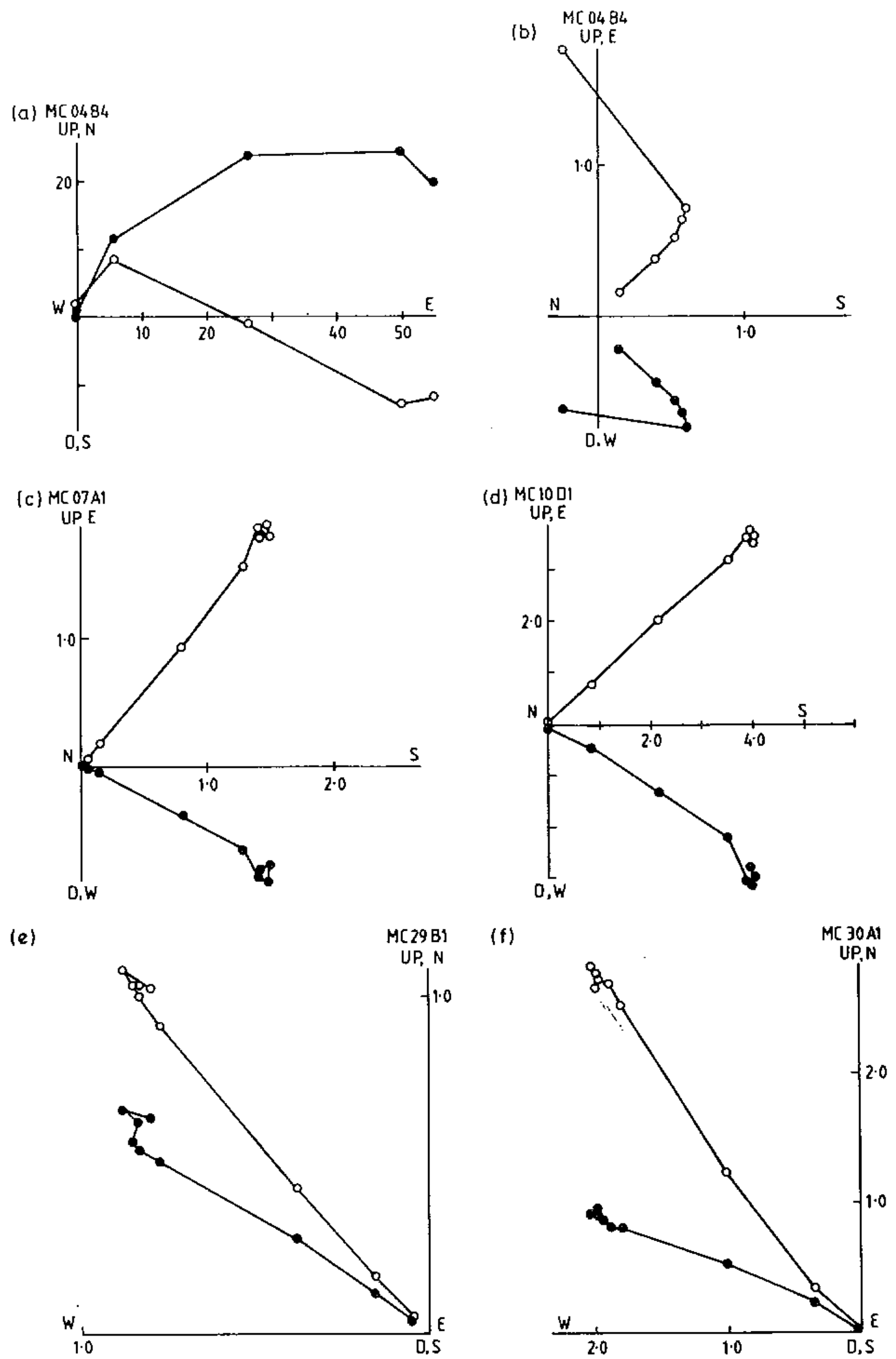

Fig. 3. Orthogonal projections of vector end points for specimens from the Millindinna Complex (*a*) for specimen MCO4B4, steps NRM, 50 Oe (5 mT), 100 Oe (10 mT), 200 Oe (20 mT), 300 Oe (30 mT), and continuing to (*b*) 300 Oe (30 mT), 400 Oe (40 mT), 500 Oe (50 mT), 600 Oe (60 mT), 750 Oe (75 mT), and 1000 Oe (100 mT), (*c*)–(*f*) for other specimens as indicated, after 400 Oe (40 mT), 200°C, 300°C, 400°C, 480°C, 505°C, 520°C, 540°C, and 560°C. Open (solid) symbols represent projections onto the vertical (horizontal) plane. Scale in units of 10^{-3}emu cm^{-3}(A m^{-1}).

the presence of a lower Curie temperature phase, similar to that shown in Figure 4*a*. The micron and submicron magnetite most probably is responsible for the very high coercivities observed while the coarser, impure grains are probably MD, whose presence is characterized by the isotropic peak at −150° (Figure 4*a*). The thermomagnetic and rock magnetic properties of these samples show an affinity with those of the Modipe Gabbro [*Evans and McElhinny*, 1969] and Usushwana Complex (M. O. McWilliams, personal communication, 1984).

Thermal demagnetization of all specimens that were pretreated at 400 Oe (40 mT) af was carried out in a stepwise manner from 200°C until complete destruction of remanence just before 580°C. Following the usual dramatic change in direction from NRM to 400 Oe (40 mT), very little subsequent vector changes occurred until close to the blocking temperature T_B when the remanence decayed quickly to the origin, reflecting a thermally discrete magnetic component. Figures 3*c* and 3*d* show orthogonal plots of demagnetization data from two specimens from the first locality with southwesterly decli-

TABLE 1. Summary of Rock Magnetic Data From the Millindinna Complex

Specimen	H_{cr}/H_c	J_{rs}/J_s	χ/J_s,* × 10^{-3} Oe^{-1}
MC02A2	1.67	0.44	0.94
MC06D2	1.63	0.39	0.72
MC30E2	1.20	0.45	1.00
MC35B2	1.62	0.50	0.35

H_{cr}, coercivity of remanence; H_c, bulk coercivity; J_{rs}, saturation remanence; J_s, saturation magnetization; χ, initial susceptibility.
*$Oe^{-1} \equiv 4\pi \times 10^{-3}$ m A^{-1}.

nations and moderate negative inclinations. Figures 3*e* and 3*f* show similar results from the second locality but with west-northwesterly declinations. All plots are with respect to present horizontal.

Table 2 gives site mean directions that were derived from LSA [*Schmidt*, 1982] of the thermal demagnetization data from both localities, while Figure 6 shows the sample directions from LSA. As discussed above, there is no thermal demagnetization data from sites 04 and 10. Other sites that have been too heavily overprinted by lightning and have not yielded tight groupings (as reflected by their α_{95} values (Table 2)) are not considered further. After correcting for apparent attitudes the locality mean directions are brought into closer proximity, but they remain significantly different. The angle between the two before correction is almost 60° and after is less than 30°. We note that *Halls and Pesonen* [1982] concluded that the attitude of igneous layering should not be used to unfold paleomagnetic data. However, from the pattern of outcrop at locality M1 (Figure 1*a*) the apparent structural relationships are consistent with the applied correction. Our

Fig. 5. Electron micrograph of "Millindinna Complex" gabbro. The scale bar is 100 μm. The dark grey phase is labradorite while the medium grey phase is pyroxene. Olivine is the slightly lighter grey phase at the bottom of the photograph beneath the scale bar. The very fine (<2–3 μm) grains were analyzed and found to be magnetite while the larger grains (5–10 μm) were found to be chrome-titaniferous magnetite. Secondary hematite can be seen along fractures, especially between olivine and pyroxene.

inability to ascertain the attitude at locality M2 is most likely the cause for this imperfect alignment. Thus, while we believe the cleaned magnetization of the "Millindinna Complex" is prefolding in age, the directions of magnetization for locality M2 are not considered to be reliable indicators of geomagnetic field directions in view of the uncertainty of the structure at

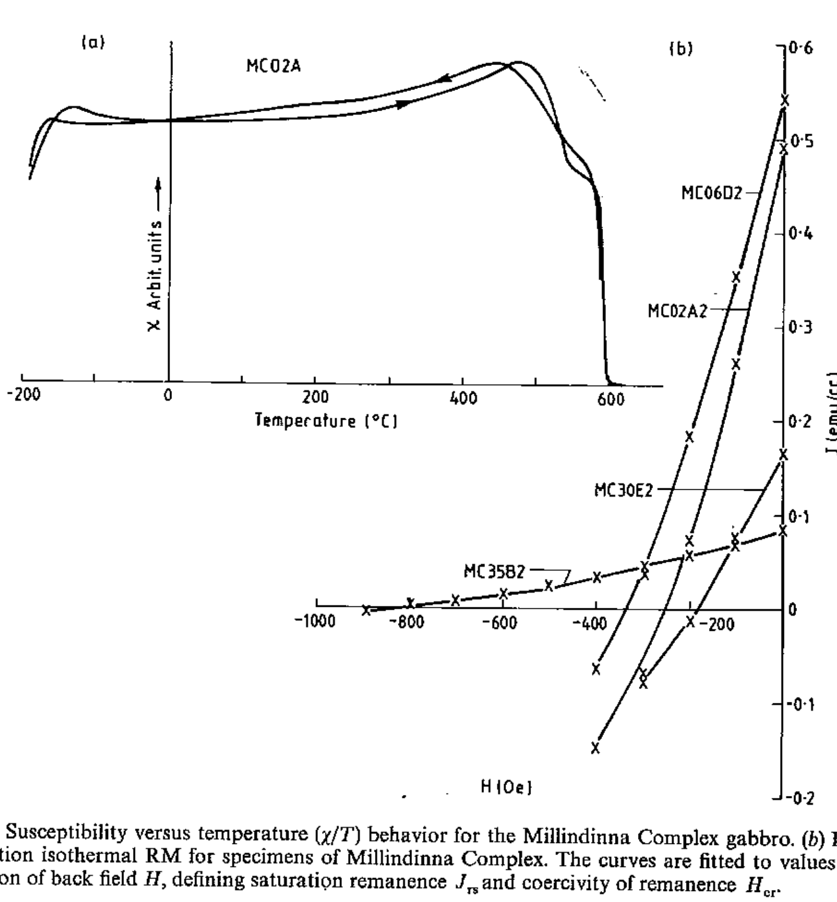

Fig. 4. (*a*) Susceptibility versus temperature (χ/T) behavior for the Millindinna Complex gabbro. (*b*) DC demagnetization of saturation isothermal RM for specimens of Millindinna Complex. The curves are fitted to values of residual IRM after application of back field H, defining saturation remanence J_{rs} and coercivity of remanence H_{cr}.

TABLE 2. Summary of Magnetizations From the Millindinna Complex

			Directions		
	N	R	D, deg	I, deg	α_{95}, deg
Locality M1: 20°55'S 117°32'E					
Site					
1	4	3.945	202.5	−40.5	12.5
2	4	3.996	210.6	−23.8	3.5
3	5	4.980	214.8	−36.2	5.5
5	5	4.994	212.7	−46.8	3.1
6	4	3.987	213.7	−43.5	6.1
7	3	2.993	210.0	−39.5	7.2
8	5	4.980	216.6	−36.6	5.4
9	4	3.983	215.6	−37.1	6.9
Mean horizontal	8	7.938	212.1	−38.0	5.2
Bedding	8	7.938	265.0	−65.1	5.2
Locality M2: 20°54'S, 117°30'E					
Site					
1	4	3.976	310.6	−38.0	8.3
2	5	4.905	294.9	−40.8	11.9
3	(3	1.760	94.6	−47.5	>90.0)
4	5	4.973	301.9	−49.6	6.3
5	5	4.994	292.3	−54.5	3.0
6	(5	2.982	12.0	−24.8	76.0)
7	(4	3.221	238.7	−30.5	54.0)
8	5	4.961	280.8	−51.0	7.6
9	(6	3.015	230.7	−53.7	79.0)
10	4	3.981	273.1	−49.5	7.4
11	4	3.853	294.7	−33.1	20.8
Mean horizontal	7	6.874	293.3	−45.8	8.8

N, number of samples; R, resultant of unit vectors; D and I, declination and inclination with respect to horizontal; α_{95}, half-angle cone of confidence [*Fisher*, 1953]. Locality M1 dips 45° south, while locality M2 is shallow dipping but of uncertain azimuth (see text). Parentheses indicate results omitted from the calculation of mean directions.

this locality. Since much greater faith can be placed in the structures measured at locality M1, these directions only have been used to calculate the virtual geomagnetic poles. The "Millindinna Complex" yields a magnetization direction with respect to the paleohorizontal of $D = 265.0°$, $I = -65.1°$ ($\alpha_{95} = 5.2°$) and a pole position at latitude = 11.9°S, longitude = 161.3°E ($dp = 6.8°$, $dm = 8.4°$).

Mount Jope Volcanics

The Mount Jope Volcanics (basalts and basaltic andesites) have been sampled on the north and the south side of an Archaean inlier, the Rocklea dome, where they are tilted sympathetically (Figure 1*d*). The northern limb is tilted 53°–013°, while the southern limb is tilted 38°–180° providing a good opportunity for utilizing a fold test [*Graham*, 1949]. In the sampling area the volcanics are assigned to an upper and a lower sequence. The upper volcanics have been sampled at 12 sites, while the lower volcanics have been sampled at 16 sites. Results from the upper volcanics were afflicted with low signal/noise ratios revealing no consistent directions. This is most probably associated with the greenschist metamorphism suffered by the volcanics. Actinolite and epidote are abundant, while pumpellyite is essentially absent. "Metamorphic actinolite has replaced the former mafic phase (probably pyroxene), which made up about 50% of the rock, plagioclase about 45%, quartz about 2% and a small quantity of Fe/Ti oxides but these have altered to sphene." (R. E. Smith as cited by *Horwitz* [1978]). Electron microprobe analysis of opaque phases present revealed rare, small (<5 μm) titanomagnetites and magnetites, along with equally rare and small grains of chalcopyrite and sphalerite (the remanence properties of one probed sample, JL13B, are shown in Figure 7).

Intensities of NRM were very low, typically less than 0.2 $\times 10^{-6}$ emu cm^{-3} (0.2 mA m^{-1}). The use of a cryogenic magnetometer was essential to measure the remanences following partial demagnetization. At least one specimen from each sample was initially thermally demagnetized, some examples of the demagnetization data are displayed as orthogonal plots in Figure 7. The Mount Jope Volcanics appear to carry up to three components of magnetization which can be resolved by thermal demagnetization. The component with the lowest T_B (removed by partial demagnetization to 300°C) is closely aligned with the regional present geomagnetic field and is of no immediate interest. By far the most prevalent magnetic component is directed northwesterly with a shallow inclination (Figures 7*a* and 7*b*). The stability spectrum of this component was found to lie between 300°C and an upper limit which was, in some instances, the maximum unblocking temperatures observed (in excess of 540°C), at which point the intensities of magnetization approached the sensitivity level of the magnetometer (5×10^{-9} emu cm^{-3} or 5 μA m^{-1} for approximately 11 cm^3 specimens).

In specimens from five sites (four from the north dipping limb, one from the south dipping limb) the above almost ubiquitous, component was survived by a third magnetization, which was resolved only above 500°C. The direction of this third component was dependent on the limb of the anticline from which the samples were derived. Figures 7*c* and 7*d*, for instance, reveal a stable component demagnetizing toward the origin above 500°C with a southerly declination and shallow positive inclinations, while Figures 7*e* and 7*f* show this last component with a north-northeasterly declination and steep positive inclination. Upon correction for tilting, these two directions are brought into close agreement in the southeast quadrant, with steep inclinations (Figure 8), clearly suggesting a positive fold test [*Graham*, 1949]. To provide a better statistical measure of this important prefolding component, a second batch of specimens from these five sites was subjected to similar temperature increments as were the initial specimens, with an additional step at 530°C.

Using the test derived by *McFadden and Jones* [1981], the hypothesis that the five site mean directions with respect to the present horizontal belong to a population with a common true mean direction can be rejected with greater than 99.9% confidence. That the five directions, when viewed with respect to bedding, belong to the same population cannot be rejected except with less than 78% confidence. Thus at the usual 95% confidence level, the high-temperature magnetizations observed in sites 1–4 and site 13 are prefolding. The age of folding is early Proterozoic [*Gee*, 1979], enhancing the significance of this test. All the directions depicted in Figure 8 were the result of applying LSA [*Schmidt*, 1982] with a 10° cutoff on MAD angles. The directions eliminated for the purpose of calculating the mean are most probably composite. Although LSA is a strong filter against composite magnetizations, when stability spectra are heavily overlapped, the chosen interval cannot resolve single components. The high-temperature directions used in the fold test clearly belong to groupings distinct from the northwest group. This is supported by a comparison of their relative stabilities in the orthogonal plots shown in Figures 7*c*–7*f*. Table 3 summarizes the characteristic components of magnetization from the Mount Jope Volcanics. The survival of a prefolding magnetization in only a few sites,

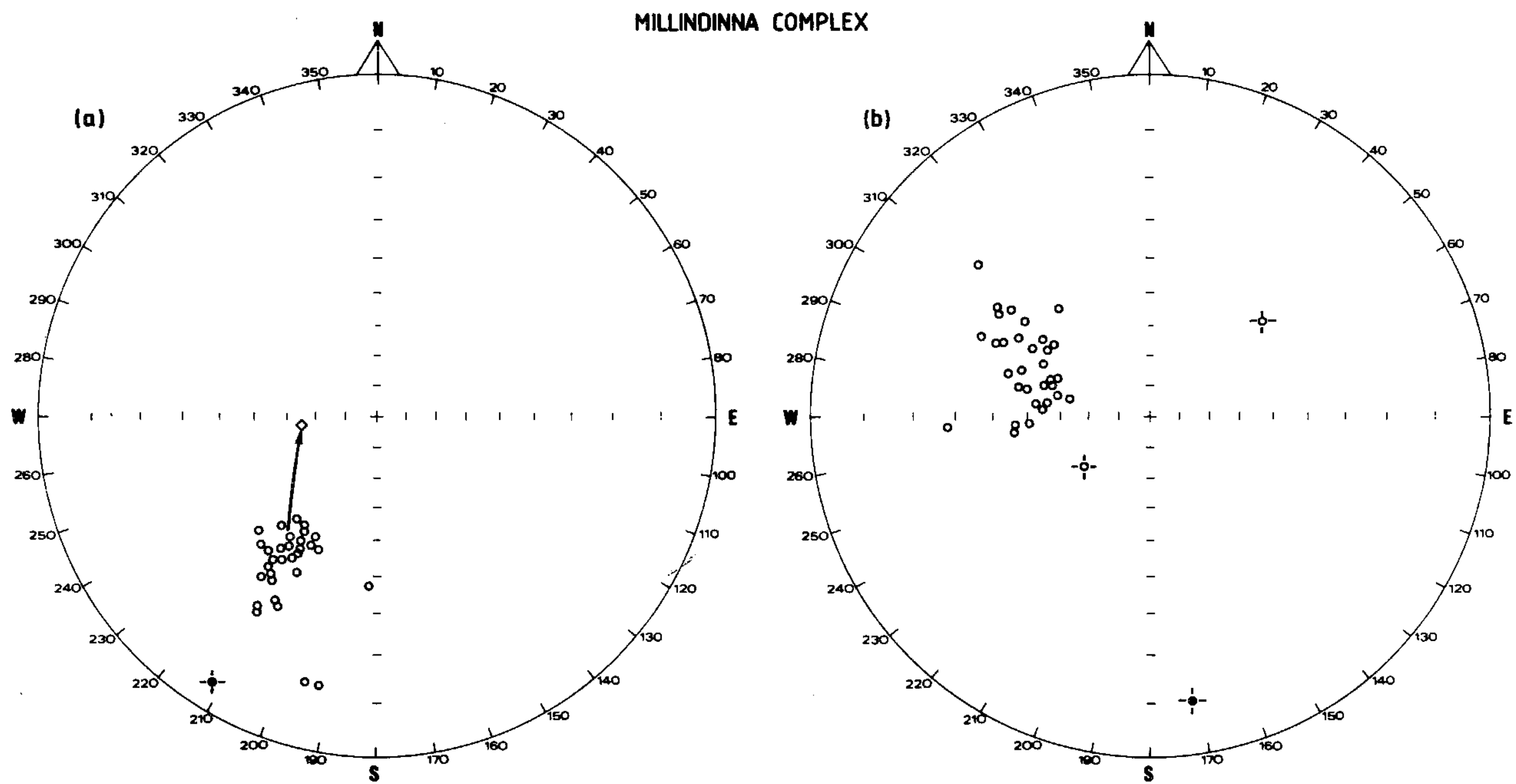

Fig. 6. Directions of magnetization determined from specimens of Millindinna Complex gabbro (*a*) locality M1 and (*b*) locality M2. Equal-angle projection, open (solid) symbols represent the upper (lower) hemisphere. The diamond represents the mean direction after tilt correction (see text). Crossed directions have been rejected.

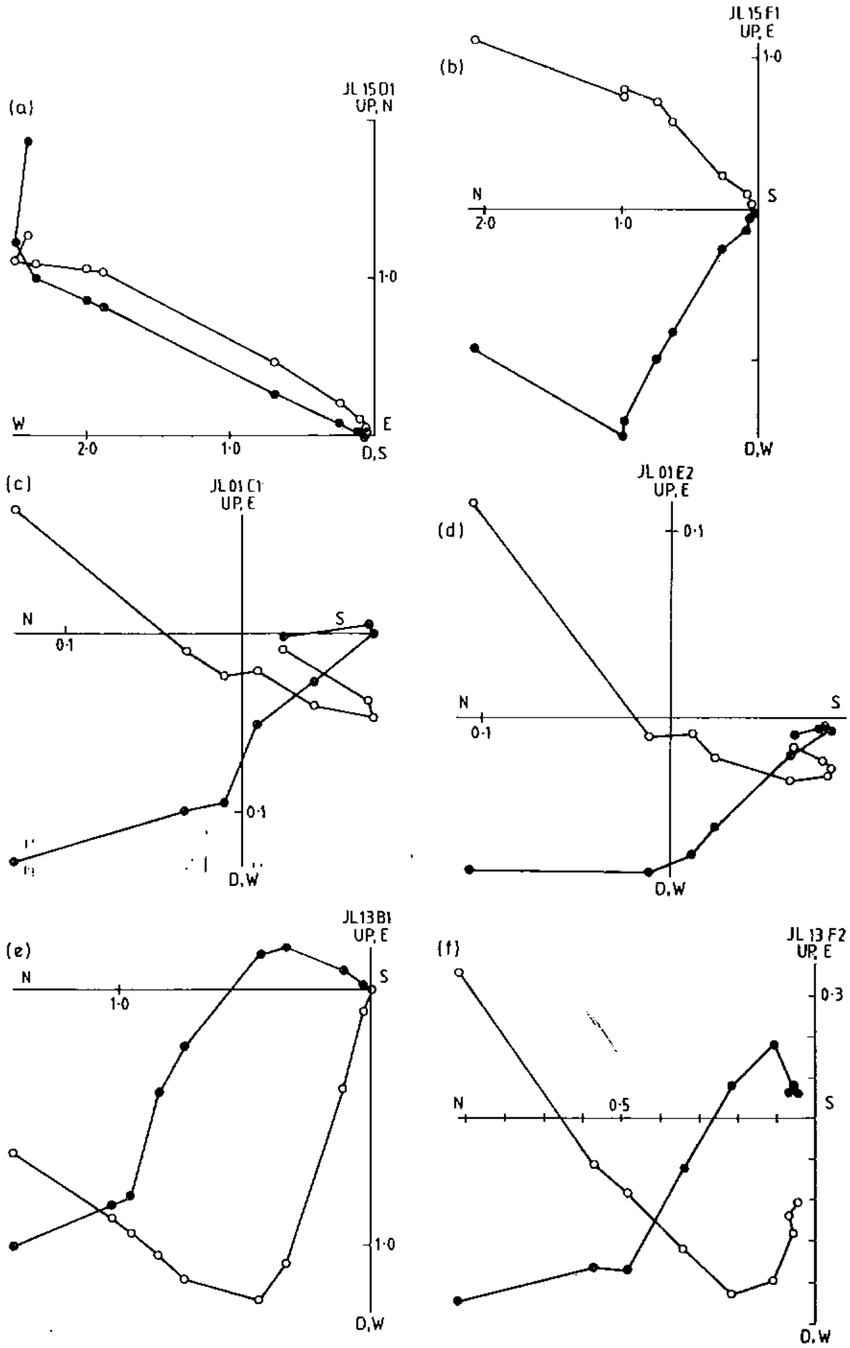

Fig. 7. Orthogonal projections of vector end points for specimens of Mount Jope Volcanics observed for NRM and after thermal demagnetization to 200°C, 300°C, 400°C, 450°C, 500°C, 520°C (plus 530°C for some), and 540°C. (*a*) and (*b*) Remagnetized samples; (*c*) and (*d*) samples from the north dipping limb; and (*e*) and (*f*) samples from the south dipping limb. Symbols as for Figure 3. Scale is units of 10^{-6} emu cm^{-3} (mA m^{-1}).

with the apparent complete overprinting or reprinting in those remaining sites, suggests that the overprinting processes were not only thermal but also thermochemical. Perhaps the magnetization that survived overprinting is carried by original magnetite that was chemically inert to events subsequent to formation, while the reset magnetizations are carried by secondary magnetite produced by exsolution of a titanomagnetite phase. Electron microprobe analysis revealed the presence of both phases. Heavily overlapped stability spectra are diagnostic of chemical remagnetization [*McClelland Brown*, 1982]. The pole position for these five sites is latitude = 40.5°S, longitude = 128.7°E (dp = 19.9°, dm = 20.8°).

To apply the fold test to the less stable magnetizations, that is, the northwest groups, is not valid because the group from the south dipping limb (Figure 8*b*) is streaked, i.e., non-Fisherian [*McFadden and Jones*, 1981; *Lewis and Fisher*, 1982]. In fact, the mean directions (denoted by the diamonds in Figure 8) cross over between their in situ positions and their unfolded positions. This is a characteristic feature of magnetizations that are penecontemporaneous with deformation [*McClelland Brown*, 1983] and indicates that the appropriate paleohorizontal lies between the bedding plane and present horizontal. We interpret these rocks to have been partially remagnetized during the emplacement of the Rocklea Dome (Figure 1) which was probably accompanied by uplift, erosion, and hence cooling. The streaking of the distribution

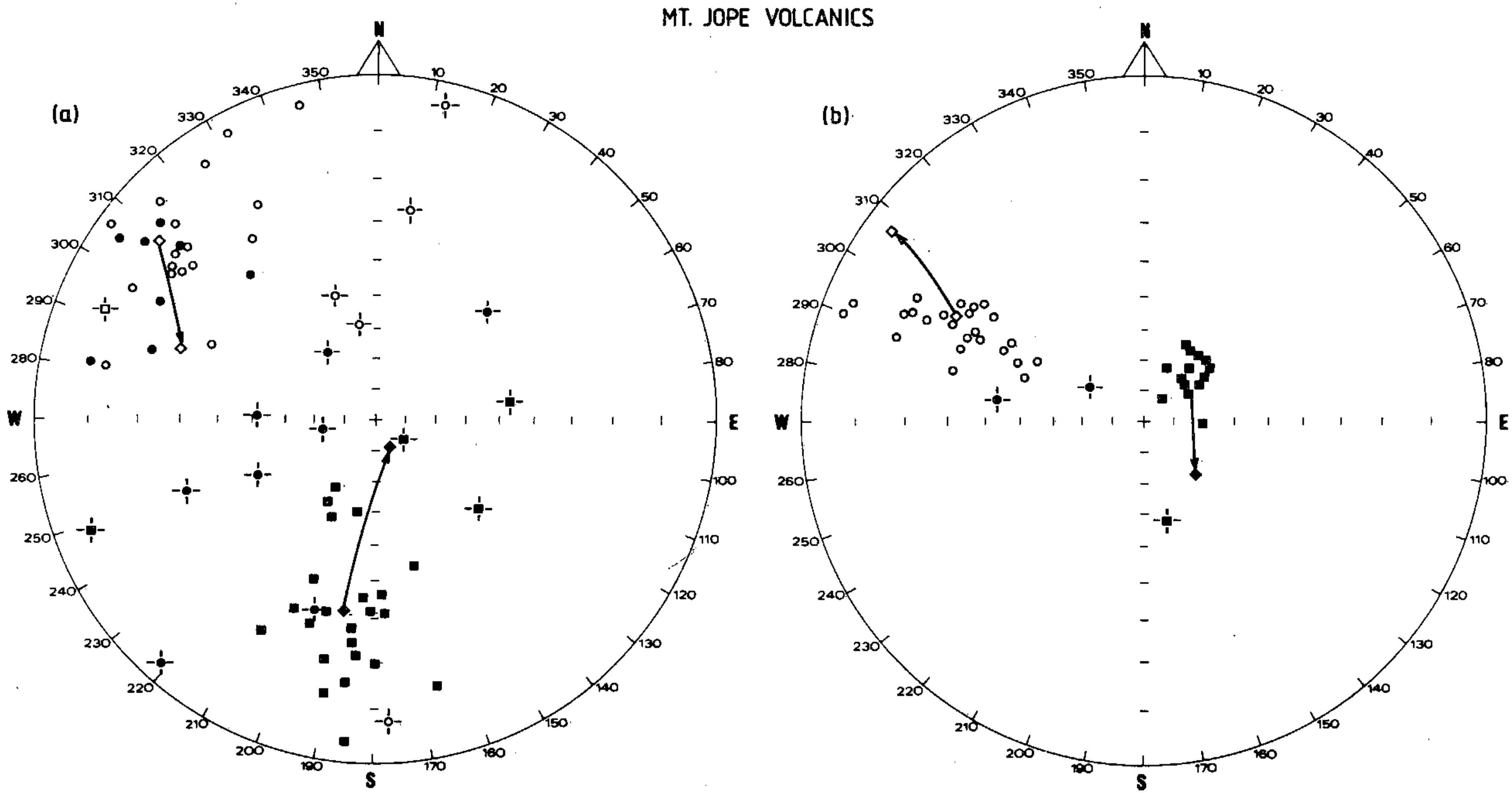

Fig. 8. Directions of magnetization determined from specimens of Mount Jope Volcanics. Conventions as for Figure 6. The circles are low-temperature components, while the squares are high-temperature components. (*a*) North dipping limb. (*b*) South dipping limb.

TABLE 3. Summary of Magnetization From the Mount Jope Volcanics

				Directions		
	T, °C	N	R	D, deg	I, deg	α_{95}, deg
			Locality J1: 22°45′S, 117°20′E			
Site						
01	400	6	5.795	314.3	−0.6	13.8
	540	4	3.962	181.2	27.9	10.3
02	400	3	2.853	287.3	−13.2	34.8
	540	2	2.000	198.2	24.4	···
03	400	3	2.915	321.7	−7.0	26.1
	540	3	2.809	182.4	32.6	40.2
04	400	5	4.098	311.3	−15.3	41.0
	540	4	3.700	194.1	38.0	30.6
05	500	4	3.886	313.4	−11.5	18.2
06	500	2	1.874	311.7	−20.8	···
07	500	5	4.662	301.0	0.8	23.2
08	500	1	···	(325.4	−24.4)	···
09	500	4	3.973	308.9	−15.0	8.7
10	500	2	2.000	310.6	−15.5	7.0
10	500	1	···	(298.2	19.2)	···
Mean horizontal	400–500	9	8.826	309.0	−11.0	7.7
Mean horizontal	540	4	3.960	189.0	30.9	10.7
Bedding†	400–500	9	8.826	304.5	−18.6	7.7
Bedding	540	4	3.960	163.3	83.0	10.7
			Locality J2: 22°55′S, 117°20′E			
Site						
12	500	5	4.859	296.5	−37.8	14.6
13	400	4	3.973	303.6	−17.3	8.8
	500	5	4.982	40.1	67.3	5.2
14	500	5	4.994	294.4	−17.1	9.1
15	500	6	5.889	298.2	−25.0	10.1
16	500	7	6.883	299.1	−31.0	8.5
Mean horizontal	400–500	5	4.945	298.4	−25.7	9.0
Bedding†	400–500	5	4.945	303.1	−18.8	9.0
Bedding	540	1	···	143.5	65.3	···

Abbreviations as for Table 2. Locality J1 dips 53°–013°, while locality J2 dips 38°–180°.
†These bedding corrections are 35% of the measured tilts based on the evidence that these magnetizations formed during folding (see text).

in Figure 8*b* may also result directly from this. To determine the appropriate bedding attitude to which to refer these directions, an iterative procedure has been used which incrementally restores the beds and searches for the tightest grouping. This method suggests that the main episode of overprinting coincided with 65% folding when the precision parameter for the group attained a maximum of 57 (cf. 38 in situ and 32 unfolded). The mean direction for these intermediate temperature magnetizations is $D = 304.0°$, $I = -18.7°$ ($\alpha_{95} = 5.3°$) and their pole position is latitude = 35.0°S, longitude = 211.5°E ($dp = 2.8°$, $dm = 5.5°$). This direction is common throughout the Hamersley Basin, and while *Embleton et al.* [1979] clearly recognized the magnetization as being secondary, this is the first instance that this remagnetization or overprinting episode can be firmly related to the tectonism associated with the folding of these beds. An alternative interpretation is that the overprint magnetizations from one area are not correlated with those from the other: however, their similar unblocking characteristics and the similarity of the cross-over signature with results from other orogenic belts [*McClelland Brown*, 1983] mitigate against this.

Mount Roe Basalt

Flows of the Mount Roe Basalt outcrop over an extensive area of the Pilbara and are gently folded. Their metamorphic grade is subgreenschist, and they appear to be much fresher than the Mount Jope Volcanics in hand sample. Electron microprobe analysis of one of these samples, RB03B, reveals very small (2–3 μm) chromiferous magnetite grains in a chlorite (biotite) host, with larger (10 μm) grains of rutile. The very small grains suggest a SD structure consistent with the high coercivites of remanence found for these samples (Figure 9). The basalts have been sampled at four localities (Figure 1) each of slightly different structural attitude. The first two localities are tilted at 20°–110° and 26°–120°, respectively, while the third locality is flat lying and the fourth locality dips 10°–185°, allowing the application of a fold test [*Graham*, 1949]. Outcrops of these rocks typically form topographic highs similar to those of the Millindinna Complex and have possibly been subjected to a similar density of lightning strikes.

NRM intensities of these basalts are much stronger than those of the more highly metamorphosed Mount Jope Volcanics, being typically less than 50×10^{-6} emu cm^{-3} (50 mA m^{-1}) but occasionally up to several thousand $\times 10^{-6}$ emu cm^{-3} (several amps per meter). Measurements of saturation remanence of these more intensely magnetized samples showed that the NRM values of these rocks are far from their saturation values (Figure 9) of approximately 0.2–0.5 emu cm^{-3} (200–500 A m^{-1}), which suggests that significant contributions to the NRM by lightning-induced IRM would seem to be much less for the Mount Roe Basalt than for the gabbros of the Millindinna Complex. Nevertheless, many samples of the basalts yielded quite different results depending upon whether they were pretreated with af. It proved necessary to apply af demagnetization to eliminate preferentially, small but

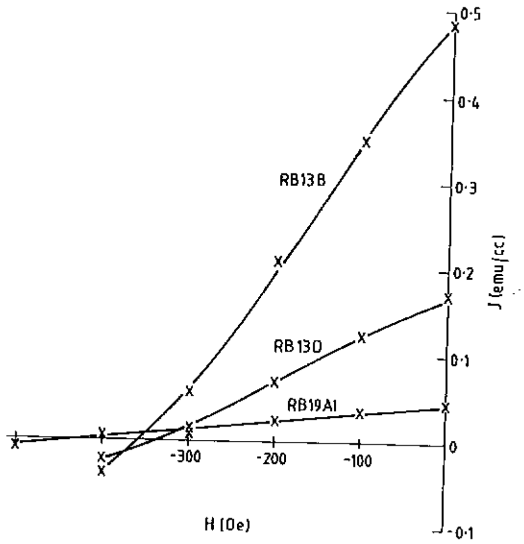

Fig. 9. DC demagnetization of SIRM for specimens of Mount Roe Basalt (see Figure 4*b*), defining saturation remanence J_{rs} and coercivities of remanence H_{cr}.

thermally distributed spurious components. We suppose that the origin of these components is related to distant lightning strikes but have not investigated this further. The orthogonal plots displayed in Figure 10 reveal the erratic directions of magnetization removed in fields up to 200 Oe (20 mT) (up to 250 Oe (25 mT) for specimens RB15B2 and RB19A1). These latter two specimens possess high H_{cr} (e.g., 440 Oe (44 mT) for RB19A1 (Figure 9)). An interesting feature of Figure 10 is the thermally discrete nature of the components remaining after af pretreatment, reflected by the cluster of points (i.e., no vector change) between the 200°C and 500°C measurements. A comparison of orthogonal plots derived solely from thermal demagnetization, and from thermal demagnetization following af, for duplicate specimens is plotted in Figure 11. The expanded regions plotted to the right clearly show the efficacy of the af pretreatment. For each sample the high-temperature portions of the orthogonal plots of the pretreated specimens decay toward the origin from consistent (either northwest up or southeast down) directions, while the comparable portions of their duplicate specimens are ill defined and rather erratic near the origin. The overall similarity of the total NRM of each sample is seen by comparing the plots on the left. Although at least one speciman from each sample has been treated with af prior to routine thermal demagnetization, some samples failed to reveal consistent within site directions. It is supposed that lightning-induced IRM components are primarily responsible.

The rigorous application of the multilimb fold test suggested by *McFadden and Jones* [1981] is invalid from the point of view that the precision parameter of locality 3 is significantly higher than those for the other localities. However, the realities of sampling basalt flows often involve the chance of missing a flow or, if one flow is particularly thick, of over sampling a flow. The latter situation would yield a higher than normal locality precision parameter, simply as an artefact of sampling. If locality 3 is in fact a single flow ($k = 425$ for three sites at this locality), or even if flows were extruded anomalously closely in time, then this locality should, for the purpose of the fold test, be treated as a single site. Whether this is real we cannot discern, but it is of interest to assume that it is and to apply the test. Doing so yields an f statistic of 5.36 with respect to the ancient horizontal and 13.7 with respect to present horizontal. Since the 95% cutoff point is 3.00, a common true mean direction with respect to both ancient and present horizontals for these four localities may be rejected at this statistical level. The dips of these limbs are too low to allow us to relate unequivocally these magnetizations to the paleohorizontal, although we do note that the directions are better grouped with respect to the paleohorizontal than they are with respect to the present horizontal (Figure 12). The low metamorphic grade and discrete thermal stability spectra of the Mount Roe Basalt over a large area, coupled with the similarity in direction with the prefolding Mount Jope magnetizations strongly favor the conclusion that the directions are in fact prefolding magnetic field directions and the pole should be calculated from such. The pole position from the 12 sites with respect to bedding in Table 4 is latitude = 52.4°S, longitude = 178.0°E ($dp = 6.4°$, $dm = 9.1°$). Either because these lavas have a simple thermal history or because of the pervasive IRM's encountered no consistent overprint directions have been recognized comparable to those found in the Mount Jope Volcanics.

Results from the Nullagine Lavas reported by *Irving and Green* [1958], over a quarter of a century ago, show a striking similarity with results reported here for the Mount Roe Basalt. Although it is unclear from which stratigraphic level the earlier collection was made, the fact that this result was obtained without the benefit of cleaning techniques indicates the stable nature of the NRM present in some of the cover sequence volcanics.

Cooya Pooya Dolerite and Spinaway Porphyry

The Cooya Pooya Dolerite and Spinaway Porphyry outcrop stratigraphically higher than the Mount Roe Basalt but below, or partly within the sequence of volcanics and sediments which are correlated with the Mount Jope Volcanics to the south (Figure 1). As noted earlier, the Spinaway Porphyry may be partly extrusive. Both the Cooya Pooya Dolerite and the Spinaway Porphyry are subhorizontal, and none of their magnetic directions discussed has been corrected for structural tilting. The magnetizations of these units are weak ($<20 \times 10^{-6}$ emu cm^{-3} or 20 mA m^{-1}) and as seen from demagnetization of the NRM (Figure 13) they are multicomponent. Thermal, af, and combined thermal and af demagnetization methods were employed. As with the studies of other units reported above af pretreatment followed by thermal proved to be the most effective. A salient feature of these magnetizations is the northwest and up direction characterizing both the least stable and the most stable components. A component of intermediate stability, however, is often seen directed to the southwest and down (Figure 13*a*). Although the resolution of these three components is sometimes poor, there is often a hint of the presence of the intermediate component reflected in the orthogonal plots which suggests that at least some of the components are CRM with overlapped stability spectra [*McClelland Brown*, 1982]. Figure 13*b* is a typical example of this behavior. Sometimes thermal demagnetization alone yielded quite straight trajectories not revealing the true nature of the remanence (Figure 13*c*), while thermal demagnetization following af pretreatment of a duplicate specimen reveals a multicomponent signature common to many samples (Figure 13*d*). As found with the other studies reported herein, the most natural explanation of this behavior seems to be lightning. The anomalous intensities and directions plotted in Figure 13*c* support this. The af demagnetization by itself was only spor-

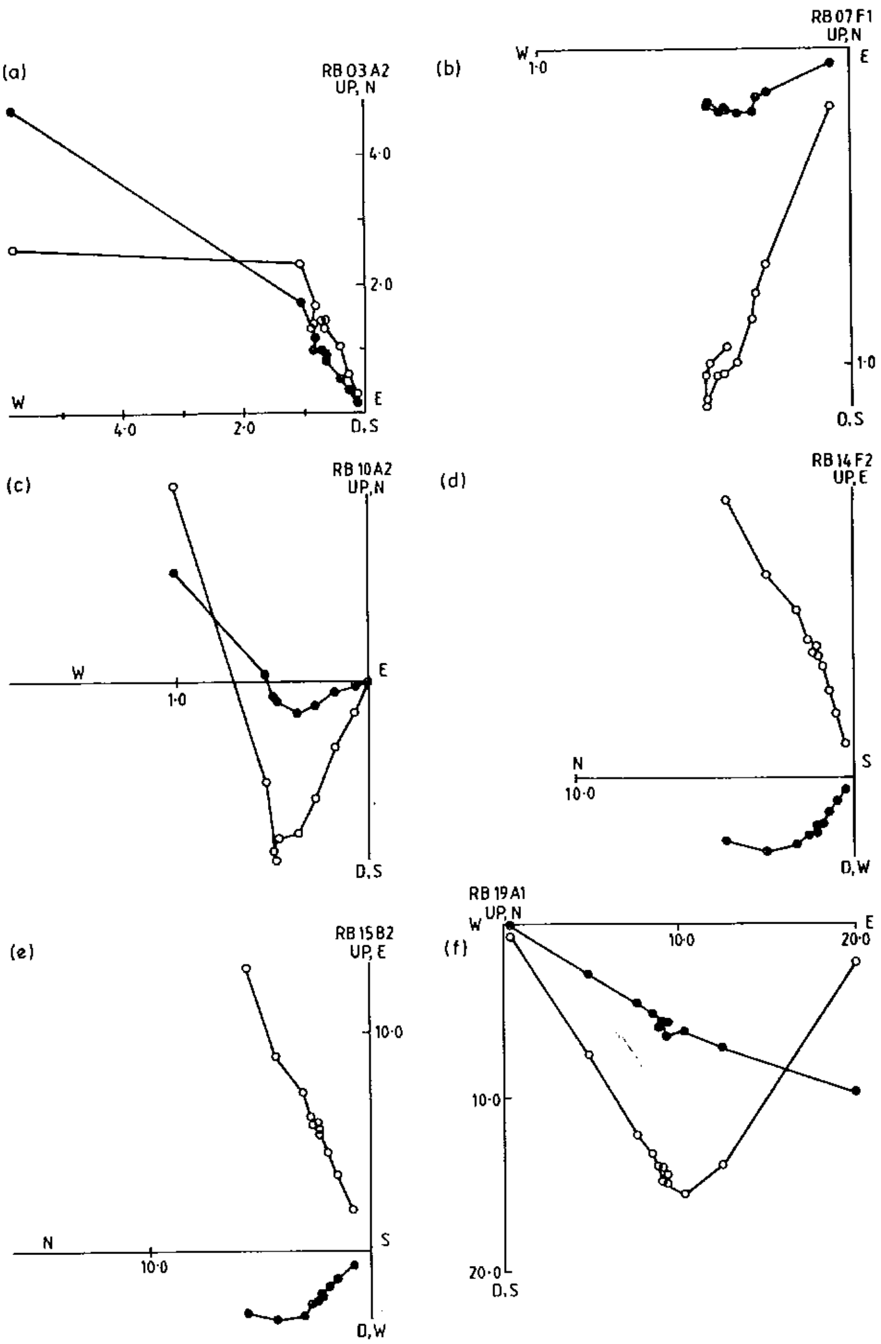

Fig. 10. Orthogonal projections of vector end points for specimens of Mount Roe Basalt observed after demagnetization steps of (*a*) to (*f*) 10 Oe (1 mT), 100 Oe, 200 Oe (plus 250 Oe for Figures 10*e* and 10*f*) followed by 200°C, 300°C, 400°C, 500°C, 540°C, 550°C, and 560°C.

adically applied since using this method the component with the highest unblocking temperature could not be isolated. This is thought to be instrumental in origin, with either gyroremanent magnetization [*Stephenson*, 1980*a*, *b*; *Edwards*, 1982] or rotational remanent magnetization [*Wilson and Lomax*, 1972; *Stephenson*, 1976; *Stephenson*, 1980*a*], depending upon which af demagnetizer was used, causing spurious magnetizations before the complete demagnetization of the softer components. Some possess discrete unblocking spectra with over 50% of the magnetization unblocking only above 560°C (Figure 13*e*), increasing to over 60% after 200 Oe (20 mT) af pretreatment (Figure 13*f*). Susceptibilities of these specimens were too weak to establish the thermal characteristics of magnetic carriers from χ/T curves. With such specimens only a northerly and up directed magnetization is seen, regardless of whether af pretreatment was applied or not.

More uniform behavior than that observed in the above results from the Cooya Pooya Dolerite was exhibited by the results from the Spinaway Porphyry. Samples from this latter unit, while clearly possessing at least three magnetizations, are affected to a greater extent by overlapping stability spectra with very poorly resolved components (Figures 13*g* and 13*h*). Nevertheless, the similarity of the magnetization of the Cooya Pooya Dolerite and the Spinaway Porphyry is apparent with a northwest and up component dominant.

The very similar, yet distinct, magnetic signatures of the

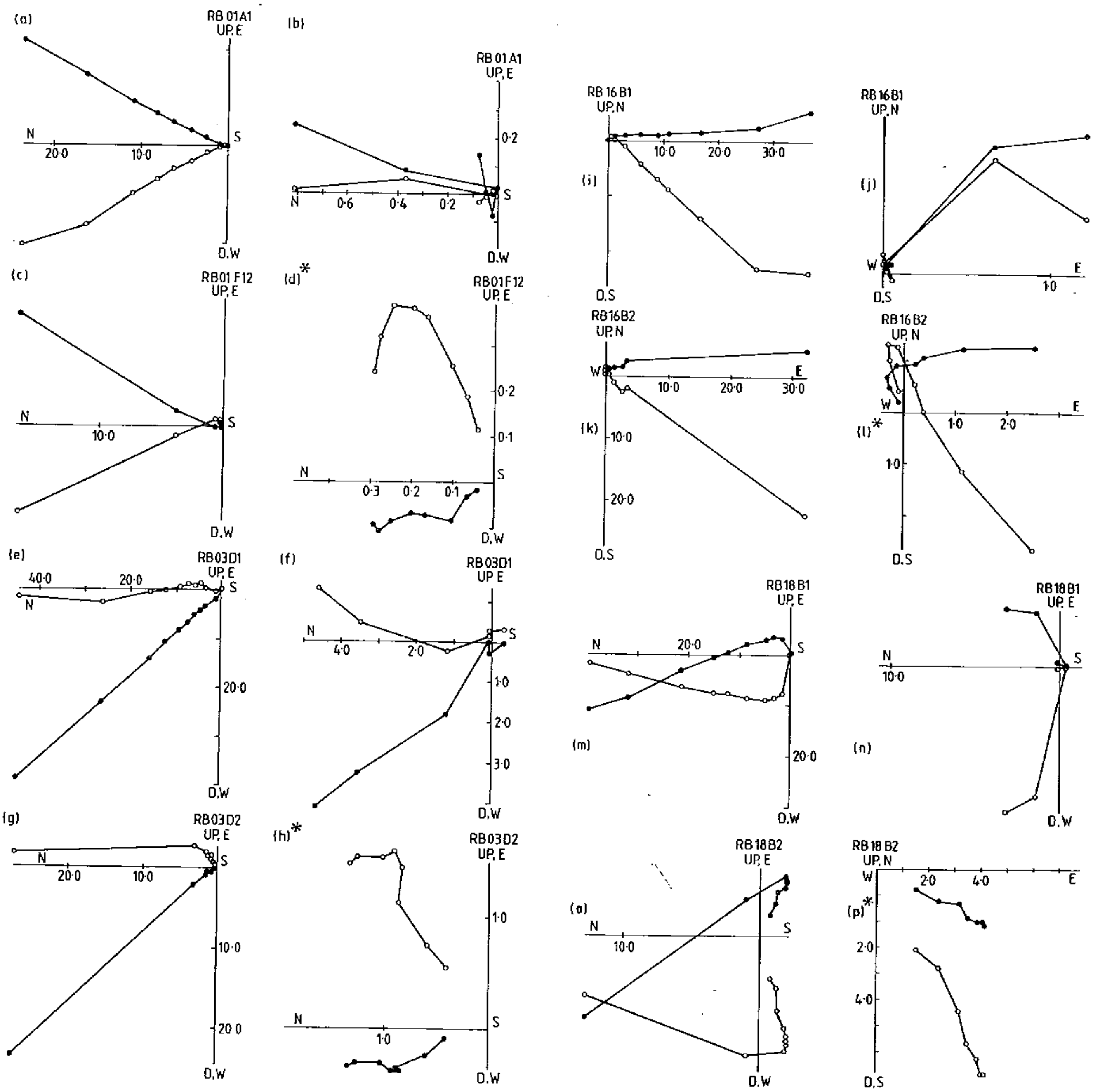

Fig. 11. Orthogonal projections of vector end points for sets of duplicate specimens of Mount Roe Basalt observed after solitary thermal demagnetization (Figures 11*a*, 11*b*, 11*e*, 11*f*, 11*i*, 11*j*, 11*m*, and 11*n*; same steps as for Figure 10), and two-stage demagnetization, thermal following 200 Oe (20 mT) af pretreatment (see text). The plots on the right-hand side are expansions of the left-hand plots. Two specimens from each of sites 01, 03, 16, and 18 show clearly the difference in these demagnetization strategies and in particular the efficacy of first applying af demagnetization, (Figures 11*c*, 11*d*, 11*g*, 11*h*, 11*k*, 11*l*, 11*o*, and 11*p*). Scale is units of 10^{-6} emu cm^{-3}(mA m^{-1}). An asterisk indicates the pretreated specimens.

Cooya Pooya Dolerite and the Spinaway Porphyry suggest a similar thermal and thermochemical history (as recorded by their magnetic mineralogies). The similarlity of the positions of these units in the stratigraphy is seen to support this.

Discussion and Conclusions

In an effort to acquire paleomagnetic and rock magnetic data to assist in unraveling the tectonic evolution of the northwestern Australia Precambrian terrain and to give us a better understanding of the variables affecting the magnetic remanences of the constituent rocks, five different igneous units have been studied. Although experiments involving the traditional application of demagnetization techniques to study the stability spectra of the NRM constitute the bulk of the work, complementary techniques to investigate rock magnetic properties have been used where applicable and include determinations of H_{cr}/H_c, J_{rs}/J_s and χ/J_s ratios, the anisotropy of susceptibility, the variation of susceptibility with temperature and electron microprobe analysis. Our approach also emphasizes the crucial role of the fold test, without which a great deal of speculation and uncertainty would mask the results. Another aspect highlighted here is the efficacy of af demagnetization

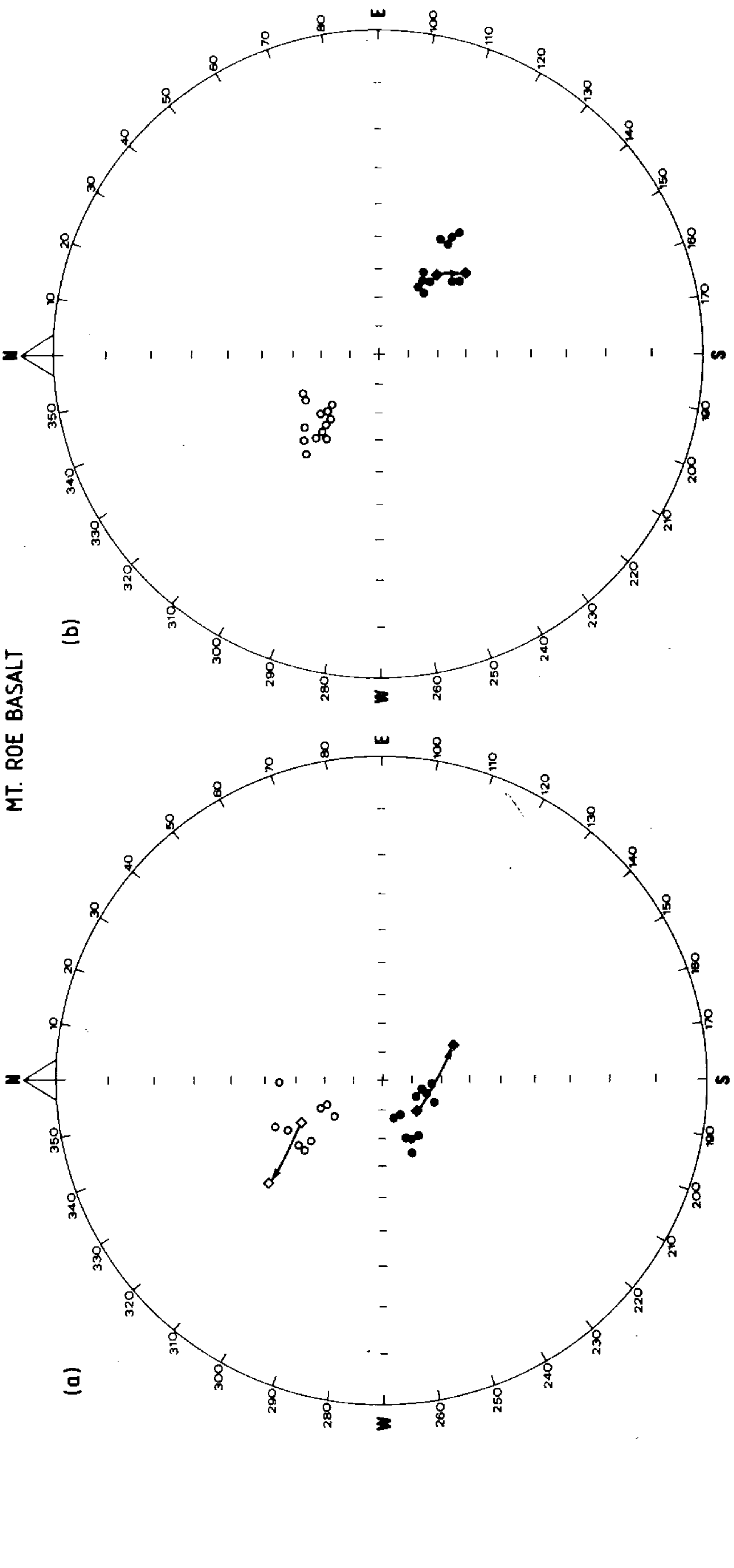

Fig. 12. Directions of magnetization determined from samples of Mount Roe Basalt. Conventions as for Figure 6.

TABLE 4. Summary of Magnetization From the Mount Roe Basalt: Directions

	N	R	D, deg	I, deg	α_{95}, deg
Locality R1: 20°55'S, 117°12'E					
Site					
01	3	2.969	347.0	−63.4	15.5
02	2	1.993	325.8	−50.5	20.9
03	4	3.956	325.9	−56.3	11.2
Mean horizontal	3	2.975	331.6	−57.1	13.8
Bedding	3	2.975	318.3	−40.5	13.8
Locality R2: 20°55'S, 117°05'E					
Site					
06	4	3.995	194.1	72.7	3.7
07	4	3.974	237.7	70.2	8.5
09	2	1.999	250.0	76.5	···
10	1	···	(247	62)*	···
Mean horizontal	3	2.977	226.5	74.5	13.3
Bedding	3	2.977	155.9	64.1	13.3
Locality R3: 20°55'S, 117°07'E					
Site					
14	4	3.979	307.8	−56.6	7.7
15	5	4.980	319.4	−61.1	5.5
16	4	3.969	312.0	−57.0	9.4
Mean horizontal	3	2.995	312.8	−58.3	6.0
Locality R4: 21°13'S, 119°42'E					
Site					
17	2	1.999	136.2	54.1	5.1
18	4	3.998	120.6	62.0	2.4
19	5	4.994	120.2	55.0	3.0
Mean horizontal	3	2.987	126.1	57.3	10.1
Bedding	3	2.987	137.3	51.3	10.1
Overall Mean	12	11.756	320.0	−53.8	6.5

Abbreviations as for Table 2. Locality R1 dips 20°–110°, locality R2 dips 26°–120°, locality R3 is flat lying, and locality R4 dips 10°–185°.
*Not including in overall mean, only one sample.

prior to thermal treatment and the caution which should be observed, particularly in terrains prone to the effects of lightning, of using solely thermal cleaning. The success of two-stage demagnetization has also been noted by other workers [e.g., *Roy and Lapointe*, 1976].

The paleomagnetic results from the "Millindinna Complex," the flood basalts, and the two major intrusions in the lower units of the Fortescue Group are consistent with a geochronological model of igneous activity that spans a relatively short period of time.

The magnetization with the best age constraint has been determined from the "Millindinna Complex." Folding in the layered intrusion occurred before the onset of deposition of the Fortescue Group. The "Millindinna Complex" has a radiometric age of 2.86 Ga while the flood basalts of the Mount Roe Basalt are generally held to have an age of around 2.8 Ga [see *Trendall*, 1983; *Blake*, 1984; *Blake and McNaughton*, 1984]. Folding in the Mount Roe Basalt and in the Mount Jope Volcanics occurred during the early Proterozoic Ophthalmian Orogeny. Sediments and volcanics of the Mount Bruce Supergroup, which includes the Fortescue and Hamersley groups, are gently warped north of the Fortescue River, but deformation becomes progressively more intense south toward the Ophthalmian Fold Belt [*Gee*, 1979]. The orientation of the fold axes is controlled primarily by early Proterozoic movement in the Archaean basement. Although precise dating of these events is difficult to ascertain, deformation in the basement cover rocks is presently assigned an age of about 2.0 Ga.

The proximity of the paleomagnetic pole positions calculated from prefolding magnetizations (Table 5) of the Mount Roe Basalt and the Mount Jope Volcanics reflects their close stratigraphic position and a comparison with results from the Black Range Dyke [*Embleton*, 1978] suggests that its magnetization is similar in age. That the north-northeast dyke swarm acted as a feeder system for the flood basalts has been argued on geological grounds [*Lewis et al.*, 1975].

Overprint magnetizations obtained from the Mount Jope Volcanics are penecontemporaneous with basement-activated folding. A comparison with the Australian APWP [*Embleton*, 1981] indicates that the overprint is not younger than about 1.8 Ga, consistent with the estimate of the age of folding in the cover sequences [*Gee*, 1979].

The predominance of overprint magnetizations in the

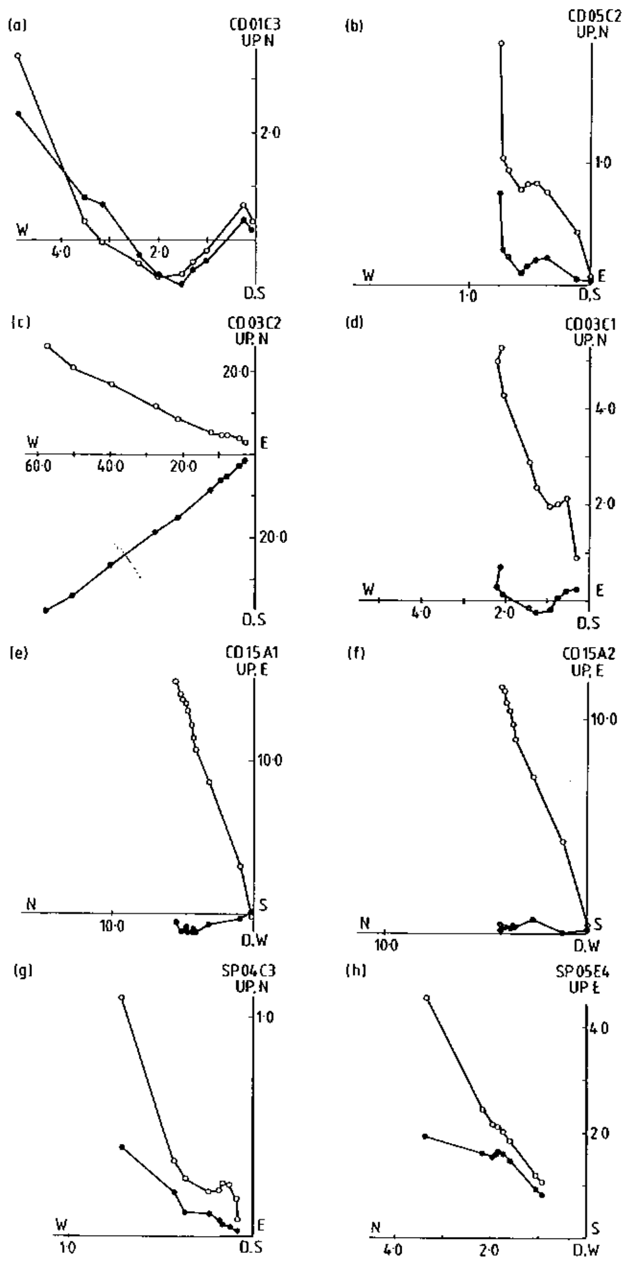

Fig. 13. Orthogonal projections of vector end points after a variety of demagnetization treatments (see text) for samples of Cooya Pooya Dolerite (CD) and Spinaway Porphyry (SP). Scale is units of 10^{-6} emu cm^{-3} (mA m^{-1}).

TABLE 5. Summary of Paleomagnetic Poles

Formation	Age	Mnemonic	Pole Latitude °S	Pole Longitude °E	Error *dp*, deg	Error *dm*, deg
Mount Jope Volcanics	postfolding	JO	35.0	211.5	2.8	5.5
Mount Jope Volcanics	prefolding	JV	40.5	128.7	19.9	20.8
Mount Roe Basalt	prefolding (2.8 Ga)	RB	52.4	178.0	6.4	9.1
Millindinna Complex	prefolding (2.86 Ga)	MC	11.9	161.3	6.8	8.4

Mount Jope Volcanics (and Hamersley Group rocks [*Embleton et al.*, 1979]) and their absence in the Mount Roe Basalt and "Millindinna Complex" to the north is compatible with the change in metamorphic grade from greenschist facies in the south of the study area to prehnite-pumpellyite facies in the north [*Smith et al.*, 1978] and implies a common cause of the overprinting and the higher-grade metamorphism, thus dating the metamorphism between 2.0 and 1.8 Ga. Using the thermal activation nomogram for magnetite (after *Walton* [1980] as plotted by *Middleton and Schmidt* [1982]) and assuming that the overprinting was viscous PTRM with no chemical remanent magnetization effects, it is possible to place some constraints on the temperature to which these rocks have been elevated since their formation. Although a unique solution is not possible at the moment, if a reasonable period of 10^7 to 10^8 years for the length of time that these rocks have been held at their maximum temperature is assumed, an estimate of about 300°C is arrived at. This is slightly lower than estimates of temperatures associated with greenschist facies metamorphism [*Winkler*, 1979]. If the overprint characteristics of other magnetic minerals (such as hematite) can also be

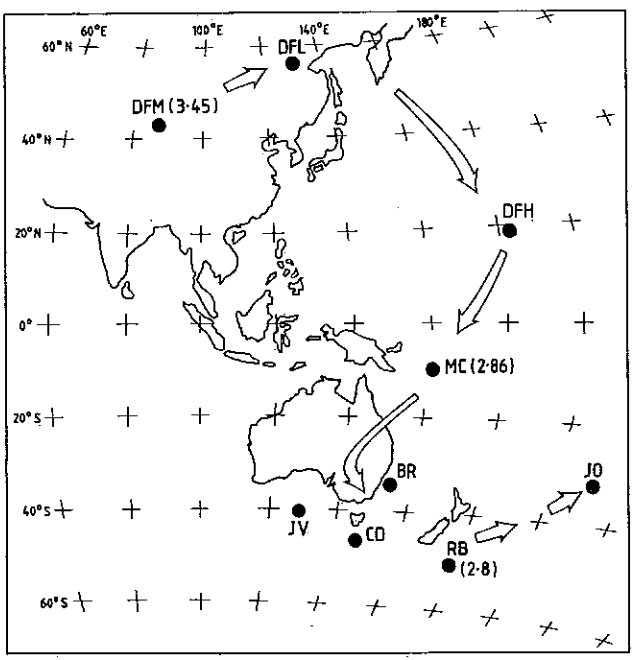

Fig. 14. Paleomagnetic pole positions from rock units of the Pilbara Craton and Lower Proterozoic cover sequences for the time interval 3.5 Ga to about 2.0 Ga. Poles for the Duffer Formation (DFM, DFL, DFH) were reported by *McElhinny and Senanyake* [1980]; for the Black Range Dyke (BR) and the Cajuput Dyke (CD) by *Embleton* [1978]; and poles MC, JV, RB, and JO are based on the results presented in this paper.

determined, then the time-temperature regime operating during the metamorphism can be theoretically constrained more tightly [*Middleton and Schmidt*, 1982]. The above serves to illustrate the need to investigate fully the multicomponent magnetizations in order to place age constraints and independent temperature estimates on the timing of metamorphic events.

The sequence of paleomagnetic pole positions shown in Figure 14 represents a rudimentary path for the Pilbara Craton and Hamersley Basin. The data may not record the full amount of APW for up to 1.5 Ga of Archaean/Proterozoic time.

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