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Age and significance of magnetizations in dolerite dykes from the Northampton Block, Western Australia

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Samples from nine dolerite dykes that outcrop in the Northampton Block, Western Australia, have been analysed to investigate the palaeomagnetic constraints that may be placed on the timing of magmatic events in relation to the widespread lead and zinc mineralization in the Northampton Mineral Field. The palaeomagnetic directions are consistent with a group of pole positions obtained from independent studies of formations of latest Precambrian and very earliest Cambrian age. The pole for the dykes lies at latitude 47.1°S, longitude 317.3°E (A_{95}=7.9°). A comparison with the palaeomagnetic catalogue suggests that the dykes cannot be younger. Results from radiometric studies yield ages for two dykes at 550 Ma and a third dyke at 750 Ma. The results indicate that the dykes were intruded considerably earlier than the mineralization age (late-Early to early-Mid Paleozoic) and hence cast doubt on the role of the intrusive event as either the source of mineralization or the principal catalyst for the mobilization of pre-existing mineral deposits.

Key words: magnetizations, dykes, mineralization, palaeomagnetisms.

INTRODUCTION AND GEOLOGICAL SETTING

The Northampton Block is a Precambrian basement terrane which lies between the late Palaeozoic to Cenozoic Carnarvon and Perth Basins. The block and its flanking sedimentary basins occupy the coastal strip of Western Australia approximately between latitudes 24°S and 34°S and are situated W of the Darling Fault (Fig. 1).

The Hardabut Fault to the W and the Yandi Fault to the E separate the Precambrian rocks from Silurian and Permian sedimentary units. In the SW of the block near Geraldton, sediments of Phanerozoic age overlap the Precambrian basement.

The Proterozoic rocks which comprise the Northampton Block have been classified into three broad units by Peers (1971): they are granulites, migmatites and granite. There is now evidence that these units are about 1800 Ma (Fletcher *et al* 1985). More than one regional metamorphic episode is thought to have been responsible for the generation of these facies; the youngest occurred probably around 1040±50 Ma (Compston & Arriens 1968). The isochron is based on whole-rock Rb–Sr analyses of eight granulite samples from a quarry at White Peak.

The Northampton Block is cut by a swarm of parallel dolerite dykes which strike in a NNE direction. According to Hocking *et al* (1982) the dolerites contain plagioclase feldspar, clinopyroxene and orthopyroxene with accessory quartz and opaques. They also report the occurrence of olivine gabbro although this more basic phase was considered too altered for palaeomagnetic sampling. The dykes follow a pre-existing set of fractures, generally with a steep westerly dip. Only broad constraints on the intrusion age of the dykes have been available. The dykes are younger than the last regional metamorphism and older than the Palaeozoic mineralization which occurs extensively throughout the Northampton Mineral Field (Blockley 1971). It is with particular reference to the origin of mineralization that interest has centred on the chronology of dyke formation. The source of the mineralizing solutions has been variously ascribed or genetically related to (i) pegmatites in the granulites [e.g. Feldtman (1921)]—although Peers (1971) regards the pegmatites as having resulted from metamorphic differentiation during formation of the granulites, and (ii) dolerite intrusion [e.g. Prider (1958) and Jones and Noldart (1962)]. Blockley (1971, p. 41) also gives consideration to the ores having been, "deposited by hot solutions given off during the last stages of the intrusion of the dolerite dykes". Clearly it is important to establish the age of the dolerite dykes to provide a further constraint on the chronology of events in relation to the genesis of the widespread lead, zinc, silver and copper mineralization.

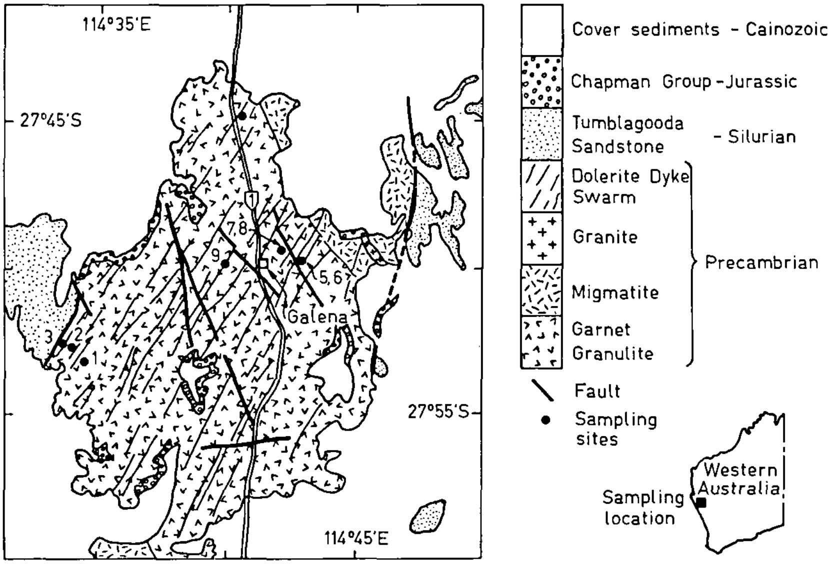

Fig. 1 Geological sketch map of the sampling localities for dykes in the Northampton Block.

Palaeomagnetic pole positions computed from primary magnetizations characterise the history of the geomagnetic field and are therefore used to establish geological correlations. By comparing components of stable magnetization measured in oriented samples of the dykes with the catalogue of palaeomagnetic data for late Precambrian and early Palaeozoic rock sequences and units obtained from independent studies, it is possible to place constraints on the age of dolerite intrusion. This strategy of using palaeomagnetism as an indirect dating technique is most successful where a detailed record of apparent polar wander (APW) is available. For the particular time span under consideration, studies by McWilliams and McElhinny (1980), Kirschvink (1978), Klootwijk (1980), Embleton and Giddings (1974) and Goleby (1980) have provided the necessary detail.

PALAEOMAGNETIC RESULTS

Fifty-one independently oriented samples from nine dykes were collected using a portable field drill. The sampling sites are shown in Fig. 1.

Routine procedures (Collinson *et al* 1967), including the use of a sun compass, were followed in the collection and preparation of oriented rock specimens, nominally 25 mm diameter and 22 mm high. The measurement of magnetic remanence was accomplished using a DIGICO complete results fluxgate magnetometer. Experiments to test the stability of remanence to alternating field (AF) demagnetization as a measure of the coercive force spectra were carried out with a SCHONSTEDT GSD-1 demagnetizer, screened from the Earth's magnetic field with μ-metal, and with a custom built three-axis AF demagnetizer housed in specially constructed field coils similar to those described by McElhinny *et al* (1970). Partial thermal demagnetisation to measure the blocking temperature spectra was carried out in a large, non-magnetic furnace again screened from the influence of the Earth's magnetic field with a custom built ten-coil field control system. Field values were maintained with feed-back in the range ± 5 nT during experimental work.

The single most noticeable feature of the natural remanent magnetizations (NRM's) is the ubiquitous influence of lightning induced magnetic overprints; or isothermal remanent magnetizations (IRM's). The direction of the NRM measured in one specimen from each independently oriented drill-core sample is plotted on a stereographic (equal angle) projection in Fig. 2. Despite the dispersing effect of the IRM, the NRM's do display a preferred orientation sub-parallel with (i) the direction of the Earth's present field (PF, Fig. 2) at the sampling locality and/or with (ii) the model dipole field direction (DP, which is nearby to PF, Fig. 2) for the respective latitude of sampling, presumably due to viscous remanent magnetization (VRM). It is immaterial in the present context which of those two fields is responsible for the VRM.

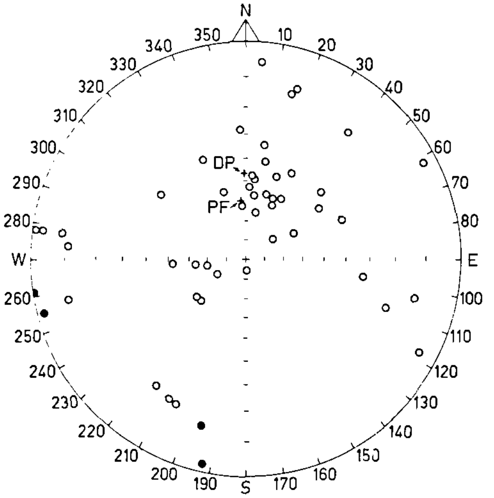

Fig. 2 Stereographic (equal angle) projection of the directions of NRM prior to the application of cleaning procedures. Directions are shown for one specimen from each independently oriented drill-core sample. Open symbols represent upward pointing (normal) vectors and closed symbols, downward pointing vectors. The direction of the present magnetic field (PF) and the dipole field (DP) direction are shown for reference.

Initial intensities of the NRM in dyke NDD 07 generally lay in the range 30–50 Am^{-1}. Following alternating field demagnetization treatment the intensity decayed rapidly but the remanence exhibited little change with directions remaining sub-parallel to the initial direction, *viz.* declinations approximately W to SW with an inclination between −60° and −75°. All specimens from two further dykes, NDD 04 and 05, also failed to reveal components other than the IRM or recent overprints. Three demagnetization strategies were adopted to investigate the degree to which the components may be isolated; alternating field, thermal treatment and a combination of both techniques. Examples of demagnetization behaviour presented in the form of orthogonal projections of the vector end-points are shown in Fig. 3. The curved trajectory typified by specimen NDD 04 Cl (Fig. 3a) indicated that, (i) two or more components of magnetization may be present in the same specimen, and (ii) their ranges of magnetic stability in response to treatment in alternating fields, are not discrete. Thermal demagnetization alone was least effective as a treatment technique due to the relative stability of IRM to this method of treatment (McElhinny 1973).

The variation of low-field susceptibility with temperature (χ–T) from −196°C to 600+°C indicates the presence of two magnetic mineral phases, one probably a titanomagnetite, with a Curie point between 350°C and 400°C and a second, multi-domain magnetite, with a Curie point around 570°C and isotropic point at just above LN_2 temperature. Pronounced Hopkinson peaks are also associated with the composition which has the lower Curie temperature (Figs 4a, b). Cooling from 600°C showed that the lower of the two Curie points had been depressed (example NDD 04, Fig. 4a), indicating production of an ulvospinel rich composition which is paramagnetic above ~ 50°C, or that the mineral species had been destroyed (example NDD 05, Fig. 4b).

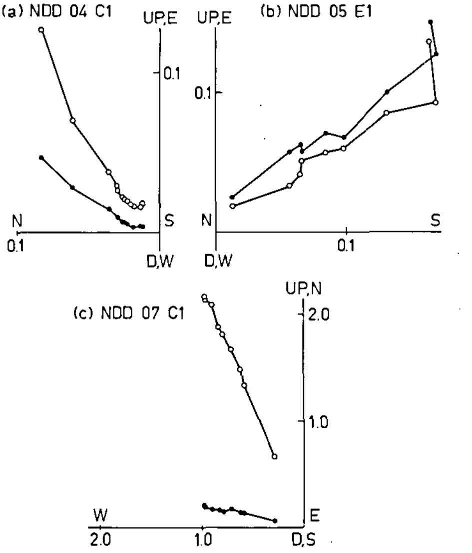

Fig. 3 Orthogonal projection of vector end-points for three specimens from dykes that yielded only overprint magnetizations. Closed symbols represent projection onto the horizontal plane, open symbols represent projection onto the indicated (N–S or E–W) vertical plane. **Fig. 3a** Alternating field demagnetization from NRM to 60 mT in increments of 5 mT. **Figs 3b, c** Thermal demagnetization following AF pre-treatment; steps 10 mT, 180°C, 280°C, 380°C, 430°C, 480°C, 530°C, 560°C and 570°C. Intensity scales are one division = 0.1 M m^{-1} for Figs 3a and 3b and one division = 1.0 A m^{-1} for Fig. 3c.

Specimens from the remaining six dykes yielded consistent results after AF cleaning with remanence directions oblique both to the IRM component, which is removed typically by AF treatment in peak fields of 10–30 mT, and to recent field overprint components of magnetization. In the majority of cases, the most effective demagnetization strategy was alternating field treatment though some specimens responded to thermal cleaning following AF pre-treatment. Examples of *X–T* curves between –196°C and 600°C are shown in Fig. 5 and may be compared with the examples illustrated in Fig. 4. The phase with the intermediate Curie temperature, although still evident, is less pronounced in the samples that responded successfully to cleaning procedures. Again the dominant phase is multidomain magnetite.

Thermal demagnetization alone was found to be inadequate. The form of the *X–T* curve indicates that the high Curie temperature phase has a narrow (un)blocking temperature spectrum, just below the Curie temperature. This implies that any directional dispersion remaining after thermal demagnetization above the intermediate Curie temperature is attributable to IRM with a high (un)blocking temperature. Thermal stability of a magnetization is not necessarily a reliable indication of a magnetization's antiquity. In this case the grains with low coercivities (and easily affected by lightning) carrying the IRM have high (un)blocking temperatures. This is not uncommon for magnetic grains of the grain size range of interest to palaeomagnetism (generally sub-micron for titanomagnetites).

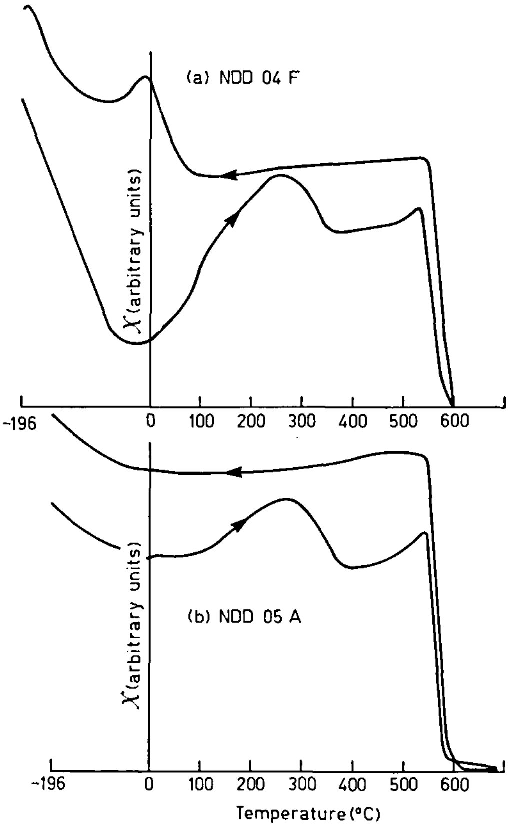

Fig. 4 The variation of low-field susceptibility with temperature (χ–*T*) for samples from overprinted dykes NDD 04 and NDD 05.

Orthogonal plots of vector end-points obtained from a pair of specimens from each dyke that yielded consistent results are shown in Fig. 6. The left-hand figures display the results of partial AF demagnetization and the right-hand figures, the results of AF plus thermal demagnetization. The component remaining after AF pre-treatment is generally resistant to thermal treatment and only exhibits substantial decay as the higher blocking temperature is approached (e.g. Fig. 6H).

Alternating field demagnetization alone (left hand figs) produces a systematic decay of intensity towards the origin as a magnetically discrete component is isolated in specimens from each of the six dykes. This component has a NNE declination with a shallow positive inclination.

Analyses of the demagnetization data have been carried out by two methods: principal component analysis (PCA; Kirschvink 1980) and linearity spectrum analysis (LSA; Schmidt 1982). In the first method, straight-line segments of the orthogonal plots, which indicate demagnetization of a single

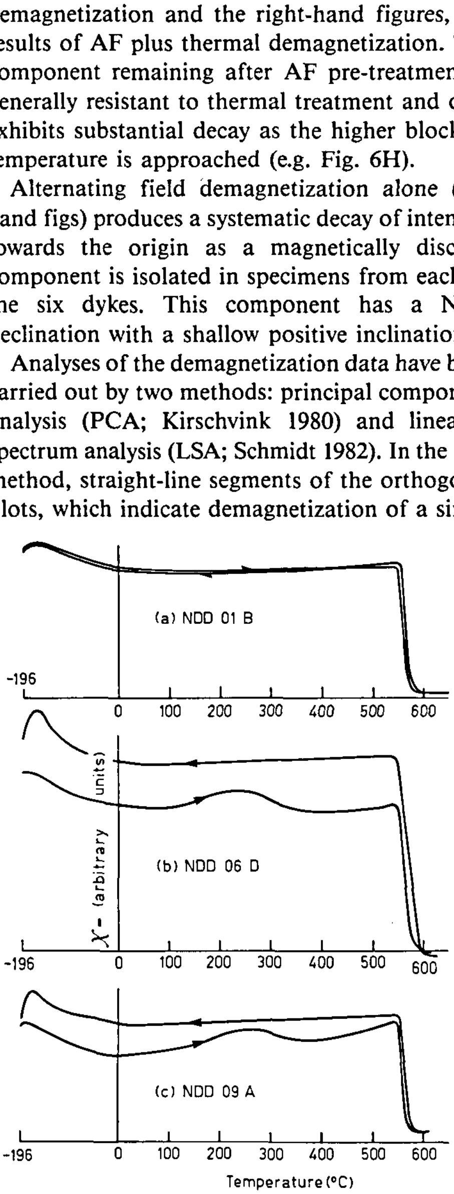

Fig. 5 χ–*T* curves for samples from dykes that retained a discrete high field/temperature component of remanence oblique to the overprint signatures.

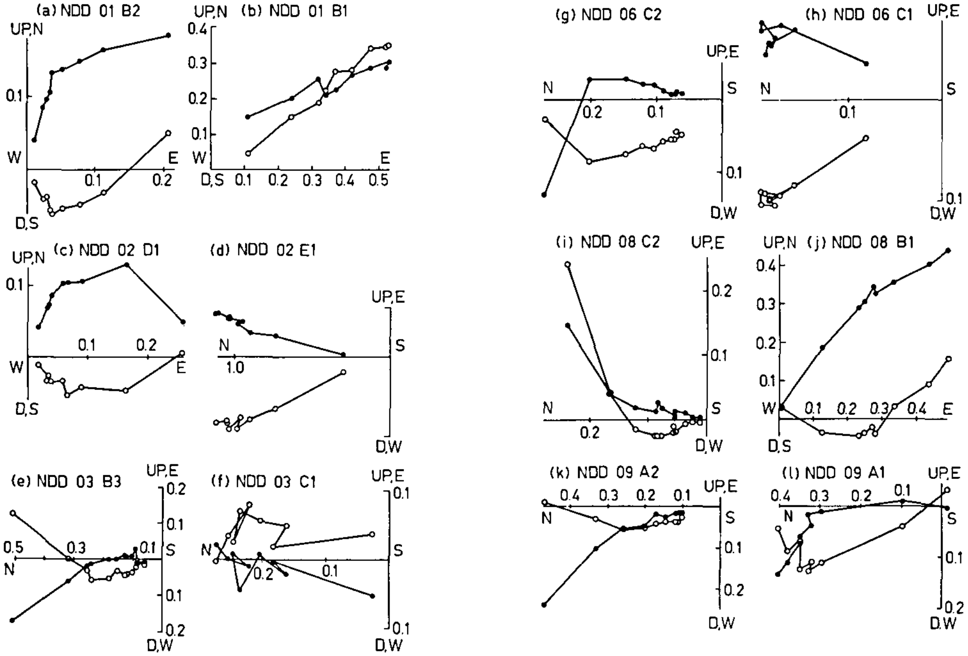

Fig. 6 Orthogonal plot of vector end-points determined from demagnetization studies. Results from two specimens from each of six dykes are shown for AF demagnetization (left-hand figures) and for thermal demagnetization, with AF pre-treatment (right-hand figures). **Figs 6a, c and k** Show nine steps from 10 mT to 50 mT in increments of 5 mT. **Figs 6e, i** Have additional steps at 2.5 mT, 5.0 mT and 7.5 mT **Fig. 6g** Has one additional step at 7.5 mT. AF plus thermal treatment **Figs 6b, d, f, h, j, l** was carried out at 10 mT, 180°C, 280°C, 380°C, 430°C, 480°C, 530°C, 560°C and 570°C. For all plots except Fig. 6d, the axes are scaled at 0.1 A m^{-1}. **Fig. 6d** is scaled at 1.0 A m^{-1}.

component, were sought using a maximum mean angular deviation (MAD angle; Kirschvink 1980) cut-off of 10°. Only those segments with a linear trajectory towards the origin were of interest. Four specimens from each of five dykes (excluding dyke NDD 08) were incremented to the same AF treatment steps and analysed using the LSA technique (Schmidt 1982), which requires specimens to be treated at the same steps. These 20 specimens represent a sub-set of the full sample. The results of both methods of analysis are shown in Table 1. The method based on the analysis of principal components with a defined MAD limit produced an overall result (declination=015.5°, inclination=23.0° $\alpha_{95}=9.1°$) that is not significantly different from the result yielded by the LSA procedure based on a sub-set of the sample (declination=010.9°, inclination=25.4°, $\alpha_{95}=5.8°$), although the confidence cone for the latter is smaller. The corresponding palaeomagnetic pole computed from the axial geocentric dipole field model lies at latitude 47.1°N (47.1°S), longitude 137.3°E (317.3°E) with an $A_{95}=7.9°$.

GEOCHRONOLOGY

In addition to the palaeomagnetic investigation to establish the age of dyke intrusion, discussed below, samples from each dyke were assessed for their suitability for radiometric analysis using the K–Ar technique. Studies of thin sections provided a qualitative measure of the degree of alteration and only those dykes which were fresh and in which the plagioclase feldspar exhibited negligible alteration were considered suitable for radiometric dating purposes (B. Gulson, pers. comm.). Samples from three dykes, NDD02, NDD03 and NDD06 were submitted to the Australian Mineral Development Laboratories (AMDEL) where the K–Ar analyses (see Table 2) were carried out on preparations of total rock samples. The most consistent palaeomagnetic data came also from these three dykes (Table 1). Samples from two dykes give an early Cambrian age (550 Ma) and from the third dyke a late Precambrian age (750 Ma). A duplicate argon analysis was carried out on the third sample which confirmed the repeatability of the analysis. Similar

Table 1 Summary of palaeomagnetic directions in dykes from the Northampton Block. N=number of specimens given unit weight in the calculation of the mean declination (Dec) and inclination (Inc). R is the resultant vector length and α_{95} (A_{95} for the pole position) the semi-angle of the cone of confidence estimated for a probability density of $P=0.05$ using Fisher (1953) statistics. The mean for the principal component analysis (PCA) has been estimated by allocating unit weight to dyke averages.

Dyke	N	Dec (deg.)	Inc (deg.)	R	α_{95} (deg.)	Lat. (deg.N)	Long (deg.E)	A_{95} (deg.)
NDD 01	8	019.9	26.6	7.755	10.5	43.8	141.8	—
NDD 02	8	013.4	23.4	7.946	4.8	47.8	134.3	—
NDD 03	7	005.1	16.0	6.968	4.4	53.5	123.1	—
NDD 06	11	014.9	34.4	10.899	4.6	41.1	133.5	—
NDD 08	3	030.3	14.6	2.929	23.7	44.1	158.9	—
NDD 09	8	009.8	22.3	7.806	9.3	49.4	129.6	—
Mean (PCA)	6	015.5	23.0	5.909	9.1	47.1	137.3	7.9
Mean (LSA)	20	010.9	25.4	19.415	5.8	(sample sub-set, see text)		

Table 2 Potassium–argon results. Constants: $^{40}K = 0.01167$ atom %; $\lambda_\beta = 4.962 \times 10^{-10} y^{-1}$; $\lambda_\varepsilon = 0.581 \times 10^{-10} y^{-1}$.

Sample	%K	$^{40}Ar^*(\times 10^{-10}$moles/g)	$^{40}Ar^*/^{40}Ar_{Total}$	Age†
NDD 02	1.008	11.2314	0.970	551 ± 6
Total Rock	1.000			
NDD 03	0.831	9.2993	0.971	552 ± 4
Total Rock	0.830			
NDD 06	0.780	12.5889	0.934	750 ± 6
Total Rock	0.781	12.5140	0.933	746 ± 6

* Denotes radiogenic Ar.

† Age in Ma with error limits given for the analytical uncertainty at one standard deviation.

results having been obtained from different dykes provide sustantial support for a younger age of intrusion. However, the 550 Ma date must be regarded as a *minimum* age. It is unlikely that intrusion took place over a protracted period of time. In fact, the two dykes yielding the younger ages are from close to the Hardabut Fault which suggests that argon loss perhaps associated with tectonism along the faults might account for the younger ages.

DISCUSSION

The NRM's measured after AF and thermal plus AF treatment are regarded as primary. The low degree of alteration or metamorphism evident in both hand sample and thin section does not support a chemical (CRM) origin for the magnetization. Following removal of the recent and IRM components, the remaining magnetization is likely to have a thermal origin (TRM) and must therefore date from the primary cooling event.

The palaeomagnetic data for Australia for the period covering late Precambrian and Cambrian time are plotted in Fig. 7. A distinctive feature of the APW track is the tendency for the palaeomagnetic pole to occupy one position for a considerable period of time (a quasi-static interval; Briden 1967) followed by its rapid shift between successive locations. The pole position obtained from the Northampton Block dykes lies in the group containing poles from the Merinjina Tillite, Angepena Formation and Brachina Formation (Flinders Ranges) (McWilliams & McElhinny 1980) and poles from the Lower and Upper Arumbera Sandstone and Todd River Dolomite (Amadeus Basin) (Kirschvink 1978).

The most likely age of dyke intrusion is latest Precambrian or possibly very earliest Cambrian. The dykes cannot have been emplaced later than the earliest Cambrian, represented here by the Todd River Dolomite and possibly the Upper Arumbera Sandstone. Figure 7 shows the APW track to the Cambro-Ordovician boundary; the average

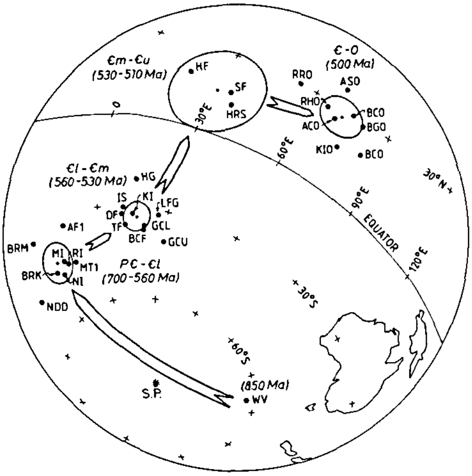

Fig. 7 Palaeomagnetic pole positions (large dots), group averages (small dots and circles of confidence) and apparent polar wander (arrows) for the period late Precambrian through Cambrian with respect to Australia. Key: WV, Wooltana Volcanics[1]; NI, Lower Arumbera Sandstone[2]; MI, Upper Arumbera Sandstone[2]; RI, Todd River Dolomite[2]; MT1, Merinjina Tillite[1]; AF1, Angepena Formation[1]; BRK, BRM, Brachina Formation[1]; TF, Tempe Formation[3]; IS, Illara Sandstone[3]; DF, Deception Formation[3]; KI, Kangaroo Island[3]; LFG, Lake Frome Group[3]; BCF, Billy Creek Formation[3]; HG, Hawker Group[3]; GCL, GCU, Giles Creek Dolomite[3]; SF, Shannon Formation[3]; HRS, Hugh River Shale[4]; HF, Hudson Formation[5]. NDD is the pole obtained for the Northampton dykes in this study. The Cambro-Ordovician group of poles is represented entirely by overprint magnetizations isolated during investigation of the Lower–Middle Cambrian formations of the Flinders Ranges and Amadeus Basin[3]. They have been interpreted by Klootwijk (1980) as records of the geomagnetic field acquired during the period of the Delamerian Orogeny. References: [1] McWilliams & McElhinny (1980); [2] Kirschvink (1978); [3] Klootwijk (1980); [4] Embleton (1972); [5] Luck (1970).

Ordovician pole lies at latitude 0°, longitude 022°E with $A_{95}=10°$ and the early Silurian pole at latitude 38.5°S, longitude 033°E with $A_{95}=7.5°$. Included in the Silurian average is a preliminary result for the Tumblagooda Sandstone (30°S, 31°E, $A_{95}=9°$; Embleton & Giddings 1974) which has a fault contact with the Precambrian basement of the Northampton Block and post-dates the extensive mineralization of the Northampton Mineral Field.

Little is known from the palaeomagnetic record covering the approximate period from 1000 Ma to 700 Ma (Embleton 1981). Results from two studies have provided pole positions in this interval of time. McWilliams and McElhinny (1980) report a palaeomagnetic pole position for the Wooltana Volcanics and assign an age of 850 Ma—this pole is plotted in Fig. 7. Giddings (1976) reports a pole position from four dykes in the southwestern part of the Yilgarn Block and assigns an age of 750 Ma to it (latitude 19.9°S, longitude 282.0°E, $A_{95}=28.1°$). Both results are of dubious significance in view of the uncertainties regarding age and reliability of the palaeomagnetic signature.

MINERALIZATION AND THE AGE OF DOLERITE INTRUSION

The NNE trending dolerite dykes which cut the Precambrian granulite, migmatite and granite terrains of the Northampton Block were intruded during the latest Precambrian, in the interval 700–560 Ma. This age range is based upon the interpreted ages of the rock formations studied palaeomagnetically (Fig. 7). The extensive lead and zinc mineralization is substantially younger, having been formed from mineralizing solutions active through the mid-Palaeozoic (J. Richards *et al*, in prep.). Both the igneous and mineralizing events followed preferentially a pre-existing fracture pattern in the basement and this has resulted in an apparent structural relationship to be inferred between the two events. However, the substantial difference in their timing, up to 250 Ma, leads to the conclusion that (i) the mineralization is genetically unrelated to the dykes and that (ii) the igneous event was not the catalytic source of heat postulated to mobilize pre-existing or contemporaneous mineralizing solutions.

The origin of mineralization in the Northampton Mineral Field remains an enigma and its source must be sought elsewhere. One possibility may be to relate the source to a particular phase of tectonic activity following the intrusion of the dolerites. The Precambrian basement did not undergo a significant degree of erosion during the formation of the overlying Tumblagooda Sandstone. The redbeds are garnet-free (Hocking *et al* 1982). Therefore much of Tumblagooda Sandstone time was tectonically quiescent. However, some movement did occur in the period leading up to the deposition of the sandstone but ceased soon after deposition commenced. Early, faulted beds are overlain by uninterrupted sequences. The occurrence of the mineralization is certainly structurally controlled. It may be postulated that a genetic relationship also exists.

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