AGSO

Australian Palaeomagnetism, Rockmagnetism and Environmental Magnetism 2000

Abstracts

Chris Klootwijk (Editor)

Record 2000/36

AGSO
AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

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DEPARTMENT OF INDUSTRY, SCIENCE & RESOURCES

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CHRIS KLOOTWIJK (EDITOR)

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CANBERRA 2000

Workshop organised jointly by the Australian Geological Survey Organisation CSIRO Division of Exploration and Mining and Research School of Earth Sciences ANU

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FOREWORD

Palaeomagnetism has long been used as standard tools for tackling geological problems ranging from plate tectonic reconstructions to the dating of marine cores using magnetic reversals. Rock magnetism is the secret to understanding the palaeomagnetic signature of rocks and alteration problems, but also forms the basis for magnetic fabric analysis and, of course, the interpretation of magnetic anomalies. More recently-developed applications of palaeomagnetism and rock magnetism include the dating of mineralisation events related to fluid flow, magnetic characterisation of hydrocarbon and gas hydrate deposits, and dating of the regolith by fitting magnetization directions, through their corresponding pole positions, to apparent polar wander paths. To this is added the rapidly growing field of environmental magnetism, which encompasses studies of environmental and climate change, and the tracing of sediment movements and pollution plumes.

Australian Palaeomagnetism, Rock Magnetism, and Environmental Magnetism 2000 is the second in the series of national meetings in Australia devoted to these subjects. The meetings are organized jointly by AGSO, CSIRO Division of Exploration & Mining, and the Research School of Earth Sciences, ANU in order to provide a focus for practitioners, users of the results, and those who wish to learn about the capabilities of palaeomagnetism, rock magnetism, and environmental magnetism.

The informal program combined the presentation of new results, discussion of problems, and development of new initiatives. Emphasis was placed on the applications of palaeomagnetism, rock magnetism, and environmental magnetism and their effectiveness for problem-solving. The first day and a half of the meeting covered a wide range of topics, and included an invited talk by Prof. Chris Powell. The second afternoon was devoted to a discussion about the Palaeozoic apparent polar wander path for Australia.

Charlie Barton (AGSO)
Phil Schmidt (CSIRO)
Brad Pillans (ANU)

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Canberra, 3rd - 4th May 2000
Program

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(Chair: Chris Klootwijk)

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15:10	**Discussion**	

PALEOMAGNETISM OF THE NEWCASTLE RANGE, QUEENSLAND

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Queensland's Thomson Fold Belt, the northern extent of the Tasman Orogen, is the structural marker of Gondwana's trailing edge during the late Paleozoic. The Newcastle Range (18.3°S, 143.7°E) is a composite volcano-tectonic cauldron in the center of the Thomson Fold Belt that has experienced relatively minor deformation, making it well suited for paleomagnetic investigation. Welded rhyolitic ignimbrites dominate the Newcastle Range Volcanics but contemporaneous lava flows and microgranitoid intrusions are common. The mid-Carboniferous segment of Gondwana's APWP is still poorly defined and it is suggested that data presented herein could provide a key pole in the definition of this part of the path. Three mid-Carboniferous (~327 Ma) volcanic formations have yielded an internally consistent paleomagnetic pole, mean declination and inclination of D=189°, I=60.3° with N=13 sites (n=72 samples), k=109.8, α_{95}=4.6° with corresponding palaeopole at 65.7°S, 127.1°E. Examples of Gondwanan poles that agree with this NRV pole, when rotated into Australian coordinates, include the Ain Ech-Chebbi, Hassi Bashir (Morocco, western Gondwana) pole located at 54.6°S, 121.3°E and the La Colina Basalt (Argentina, cratonic Gondwana) pole of 51.2°S, 119.4°E, mid-Carboniferous paleopoles that are significantly south of previously published APWPs for Paleozoic Australia. Specimens from the Brousey Rhyolite, Kitchen Creek Rhyolite and the Routh Creek Dacite are characterized by a distinctive south and moderately down direction, reversed polarity and univectorial thermal demagnetisation curves. Samples from the Brousey Rhyolite and a site in the Routh Creek Dacite where an associated ring dyke is exposed display both the reversed direction (ignimbrites) and a complementary normal polarity (dyke samples). Rock magnetic tests suggest the primary magnetic carriers are PSD titanomagnetite and titanohematites, particularly stable combinations and providers of additional evidence that the characteristic directions are primary. A less well defined Permian pole (Brodies Gap Rhyolite) determined during this investigation has a mean declination and inclination of: D=215.1°, I=80.0°, N=4, k=39.36, α_{95}=14.8°. The paleopole location, 33.7°S, 130.4°E, although poorly constrained, agrees with previously published Permian poles for cratonic Australia. The dominant magnetic carrier in the Permian is titanohematite.

CLIMATE CHANGE AND SECULAR VARIATION RECORDED IN TASMANIAN LAKES

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[2]Department of Geography, University of Newcastle, Newcastle, NSW 2308

Tasmania experienced a sequence of glaciations during the past few million years. Whereas many northern hemisphere lakes were scoured out by the last glaciation, which peaked about 20-18 thousand years ago, Tasmania is well-supplied with lakes that lay at the fringe or beyond the limit of glaciation. Some of these lakes preserve excellent sedimentary records of environmental conditions leading to the onset of glaciation, post-glacial recovery, and the subsequent impact on the vegetation of fires and human occupation.

Little or nothing was known about the sedimentary record in any of Tasmania's many lakes until a few years ago. Work undertaken by AGSO in collaboration mainly with the University of Newcastle (participants Sharon Anker, Tony Fowler, Feli Hopf, and Warwick Dyson) has established the basic characteristics of selected lakes in critical locations (Figure 1).

Dove Lake and Lake St. Clair lay at the ice front of the last glaciation and contain typical late glacial-Holocene records, namely a basement zone of grey, thixotropic glacial flour produced under late glacial conditions, overlain by organic-rich Holocene muds. Records of this type are common in northern hemisphere lakes in glaciated regions. The grey clays contain pollen that indicates the presence of herbaceous and alpine shrub vegetation communities before 11-10 thousand years ago. Wet forests developed during the Holocene that were dominated by Southern Beech and Eucalyptus spp.

Lake Johnson, situated a short distance below the summit of Mt. Read near Rosebery lies in a basin containing a very diverse range of plant life, including the highest-elevation growths of Huon pines yet found. One of the Huon pines here has been dated at 5000 years, which makes it the oldest known tree in the world. Because of its remarkable vegetation and sensitivity to climatic change, the region has attracted widespread interest from Quaternary scientists. Pollen analysis shows that the Huon pine has been present in similar quantity to present for the last 10,000 years, and is a high altitude relict species surviving from the last glaciation. The sediments preserve a record of gradual changes in direction of the geomagnetic field which can be correlated with the dated master curve for Lake Keilambete in SW Victoria. The resulting magnetic timescale is generally compatible with the radiocarbon ages for Lake Johnson.

Great Lake (max. depth 20 m) and Lake Echo (max. depth 23 m) on the dolerite central plateau at an elevation of about 850 m, and Lake Selina (max. depth 7 m) situated at the foot of Mt Murchison in the west, each escaped scouring during the last glaciation. These lakes contain fascinating records of the waxing and waning of glacial conditions going back to the penultimate glaciation over 130,000 years ago. The pollen record in Lake Echo shows a sequence of shifts in Eucalyptus forest and alpine/steppe vegetation across the southeastern central plateau. The Last Glacial Maximum was dry with predominantly herbaceous vegetation. Surface sediments in Great Lake contain evidence that eucalypt pollen is readily transported over large distances, implying that the now treeless plain that is adjacent to the lake reflects human impact and is not a natural feature of the land.

Lake Selina is a shallow lake 90 km to the northwest of Lake Echo. The Last Glacial Maximum is marked by a prominent peak in magnetic susceptibility that occurs at 100 cm depth in a core from Lake Selina (from the deepest part of the lake). This has a counterpart at 115 cm sediment depth in Lake Echo (cored in 18.5 m of water). An additional magnetic susceptibility high also appears lower in the Lake Echo sequence, which is considered to mark the penultimate glacial maximum. These susceptibility peaks are attributed to strong erosion of mineral sediment in the catchments during peak glacial conditions. The pollen and vegetation record in Lake Selina is one of the best in Australia for the entirety of the last glacial-interglacial cycle extending back to ca. 130 ka, and is the first Australia continental record of all the isotope substages of Zone 5 (i.e., 5a to 5e, spanning the interval 73 to 128 ka). The record shows that substages 5a, 5c and 5e had rainforest vegetation, and that rainforest during the peak interglacial was more prominent than during the Holocene.

Macquarie Harbour was cored this year during a project conducted by Paul Augustinus, University of Auckland and David Hannan, University of Tasmania. Sediment accumulation in the Harbour is rapid and the 6-m long sequences of sulphurous brown muds recovered are thought to span no more than the late Holocene. Issues being addressed include the history of influx into the Harbour of mine waste from the Mt Lyell mine via the King River, and the acceleration of bank erosion in the lower reaches of the Gordon River caused by boats.

AGSO's Mackereth lake-bed corer has been used to collect the sediment cores. The device is lowered to the floor of a lake and is operated remotely from a small dingy by compressed air stored in dive bottles. Coring is accomplished by pneumatically driving 6-m length PVC drainpipes into the sediment column. On completion of coring, air is diverted into a buoyancy drum, which raises the corer to the surface. The light-weight equipment is ideal for operating in remote locations and can be used in water depths of up to 100 m. The PVC core tubes serve as permanent core retainers and, being non-magnetic, permit rapid "whole-core" scanning for magnetic properties such as susceptibility.

Analysis of the cores collected has focussed mainly on the pollen content, which is diagnostic of vegetation cover, C-14 dating (by the University of Sydney and the Australian Nuclear Science and Technology Organisation), and palaeomagnetic properties. The latter provide stratigraphic information and, under favourable conditions, an independent timescale based on the dated master curve of geomagnetic secular variation in southeastern Australia.

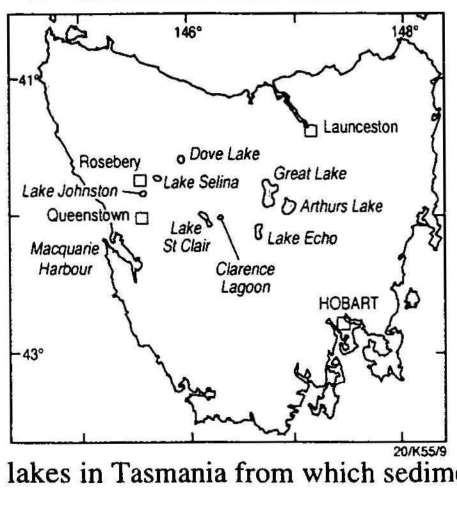

Figure 1. Locations of the lakes in Tasmania from which sediment cores have been recovered.

APPLYING ENVIRONMENTAL MAGNETISM TO SEDIMENT SOURCE TRACING IN AUSTRALIA

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A new approach to sediment tracing using natural mineral magnetism has been developed to determine relative sediment contributions at stream junctions. This method is developed on the basis that well mixed assemblages of magnetic minerals exist in sediment that is delivered to a stream junction, and that relative tributary contributions can be determined at confluences where the magnetic properties of the sediments are distinguishable. The method uses linear relationships between two mineral magnetic parameters to calculate relative tributary contributions to the resultant binary mix in the reach downstream of the confluence. The dominant sediment source catchments may thus be identified by a sequence of confluence measurements along a drainage network. The requirements of this technique are that the tributaries and the downstream reach have constant average magnetic parameter relationships (i.e. the sediments are well mixed) over an appropriate period. This is possible because sediment transport mechanisms have an averaging effect as sediment is delivered first to a stream channel, and then transported within the channel. A simple model was developed to explain how random mixing of fluvial sediment can generate linear magnetic parameter relationships, and how mixing of linear relationships occurs at confluences. The study empirically examines the spatial and temporal constancy of the magnetic mineral component of fluvial sediments using mineral magnetic parameters. Spatial and temporal constancy is important, because without it spurious estimates of source contributions can occur if the magnetic properties of sediment are altered in some way between the sources and the sediment sink. Also tested in the study is how representative the magnetic mineral fraction is of the sediment as a whole. The binary combination of sediment at a confluence is the simplest possible mixing situation, requiring a relatively simple calculation to determine proportionate contributions along with statistical uncertainties. The tracing method is not affected by the enrichment or dilution of the magnetic mineral component (i.e. concentration changes), with a noted exception of fine suspended sediment transported over large distances. In such circumstances the method cannot be applied. Homogenization processes that occur during sediment transport ensure that representative sampling along river reaches is not difficult. The method is applicable at any scale where two distinguishable sources of sediment exist, including stream junctions, or any location in a drainage basin where sediment is transported.

EARLY PERMIAN PALAEOMAGNETIC POLES FROM AUSTRALIA: THE MOUNT LEYSHON INTRUSIVE COMPLEX AND THE TUCKERS IGNEOUS COMPLEX, NORTH QUEENSLAND

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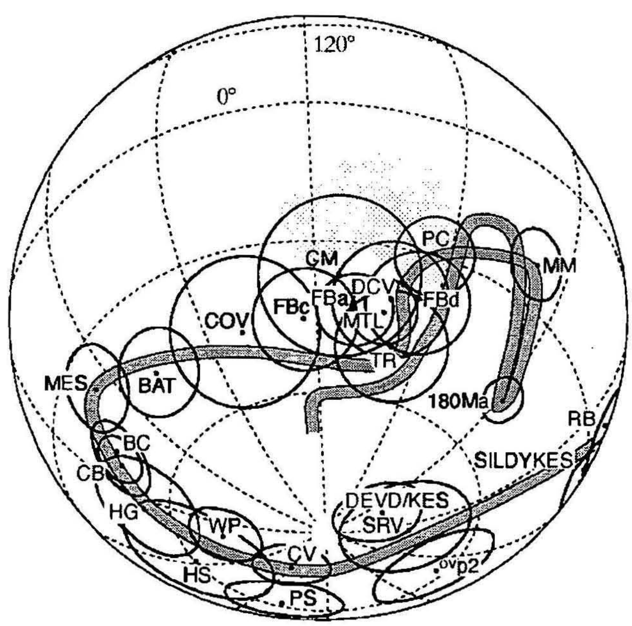
This study provides reliable, well-dated and precisely defined Early Permian (285 ± 5 Ma) palaeomagnetic poles for Australia from the Mount Leyshon Igneous Complex (MLIC) and the Tuckers Igneous Complex (TIC). These data indicate that Australia occupied high latitudes in the Early Permian. The mean direction obtained from the MLIC is Dec = 196.3°; Inc = +77.4° (N = 34; k = 53.5; α_{95} = 3.4°), while the mean direction obtained from the intrusive phases and the aureole of the TIC is Dec = 186°, Inc = +74° (N = 4; k = 216; α_{95} = 6.3°). The pole positions are: MLIC: Lat = 43°S, Long = 137°E (dp = 6.0°, dm = 6.4°), TIC: Lat = 49°S, Long = 142°E (dp = 10.3°, dm = 11.4°). The primary nature of the Early Permian palaeomagnetic signature is established by full baked contact/aureole tests at both localities. Adjacent to the intrusions the host rocks are completely remagnetised and exhibit reversed polarity palaeomagnetic directions that are identical to those of the intrusions. At somewhat greater distances the country rocks bear a Permian overprint on a more ancient component and at sufficiently large distances the host rocks show no signs of Permian overprinting. Permian overprinting is detectable at considerable distances from the MLIC (2-3 km), well beyond the zone of visible alteration. Proximal overprinting is generally associated with secondary magnetite, but distal overprinting appears to be associated with precipitation of secondary hematite. A similar pattern of overprinting is found at the TIC, where the pronounced Permian overprinting persists well outboard of the biotite/secondary amphibole hornfels zone. However, the distal overprinting associated with the TIC appears to be purely thermal, with no evidence of secondary magnetic minerals outside the mappable hornfels zone.



Silurian-Cretaceous Apparent Polar Wander Path for Australia. Poles are shown with associated errors. TR, Tuckers Igneous Complex. MTL, Mount Leyshon Igneous Complex.

MIDDLE CAMBRIAN PALEOMAGNETISM FROM THE AMADEUS BASIN, REVISITED

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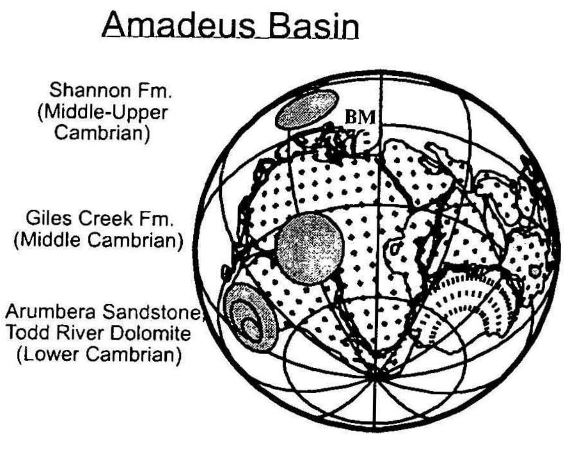
Recent speculation of an Early Cambrian episode of rapid true polar wander (TPW; Kirschvink et al. 1997) has endured heated debate (Torsvik et al. 1998, Evans et al. 1998, Evans 1998, Meert 1999, Evans and Kirschvink 1999). One argument against the hypothesis focussed on a lack of reliable Middle Cambrian paleomagnetic data from Gondwanaland, crucial for testing how much anticlockwise rotation of that continent occurred during which portions of the Cambrian. Kirschvink et al. (1997) proposed that a 90° rotation occurred entirely within the Early Cambrian, whereas Meert (1999) suggested only 30° of rotation during that interval, based on data from various localities in the Amadeus basin and Flinders Ranges (Klootwijk 1980). As shown in Figure 1, however, these data are internally inconsistent, warranting further study. Here we present preliminary data from the early Middle Cambrian Hugh River Shale, in the central Amadeus Basin, that bear directly on the Cambrian TPW controversy.



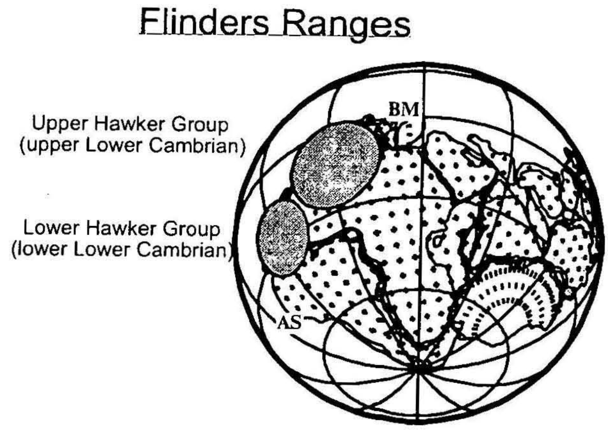


Figure 1. Selected Cambrian paleomagnetic poles from Australia. The studied rocks could bear directly upon the Cambrian TPW controversy, but present data show an inconsistency between the two studied regions (poles from Kirschvink 1978, Klootwijk 1980). AS= Arumbera Sandstone (Kirschvink 1978), BM= Black Mountain (carbonate) Cambrian-Ordovician boundary section (Ripperdan and Kirschvink 1992); these magnetostratigraphically based results were selected by Kirschvink et al. (1997) as the most reliable Gondwanaland results, supporting a TPW model for Early Cambrian time (for further discussion see Evans et al. 1998). Gondwanaland is reconstructed in the Australian reference frame (Powell and Li 1994).

Red, argillitic sediments of the Hugh River Shale are poorly exposed but are mappable ~100 km along-strike within the near-vertical, south-facing homocline that demarcates the northern edge of the Amadeus Basin in central Australia (Lindsay 1993). Aerial photographs show that the best exposure of this formation is located at Ellery Creek, near the center of the homocline (Warren and Shaw 1995). There, about 20 dolomite ridges (0.5–2 m thick) stand out among an elevated fluvial terrace that is otherwise floored by red shale-derived colluvium. About 1 km east of Ellery Creek, a tributary network has incised up to 4 m of the Cambrian bedrock, best exposing the dolomite layers but also some areas of fresh, red-purple mudstone and siltstone in the erosional "shadows" of the resistant carbonate beds.

About 75 portable drill-core samples were collected from the 500 m-thick Hugh River Shale at this locality; these were positioned lithostratigraphically among several measured sections. Samples 1–63 were from the best outcrop areas, measured with 5 cm resolution. Thereafter, stratigraphic levels among widely spaced streambed exposures were estimated by pacing, at probably ~1 m resolution. The uppermost sample horizons extend into the basal beds of the overlying Jay Creek Limestone, sampled up a narrow gully ~100 m west of Ellery Creek. In addition, 12 samples of Hugh River Shale were drilled from road-cuttings ~5 km east of Ellery Creek. The road-cut samples are placed stratigraphically within the upper 10 m of the formation.

Right-cylindrical specimens, one cut from each sample, were analysed by a 2G cryogenic magnetometer. Partial demagnetization was carried out at 5, 10, and 15 mT, followed by thermal steps of 150, 250, 375, 500, 550, 575, 590, 610, 630, 645, 655, 662, 668, 672, 676, 680, 684, 688, 690 and 692 °C, or until specimen behavior was convincingly unstable. The median highest applied step was 676 °C. The sampled suite varies in magnetic behavior, most commonly containing two, but sometimes three, components per specimen, the first being a present-field overprint. The second component, persisting to ca. 600-630 °C, is well clustered in a shallow NW direction. This single-polarity component may be diagenetic in origin. Although the highest-temperature components have not yet been fully analysed, least-squares linefitting to the best-behaved specimens yielded a two-polarity, mean tilt-corrected direction of (D=077°, I=17°, α_{95}=13°, N=23; westerly directions inverted). The mean may change slightly in the final analysis. It is noted that the applied tilt corrections, about horizontal, nearly E-W axes, do not greatly affect the high-temperature component directions nor their mean.

The corresponding pole position at (08°S, 029°E, dp=7°, dm=13°; compare with Fig. 1) is dissimilar to all younger poles for Gondwanaland or Australia, except for Lower-Middle Ordovician. Only minor tectonic movements affected the Amadeus Basin throughout that time, and as such were likely to be extensional rather than compressional (Hand et al. 1999). A much greater possibility of magnetic overprinting would arise from the more pervasive, Devonian, Alice Springs Orogeny (ASO; Kirschvink 1978, Klootwijk 1980). Because my Hugh River Shale magnetic remanence clearly pre-dates the ASO — because of its dissimilarity to all Devonian and younger results — and thus has proven to withstand that overprint event, it is unlikely that it could have arisen as an overprint from some much less pervasive, earlier movement. In addition, the Early Ordovician Horn Valley Siltstone at Ellery Creek has a conodont-alteration-index value of 1–1.5, indicating maximum post-depositional temperatures of ~50-90 °C (Gorter 1984). Finally, at stratigraphic levels where overlapping sections were sampled, the polarity pattern of remanence appears consistent with the lithostratigraphy. For these reasons, an overprint-origin for the hematitic remanence component appears unlikely.

The Hugh River Shale paleomagnetic pole, with its uncertainty of the mean direction, barely overlaps with that from Embleton's (1972) previous study of the Hugh River Shale at Ellery Creek (pole at 11°N, 037°E, dp=5°, dm=9°). This earlier result, determined by "blanket" thermal demagnetization at 600°C of only 18 specimens from 7 samples, may be contaminated by incomplete removal of a present-field overprint, which would have affected the westward-up directions more because of their dominance in numbers (13 vs. 5 eastward-down directions). Alternatively, Embleton's (1972) samples may have been derived from higher stratigraphic levels than our best-defined specimens; his sample locations are not precisely specified.

My new result agrees with those reported by Klootwijk (1980) from the upper Hawker Group in the Flinders Ranges, but well away from the presumably coeval Giles Creek Dolomite in the eastern Amadeus Basin (Fig. 1). It is noted that all of the Australian Cambrian results are consistent if the Giles Creek Dolomite pole is discounted. Perhaps that formation, characterized by marked thrombolitization and weak magnetic moments, is simply unsuitable for preserving a primary magnetic remanence. I am currently processing samples of the upper Giles Creek and Shannon Formations from Ross River Gorge, to assess this possibility.

The new Hugh River Shale pole is separated from Kirschvink's (1978) upper Arumbera Sandstone pole by 58 ±18° (dm uncertainties added). That formation (as defined by Kirschvink; now known as Arumbera II) lies just below the Proterozoic-Cambrian boundary, and thus has a numerical age of ~545 Ma (probably ±1 Ma; Grotzinger et al. 1995). According to biostratigraphic data summarized by Shergold (1986) and sequence-stratigraphic correlations by Kennard and Lindsay (1991), the lower Hugh River Shale (containing most of our best-behaved samples) at Ellery Creek should have an age of Ordian, which is correlated with the uppermost Lower Cambrian (Toyonian) of Siberia (Gravestock 1995). Based on recent augmentations to the Cambrian timescale by high-precision U-Pb results on phreatomagmatic zircons (Landing et al. 1998), the Ordian should be about 511 Ma, with reasonable limits of ±3 Ma. Combining these results, Australia experienced 58 ±18° of apparent polar wander (APW) in 34 ±4 Myr, or 1.7 +0.8/-0.6 °/Myr. Because the polar path crosses the Amazonian and West African sectors of Gondwanaland, which should have been assembled by Early Cambrian time at the latest (Trompette 1994), these sectors would have borne the full latitudinal velocity of the APW rotation, or 19 +9/-7 cm/yr. This rate, taken at the mean value, exceeds the fastest present oceanic spreading rate, and matches even India on its Cretaceous-Eocene sprint toward Asia (Klootwijk et al. 1992) as well as all other observed bursts of Paleozoic continental motion (Meert et al. 1993).

The new Hugh River Shale result appears to invalidate the hypothesis by Kirschvink et al. (1997) that 90° of TPW occurred during Early Cambrian time. On the other hand, Meert's (1999) alternative estimate of ~30° Early Cambrian APW is too low. The observed Early Cambrian 60° rotation of Gondwanaland may have been due primarily to true polar wander (TPW); this would be consistent with the extended hypothesis of multiple Vendian-Cambrian TPW episodes, all within the context of the fragmented Rodinia supercontinent (Evans 1998, Evans and Kirschvink 1999). However, any TPW model requires paleomagnetic verification from coeval rocks on other continents (cf. Grunow and Encarnación 2000).

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PALAEOMAGNETIC RESULTS INDICATE ANTICLOCKWISE ROTATION OF THE SOUTHERN TAMWORTH BELT DURING THE HUNTER-BOWEN OROGENY

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Visean ignimbrites from the Rouchel, Gresford and Myall blocks have been sampled in order to identify and quantify the allochthonous nature of the southern Tamworth Belt. About 50% of the ignimbrites sampled retain a pre-folding high temperature remanence, carried mainly by magnetite. These ignimbrites mostly retain two components of magnetisation; the low temperature present field overprint, and a high temperature primary component. Some, however, retain three components: with the addition of a moderate temperature pre-folding overprint.

Palaeomagnetic data indicate that the southern Tamworth Belt occupied low to moderate palaeolatitudes during the Early Carboniferous, in accordance with the Australian craton. Normal and reversed polarities of moderate inclination suggest that latest Carboniferous to earliest Permian overprints are absent from the high temperature dataset.

The mean characteristic remanence direction of 56 early to middle Visean ignimbrite sites from the Rouchel block is dec=155.1°, inc=37.1° (α_{95}=7.0° and k=8.3) corresponding to a palaeopole at Lat=-65.0°, Long=262.1° (dp=4.8° and dm=8.2°), indicated as RB in Figure 1a. Thirty six middle to late Visean ignimbrite sites from the Gresford block retain a mean remanence of dec=162.3°, inc=55.4° (α_{95}=6.2° and k=15.7), which corresponds to a palaeopole at Lat=-75.0°, Long=223.8° (dp=6.3° and dm=8.8°), mnemonic GB in Figure 1a. Despite widespread overprinting throughout much of the Myall block, reliable information was obtained from five middle Visean sites, with a mean direction of dec=118.1°, inc=42.5° (α_{95}=12.0° and k=41.6), from which a palaeopole of Lat=-35.7°, Long=233.1° (dp=9.1° and dm=14.7°) was calculated and is presented in Figure 1a as MB.

The calculated palaeopoles do not fall on the Early Carboniferous segment of the published Apparent Polar Wander Path for Australia (Figure 1) and, because the palaeolatitudes concur with those of Early Carboniferous rocks within the craton, the data is interpreted to indicate that the southern Tamworth Belt has undergone significant anticlockwise rotation relative to cratonic Australia, probably towards the end of the Carboniferous Period. Inferred rotations for the Rouchel, Gresford and Myall blocks are 80°, 80° and 120° respectively. Rotation corrected palaeopole positions are highlighted in Figure 1b. The interpreted rotations are consistent with geological evidence and are thought to result from the existence of a sinistral strike-slip margin during the latest Carboniferous to earliest Permian.

Figure 1a

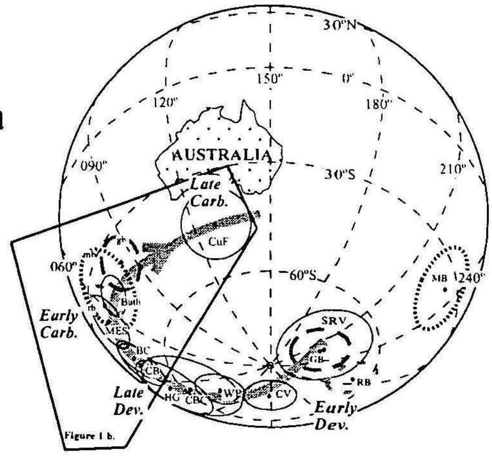

Figure 1b

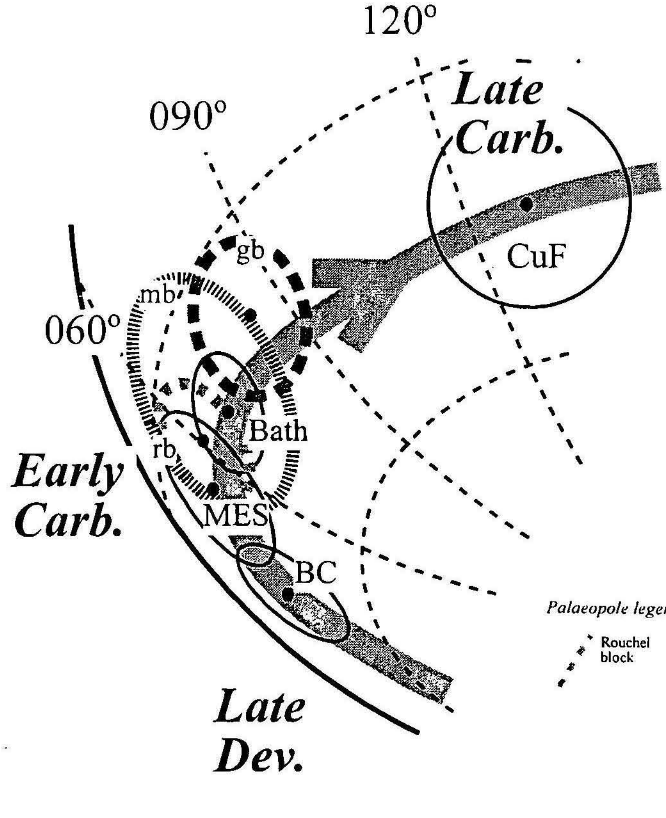

Figure 1(a) Published Australian APWP. **(b)** Expanded view of the Late Devonian to Late Carboniferous section of the APWP illustrating the overlap of rotation corrected Early Carboniferous southern Tamworth Belt palaeopoles with the Early Carboniferous Mount Eclipse Sandstone and Bathurst Batholith palaeopoles. Thick grey line marks APWP.

PRE-FOLDING OVERPRINTS IN THE SOUTHERN TAMWORTH BELT

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A pre-folding latest Carboniferous to earliest Permian magnetic overprint has been found in many Early Carboniferous rocks in the Rouchel, Gresford and Myall blocks of the southern Tamworth Belt, southern New England Orogen. Despite a positive conglomerate test, the overprint is widespread. The overprint is observed in three different scenarios (Table 1); the moderate temperature component where three components are retained, and the high temperature component in both sedimentary rocks and altered ignimbrites. Each of the three scenarios has a mean remanence direction that is statistically indistinguishable from the others, however, all three mean directions are significantly different from the mean Visean direction (see Geeve this issue), using McFadden and Lowes (1981) test.

Scenario		*Remanence direction*					*Palaeopole position*			
		N	dec	inc	α_{95}	k	Lat	Long	dp	dm
3 components	*in situ*	7	250.2	69.2	42.6	3.0	-38.8	150.5	43.7	43.9
	corrected	7	185.3	86.7	22.1	8.4	-32.5	143.5	43.7	43.9
Sediments	*in situ*	10	313.3	80.2	21.4	6.1	-22.6	147.8	16.8	16.9
	corrected	10	341.4	84.9	8.6	32.7	-23.6	157.3	16.8	16.9
overall	*in situ*	37	296.0	83.5	10.9	5.6	-30.3	155.3	10.9	10.9
	corrected	37	059.7	88.0	5.5	19.1	-35.4	154.5	10.9	10.9

Table 1. Summary of overprint directions and palaeopoles of different scenarios.

The overprint has a mean bedding corrected direction of dec=059.7°, inc=88.0° (a_{95}=5.5° and k=19.1) from 37 sites, which yields a palaeopole of Lat=-30.3°, Long=155.3° (dp=10.9° and dm=10.9°) (Figure 1; **OP**). The significance of this finding is that the overprint was acquired prior to folding, which is neither the case in the northern Tamworth Belt (Lackie and Schmidt 1993), nor the generally held view in the USA. The strongest evidence that the overprint is a remagnetisation and not a biased dataset comes from the three component sites (Figure 2). Clearly, as the moderate and high temperature components are distinguishable and statistically different they were acquired at different times. The high inclination of the overprint is in accordance with acquisition during the latest Carboniferous to earliest Permian.

The overprint palaeopole position is significantly different from the Mount Leyshon palaeopole from the Thomson Fold Belt (MtL; Figure 1) and the Barrington Tops Granodiorite palaeopole from the southern Tamworth Belt (BT; Figure 1) and is interpreted to have been rotated at least 80° anticlockwise. This implies that the overprint was acquired prior to or early on during the process responsible for the rotation of the Rouchel, Gresford and Myall blocks. The tightest constraint on the timing of rotation is between 306 and 295 Ma. Within this interval, an hiatus in deposition precedes the onlap of Early Permian sediments of the Sydney Basin over the southern margins of the Gresford and Myall blocks, and may be related to uplift associated with the rotation of the blocks.

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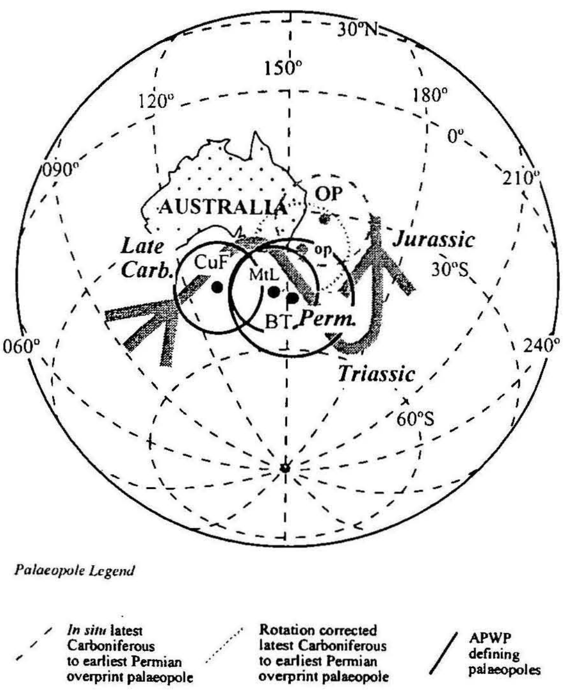

Figure 1. Australian Apparent Polar Wander Path (thick grey line) for the Late Carboniferous to Jurassic. BT, Barrington Tops Granodiorite; **OP**, uncorrected latest Carboniferous to earliest Permian overprint; **op**, rotation corrected latest Carboniferous to earliest Permian overprint.

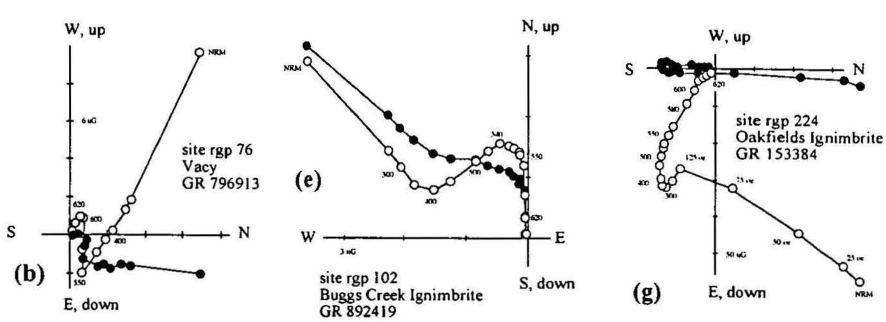

Figure 2. Z-plots of sites with three components of remanence.

ROCKPROPERTY — STRUCTURAL GEOLOGY SYNERGY AT WORK IN BROKEN HILL: A CASE FOR STRUCTURAL CONTROL OF LINEAR MAGNETIC ANOMALIES

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Background

The delivery of a new generation of high-resolution aeromagnetic data for the Broken Hill Block (BHB, Haren et al. 1997) has played a significant role in helping the Broken Hill Exploration Initiative (BHEI) successfully achieve its brief of stimulating exploration activity (Denham et al. 1998) in the region. They have yielded new insights into the geological development of the region with the expectation that more effective exploration strategies may be defined. Geological realism in interpretations of those data however, is underpinned by our level of understanding of what we are tracing with the anomalies and of their petrophysical properties: source magnetic mineralogy and the magnitude and significance of the different parameters employed in magnetic modelling studies. The more informed our understanding is, the more likely the interpretations will increase the chance of success in exploration. We present a brief look at a combined rockproperty-structural geology study that clearly demonstrates that linear magnetic anomalies in the BHB can be structurally-controlled, challenging the long-held view that they reflect stratigraphy and introducing a cautionary note into their use as markers in extrapolating lithology undercover (Maidment et al. 1999).

Study area

The linear magnetic anomalies we chose to study are part of a broad belt that sweeps across the BHB from north to southwest, changing strike in the process from north-northeasterly to northeasterly. Our more informed understanding of those anomalies and our assessment of the significance of the different parameters employed in magnetic-modelling is based upon combined magnetic field profiling, magnetic mineralogy determination, measurements of magnetic remanence and anisotropy of susceptibility, and detailed geological and structural mapping along traverses orthogonal to the strike of the anomalies. We targeted three anomalies, located from north to south: north of Waukaroo Bore (WB), trending ~27°E and hosted by the Sundown Group; northwest of Acacia Vale HS (AV), trending ~38°E and hosted by the Thackaringa Group; and the Monuments/Archery Range area (MA), northwest of Broken Hill, trending ~45°E and hosted by the Sundown Group. Apart from the Monuments anomaly (traversing and total field measurements conducted by NSW DMR, a co-partner in BHEI), traverses were ~500 m long to ensure complete capture of anomaly profiles. Total magnetic field measurements were recorded every 5 m. Field susceptibility measurements were made every 10 m and helped locate the boundaries of the anomalous zones. Oriented cores of rock (30–50 per traverse) were collected along the traverses for magnetic property measurements.

Magnetic properties and modelling

We identified the magnetic mineral systems in the anomalous zones and gained an insight into their grain-size distribution from the temperature (T) variation of magnetic susceptibility (k) between -195°C and 700°C (Schmidt 1993), using AGSO's very sensitive, Czech-built, KLY3

Kappabridge. Without exception, strongly magnetic samples yield k/T curves that show sharp drops in susceptibility in the range ~585–595°C, a Curie point that tells us that we are dealing with pure end-member magnetite in the titanomagnetite solid-solution series $Fe_{3-x}Ti_xO_4$ (x=0, magnetite). They also all show, at low temperature, significant increases in susceptibility, with values peaking between - 140°C and - 150°C, indicating that a coarse-grained (multidomain) magnetite fraction is present. These findings are consistent with the fact that metamorphic magnetite is generally pure and coarse grained (Thompson and Oldfield 1986) and confirm geological evidence for magnetite as the source of these anomalies. Minor maghemite is present and is probably a weathering product. Importantly, for the susceptibility anisotropy work, there is no indication of pyrrhotite (Fe_7S_8), an important magnetic mineral after the iron oxides that is characterized by a strong anisotropy related to its crystal structure.

In view of the ideas circulating that certain BHB structural fabrics are magnetite-enriched, we looked at whether any relationship exists between the magnetite and petrofabric by measuring the anisotropy of magnetic susceptibility (AMS) of the oriented samples using the KLY3. This technique detects the presence of any preferred plane (fabric) of maximum susceptibility (plane containing the k_{max} and k_{int} axes with the k_{min} axis the pole to that plane) and for magnetite is primarily grain-shape dominated (Borradaile and Henry 1997). The AMS measurements also yielded the bulk susceptibilities (range 1100–5000 x 10^{-5} SI for anomalous zone samples) used in magnetic modelling. The AMS results demonstrate that indeed a well-defined, steeply-dipping, magnetic fabric is present for each anomaly and that the orientation of the fabric varies between anomalies. A simple pattern emerges: as we come south, from WB in the north, through AV, to MA the magnetic fabric plane veers around from an azimuth of 19°E and steep dip of 82° ESE (WB, anomaly trend ~27°E), through 38°E and dip of 74° SE (AV, anomaly trend ~38°E), to 46°E and dip of 77° SE (MA, anomaly trend ~45°E). The geological significance of this pattern is revealed by comparing it with the regional, structurally-mapped S_3 fabric of Gibson (1999): the AMS fabric quite clearly tracks S_3, both in azimuth and dip. Importantly, the anomaly trends lie along the magnetic fabric trends and hence S_3.

We investigated source body geometry by modelling the magnetic profiles in detail using the rockproperty parameters as a guide to ground-truth. The shapes of the magnetic profiles indicate that each is a composite of two sources: a steeply-dipping (~80° ESE — WB; ~70° SE — AV), tabular body (~125 m width), 20–50 m below the surface and of great depth extent, that gives the gross shape of the profile; and a number of narrower, near-surface bodies that extend down to the deeper body and give high-frequency detail to the profile. These finger-like, thin tabular bodies mimic the observed and marked spatial variation in surface susceptibility (up to two orders of magnitude within metres) that reflects the inhomogeneous distribution of magnetite within the anomalous zones. Modelling with induced magnetization alone and in conjunction with magnetic remanence allowed us to assess the importance of remanence to modelling. Initial remanence directions (freed of temporary components acquired prior to measurement and of lightning-struck samples) in each case are moderately-steep, upward-pointing (normal, in the vicinity of the Earth's field) and downward-pointing (reverse), and obliquely-streaked in between. We find that the reinforcement of the induced magnetization by the normal remanence is markedly diminished in its importance by the counteracting reverse and oblique remanence, to the extent that the mean remanent field magnetizations are 4–8 times smaller than individual sample magnetizations. As a result, we find that for these magnetite-sourced linear anomalies, remanence may be ignored in modelling the deeper tabular features, but that individual sample remanences are useful for getting the best fit to the high-frequency detail caused by the near-surface, thin tabular features. In fact, the difference between models (induced only and induced plus remanence) is essentially one of repositioning of the relatively-unimportant, near-surface bodies to realign the computed profile for the effect of remanence: the shape and dip of the main tabular bodies remain unchanged.

Structural control of anomalies by S_3

How do the models fit with the mapping and AMS data and what is the bearing of the results on the debate concerning stratigraphic versus structural control of anomalies in BHB (Gibson et al. 1996; Haren et al. 1997)? We note that the dip and dip sense required of the tabular bodies by the shape of the anomaly profiles are consistent with the dip and dip sense of the magnetic fabrics measured for the anomalous zones and that those fabrics are the S_3 fabric. Hence the tabular bodies must represent the magnetite-rich S_3 fabric. For WB, the geological cross-sections show that the enveloping surface to S_0 (bedding) dips shallowly to the NE and SW. However, we demonstrated that the anomalous zone here dips ~80° ESE and is the magnetite-rich S_3 fabric. Clearly, this is a case of an anomaly controlled by structure, not stratigraphy: magnetite-impregnation of S_3 was probably associated with circulating fluids, triggered perhaps by the deformation event. Results indicate a similar origin for the MA anomaly. For AV, the situation is equivocal: S_0 and S_3 have similar steep dips so the case for structural control can be challenged on the basis that S_3 could have inherited a pre-existing, magnetite-rich S_0 fabric (bedding — stratigraphic control). Irrespective of the control mechanism for the AV anomaly, this study adds another cautionary note to others concerning the use of linear anomalies for mapping geology in concealed areas: although some undoubtedly reflect lithology, others will certainly reflect structure. Conceptually, recognition of structurally-controlled anomalies and the implications for mineralization stemming from their association with fluid movement clearly opens up a new avenue in BHB exploration strategy.

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Tony Meixner and Peter Gunn are thanked for introducing us to the process of magnetic modelling.

A PRECISELY DATED PROTEROZOIC POLE FROM THE NORTH CHINA CRATON AND ITS RELEVANCE TO PALEOCONTINENTAL RECONSTRUCTION

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Positive palaeomagnetic contact tests on two dykes from the Taihang dyke swarm of the North China craton suggest that the remanent magnetization is primary and formed during initial cooling of the intrusions. The age of one of these dykes, based on U-Pb dating of primary zircon, is 1769.1±2.5 Ma. The mean palaeomagnetic direction for 19 dykes, after structural correction, is D= 36°, I= -5°, k= 63, α_{95}= 4°, yielding a paleomagnetic pole at Plat= 36°N, Plong= 247°E, dp= 2°, dm= 4° and a palaeolatitude of 2.6° S. Comparison of this pole position with others of similar age from the Canadian Shield allows a continental reconstruction whereby Laurentia, Siberia and the North China craton have remained more or less in their present configuration since about 1800 Ma.

Australian Palaeomagnetism, Rockmagnetism, Environmental Magnetism 2000

THE MAGNETIC INCLINATION "ANOMALY" IN EURASIA: A REALISTIC EXPLANATION

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The observed inclination of the Earth's magnetic field has been reported to be shallower than what it was expected to be at different geological times. The most famous example is what is known as the "inclination anomaly" during the Tertiary in Eurasia. Available paleomagnetic studies of Tertiary rocks from Eurasia all display inclinations 15 to 30 lower than inclinations expected from the Eurasian apparent polar wander path (APWP). We present here results of a paleomagnetic study of 39 sites from 5 Tertiary sections carried out in continental red bed formations from the Qiangtang and Kunlun blocks and from the Xining basin. In the Qiangtang block, we have sampled the Eocene Xialaxiu section (32.8°N, 96.6°E). The West Yushu (33.2° N, 96.7°E) and Tuoluo lake (35.3°N, 98.6°E) sections in the Kunlun block are both of Neogene age. In the Xining basin, we have sampled the Neogene Jungong section (34.7°N, 100.7°E) and the Eocene Xining section (36.5°N, 102.0°E). Apart from Tuoluo lake locality, thermal demagnetization of samples displayed a high temperature component which we interpreted as being of primary origin and of which the paleomagnetic poles are situated at 52.6°N, 352.0°E (dp/dm=6.0/10.7), 53.9°N, 205.4°E (dp/dm=5.6/10.0), 66.0°N, 228.6°E (dp/dm=3.6/6.9) and 61.6°N, 211.3°E (dp/dm=9.7/16.1) respectively for Xialaxiu, W. Yushu, Jungong and Xining localities. In these studies, the paleomagnetic inclinations we have obtained are lower by 22 to 26° than those expected for the localities based on the Eurasian reference APWP at 10 and 20 Ma for the Neogene sections, and at 50 and 60 Ma for the Eocene sections. Traditionally, this has been interpreted as due to a non-dipolar earth magnetic field during the Tertiary or to compaction processes that would have induced grain rotations. By compiling Eocene data from South China Block, Tibet and Central Asia, we suggest that the two reasons quoted above are not convincing and propose a tectonic origin to the "inclination anomaly". Our idea is that the Eurasian APWP does not reflect the evolution of Siberia craton during the Tertiary, pointing out a non-rigid behaviour of Eurasia plate and possible tectonic events between its western part and Siberia during the Tertiary. Concerning our Neogene results, when compared to the Indian APWP, they suggest that the studied red bed formations are most probably older than Neogene pointing out the problem of dating continental red beds, which is largely based on lateral continuation of facies.

LATE PALAEOZOIC POLEPATH FOR THE NEW ENGLAND OROGEN: CONSTRAINTS AND IMPLICATIONS FROM THE ROCKY CREEK BLOCK, TAMWORTH BELT

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The Carboniferous-Early Permian succession of the Tamworth Belt has proven very prospective for defining the Late Palaeozoic polepath for the New England Orogen. The abundant felsic volcanic intercalations within the mainly volcaniclastic succession are highly suitable for determining primary magnetizations, despite the presence of various magnetic overprints, and for SHRIMP U-Pb zircon dating. The Tamworth Belt's Late Palaeozoic polepath also has representative potential for cratonic Australia. The precursor terrane of the Tamworth Belt, the Gamilaroi Terrane of the southern New England Orogen, became accreted to the Lachlan Orogen by the Late Devonian (Famenian, Flood and Aitchison 1992) and its northern New England equivalent, the Calliope Terrane accreted to the Thomson Orogen during the Middle Devonian Tabberabberan Orogeny (Murray 1986, Scheibner and Basden 1996). Subsequent tectonism, such as the latest Carboniferous-Early Permian initiation of the Bowen-Gunnedah-Sydney Basin system together with oroclinal deformation of the southern New England Orogen and the Permo-Triassic Hunter-Bowen Orogeny, may well have affected the shape of the polepath. These are most probably second-order effects, which can be identified and corrected for in the wider representation of the polepath. If first-order representation for cratonic Australia can be confirmed, then the Tamworth Belt polepath can contribute considerably to resolve the current prominent dilemma of two different interpretations of the Late Palaeozoic polepath for cratonic Australia and Gondwanaland (the SLP- and KG-polepaths, see Klootwijk 1997) with differing implications for regional and global tectonics.

Palaeomagnetic results from reconnaissance studies on four tectonic blocks of the Tamworth Belt — the Rocky Creek, Werrie, Rouchel and Gresford Blocks — have previously been compiled into an initial (TB-) polepath for the New England Orogen (Klootwijk 1997). This preliminary polepath resembles the KG-polepath for cratonic Australia, but not so the SLP-polepath. Extensive palaeomagnetic, rockmagnetic and magnetic fabric follow-up studies throughout these four blocks of the Tamworth Belt are now nearing completion, with results substantiating and refining the outline of the preliminary TB-polepath. Results are reported here for the Rocky Creek Block, the first of these follow-up studies, and wider implications for Australian and Pangean tectonics during the Late Palaeozoic are discussed.

Detailed thermal demagnetization studies of Visean (Caroda Formation) to Westphalian (Lark Hill Formation) felsic, mainly ignimbritic, volcanics and volcaniclastics (64 sites, 734 samples) have established well-defined primary magnetization results for 29 sites, and evidence for four magnetic overprint phases of widespread occurrence (related to Recent or middle Cainozoic weathering and to the Permo-Triassic Hunter-Bowen Orogeny) or more local occurrence (related to Late Cretaceous opening of the Tasman Sea and to latest Carboniferous-Early Permian initiation of the Bowen-Gunnedah-Sydney Basin system). The primary magnetization results for these 29 sites have been combined into 7 mean-site poles covering 26 site-mean results, with positive foldtests (McFadden 1990) for 5 mean-site results and with confidence levels above 95% (1 result) or 99% (3 results). A further 3 single-site results provide additional defining information for the polepath. These 10 pole positions define an extensive Visean to Westphalian polepath for the Rocky Creek Block, which refines and provides more detail for the preliminary TB-polepath for the Tamworth Belt.

The new palaeomagnetic, rockmagnetic and magnetic fabric results for the Rocky Creek Block demonstrate the following:

- No noticeable rotational deformation between the three major thrust sheets of the Rocky Creek Block: the Rocky Creek, Kathrose and Darthula Thrust Sheets.
- Consistent flow transport directions in the older succession, Caroda Formation to Clifden Formation, and more variable transport patterns in the younger succession, Rocky Creek Conglomerate and Lark Hill Formation.
- Good agreement between contemporaneous pole positions for the Rocky Creek Block (the High Valley andesite tuff of the Caroda Fm., the Peri Rhyodacite Tuff of the Clifden Fm.) and for the Rouchel and Gresford Blocks (the Native Dog Member of the Isismurra Fm., the Mirannie Volcanic Member of the Seaham Fm.). This indicates absence of significant rotational deformation between the northwestern and southwestern parts of the Tamworth Belt and contrasts with interpretations of 70 to 80 degrees rotation of the Rouchel and Gresford Blocks versus cratonic Australia (e.g. Geeve 1999).
- Further evidence for a Late Devonian- Early Carboniferous northward excursion over more than 30 degrees of latitude, culminating in the middle Visean. If proven representative for the Australian craton, this excursion provides a novel and provocative mechanism for the Early-to-middle Carboniferous Kanimblan and Alice Springs Orogenies as caused by far-field stresses originating from convergence between Greater Australia and the Central Asian Fold Belt on the southern periphery of the Siberian craton.

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ALTERNATIVE LATE PALAEOZOIC CRATONIC POLEPATHS: THE SLP-PATH AND THE KG-PATH

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The shape of the Late Palaeozoic polepath for cratonic Australia continues to be a matter of contention for Australian palaeomagnetists and a source of confusion for others. More than a dozen, sometimes radically, different polepaths have surfaced over the past four decades: two, or perhaps three, surviving concepts are actively debated. The Australian quagmire is reflected in, if not the cause of, continued debate about Gondwanaland's Late Palaeozoic polepath. Whilst there is general consensus about the Late Palaeozoic polepath for Laurussia/Laurasia, continuing uncertainty about the Australian/Gondwanaland polepath has worked through in ongoing debate about the formation of Pangea and the origin and evolution of the Variscan Orogeny.

Two alternatives for Australia's Late Palaeozoic polepath are currently promoted. The SLP-path, proposed by Schmidt, Li, Powell and coworkers, is characterised by a Devono-Carboniferous "westward" loop with a Visean apex. The KG-path, proposed by Klootwijk and Giddings, in contrast, features an "eastward" Devono-Carboniferous loop. The Late Carboniferous to Early Permian segments of the two polepaths are in general agreement. The SLP-polepath is based on, in part hierarchical, quality filtering of published palaeomagnetic data. The KG-polepath accommodate all poles used in defining the SLP-polepath. It also includes various published poles excluded from the SLP-polepath but reinterpreted as overprints induced during the Early Carboniferous Kanimblan Orogeny, and, in addition, a set of Middle to Late Palaeozoic poles from as yet unpublished and mainly preliminary studies on the Tasman Orogenic System and cratonic basins.

The SLP-polepath has a simple and attractive shape and may be touted as the more attractive alternative if its original defining, limited, database is considered alone. Preference for the KG-polepath alternative will be argued for instead, based along lines as follows:

- Inconsistencies in the SLP-database, in part arising from refined age control for some Late Devonian data (Hervey Group, Worange Point Fm.), backed-up by as yet unpublished data from the latest Devonian to Early Carboniferous Mt Eclipse Sandstone.
- Potential Kanimblan overprint origin for some of the SLP data (e.g. Snowy River Volcanics) based on similarity with presumed overprint poles from Late Devonian-Early Carboniferous volcanics (Dandenong Volcanics, Star of Hope Formation) and African poles (Aïr Massif, Gilif Hills) of suggested overprint origin.
- Gross similarity between the KG-polepath, the TB-polepath for the Tamworth Belt (this workshop), and Goleby's polepath (G1-G6 poles) developed from Middle Ordovician to Middle Devonian volcanics and sediments from the Eastern Lachlan Orogen.
- Better performance of the KG- and TB- polepaths versus the SLP-polepath in testing geological models, e.g. Late Palaeozoic Gondwanaland-Laurussia convergence, Cathaysia-Gondwanaland reconstruction, oroclinal bending of the New England Orogen.

PALAEOMAGNETIC INVESTIGATION OF LATE PALAEOZOIC VOLCANIC UNITS FROM THE NORTHERN NEW ENGLAND OROGEN, QUEENSLAND

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The New England Orogen comprises a number of Palaeozoic and Mesozoic terranes. This paper presents the results of a palaeomagnetic study of volcanic units from the southern part of the Connors-Camboon Province in Queensland. The age range of the Province is 320 - 280 Ma, with this study concentrating on the Late Carboniferous Torsdale Volcanics and the Early Permian Camboon Volcanics from the Cracow area (25.3°S, 150.3°E).

The Camboon Volcanics sampled were generally andesitic ignimbrites and lavas yielding a primary direction in both magnetite and haematite carriers. All directions were reversed and analysis of the data shows a southerly steep down direction with a mean direction of Dec = 171.7°, Inc = 76.6° (α_{95} = 6.1°, k = 52, N=12) which results in a palaeomagnetic South pole of 50.4°S, 155.9°E (10.5,11.3). This is consistent with other Australian Early Permian data indicating a primary magnetisation age.

The Torsdale Volcanics sampled were generally silicic ignimbrites that yielded a primary direction in both magnetite and haematite carriers. The directions are generally reversed, although some normal polarities are observed. The directions are not as steep as those observed for the Camboon Volcanics and show a more westerly character, with a mean direction of Dec = 217.8°, Inc = 68.8° (α_{95}= 7.9°, k = 59, N=7) which results in a palaeomagnetic South pole of 50.9°S, 113.8°E (11.4,13.4). The pole is consistent with the Late Carboniferous age of the unit.

PALAEOMAGNETIC EVIDENCE FOR UNIFICATION OF THE NORTH AND WEST AUSTRALIAN CRATONS BY CA. 1.7 GA: NEW RESULTS FROM THE KIMBERLEY BASIN OF NORTHWESTERN AUSTRALIA

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A palaeomagnetic study of the Elgee Formation red siltstones and shales in the Palaeoproterozoic Kimberley Basin of northwestern Australia has been carried out. All seven sampling sites revealed an extremely stable magnetic remanence carried by hematite. The age of the formation is confined by precise SHRIMP U-Pb ages of early-diagenetic xenotime from rocks both above and below it to be 1704 +7/-14 Ma, but this may represent a minimum age. The youngest detrital zircon grains in the underlying formation provide a maximum age of 1786 ± 14 Ma for the formation. The extreme stability of the remanence, the dissimilarity of the remanent direction from expected younger palaeomagnetic directions, and the lack of regional overprint in the 1790 ± 4 Ma Hart Dolerite just north of the study region, support a primary origin for the remanence, as does a marginally positive fold test. The mean-direction of D= 92.2°, I= 14.9°, α_{95}= 6.4° gives a palaeopole at (4.4°S, 210.0°E) with dp= 3.3°, dm= 6.5°. This pole, together with a previously reported palaeopole from the Hart Dolerite and ca. 1700 Ma overprint poles from the Pilbara Craton, all agree with palaeopoles of similar ages from the McArthur Basin of northern Australia. Palaeomagnetic results thus suggest that the North and West Australian Cratons were possibly together by ca. 1.7 Ga.

MULTI-RELATIONSHIPS BETWEEN MAGNETISM AND CLIMATE/PEDOGENESIS IN AEOLIAN LOESS DEPOSITS: AN INTERPRETATION OF PEDOGENIC MODIFICATION POST-DEPOSITION

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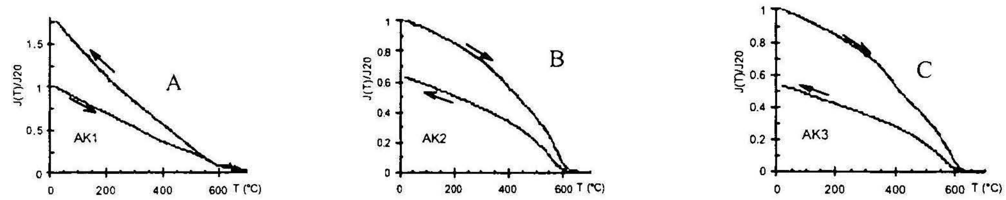
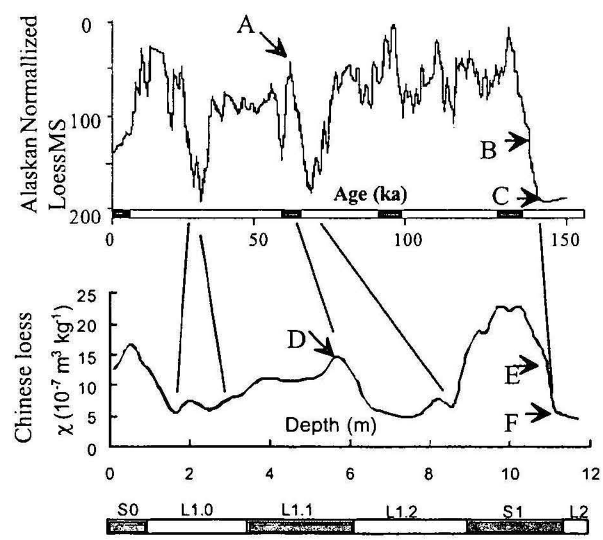
Aeolian loess and loess-like deposits cover about 10% of the Earth's continental surface. They are mainly distributed in the arid middle latitude Temperate Zone in both southern and northern hemispheres, with thickness varying from a few meters to hundreds of meters. These geological sequences have recorded valuable information on palaeoclimatic change, especially valuable in research on Quaternary palaeoclimate. Loess is aeolian dust accumulated mainly during dry-cold glacial periods (and seasons) while palaeosol is developed from loess material under relative warm-humid interglacial periods (and seasons). The loess/palaeosol sequence is therefore a direct product of palaeoclimate, the degree of pedogenic development (or palaeoclimate) can generally be recognised by an experienced pedologist from field observations. This way, however, only a qualitative description for the palaeoclimate can normally be achieved. In recent years, people more frequently reconstruct palaeoclimate from the loess/palaeosol sequence through indirect methods — using climatic proxy indicators. For example, the use of magnetic susceptibility as an indicator of pedogenesis is one of the more successful methods. In the central Loess Plateau of China, the highest susceptibility value is found in the most developed soil unit S5 while the lowest susceptibility is found in the least weathered silty-loess (Liu et al. 1992), indicating a good positive relation between them. The magnetic susceptibility measured from the central Loes Plateau can thus be used as a proxy palaeoclimatic indicator, with this the palaeoclimatic investigation can be transferred from qualitative pedogenic description to quantitative or semi-quantitative analysis. The magnetic susceptibility as a palaeoclimatic indicator in the loess-palaeosol sequences has therefore become one of the simpler but highly successful methods widely used by Quaternary scientists during the past two decades (Heller and Liu 1982, 1984; Kukla et al. 1988; Hoven et al. 1989; Pepit et al. 1991). As soil units generally contain finer and greater amounts of magnetic minerals (magnetite and maghemite) than loess, *in-situ* pedogenic enhancement of ferrimagnetic content is normally believed to be the main reason for the increase of susceptibility in soil units and for the above described positive relationship (Liu et al. 1992, 1995).

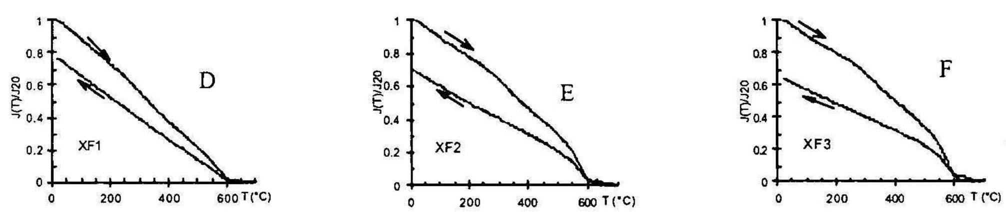
This positive correlation is one of the relationships which is popularly reported in European and Asian countries (Heller and Evans 1995). The pattern of high magnetic susceptibility in palaeosols, and lower values in loess, is not replicated in some loess deposits. Different relationships between magnetism and pedogenesis have also been reported. Alaskan (Begét 1996) and Siberian (Chlachula et al. 1998) loess deposits display a completely different susceptibility behaviour: high values in loess and low values in palaeosols. This inverse relationship has been explained by wind intensity/ velocity. The magnetic susceptibility is reflecting the magnitude of an aeolian ferrimagnetic component of consistent mineralogy, the grain size of which is related to average wind velocity. Magnetic study of Alaskan samples (Liu et al. 1999) suggests that there are notable differences in magnetic properties between Alaskan loess and well-developed palaeosol thereof, not only in magnetic grain-size and concentration but also in magnetic mineralogy. It is difficult to explain these observations through variation in wind strength alone. Instead this implies that the low magnetic susceptibility values in the Alaskan palaeosol units are a reflection, at least in part, of the alteration of the ferrimagnetic content by post-depositional processes. Recent magnetic susceptibility curves from Argentina (Orgeira et al. 1998), Pakistan (Akram et al. 1998) and from New Zealand (Liu, unpublished data) have demonstrated a weak, even none at al, correlation between soil magnetism and palaeoclimate/pedogenesis, indicating that the linkage between them is not a simple one.



Pedogenic development (temperature and moisture increase)

With increase of pedogenesis Alaskan samples first show a decrease in the relative maghaemite content. A new phase of mineral (greigite) is finally produced under a stronger pedogenic conditions of higher moisture and temperature.





Pedogenic development (temperature and moisture increase)

With increase of pedogenesis at Xifeng (Chinese loess) there is a gradual increase of relative magnetite content, but relative decrease in the content of thermally unstable maghaemite.

Figure 1. Thermomagnetic curves for samples from Alaska (A-C at top) and China (D-F at bottom), and their positions in the loess-palaeosol sequence (middle). An increase of magnetization for sample A, which differs from the others, implies the presence of greigite, a mineral generated and preserved under reducing conditions.

Here are my initial interpretations. Magnetic susceptibility shows variable behaviour corresponding to different pedogenic temperature-moisture environments. Ferrimagnetic minerals are produced (showing positive correlation) under pedogenic conditions resulting from low precipitation and high evaporation, but these will be destroyed (showing negative correlation) under high moisture (waterlogged) pedogenic conditions. If pedogenic development occurs under pedogenic conditions oscillating between ferrimagnetic formation and destruction, then it may be difficult to find a correlation between them. Great care should be taken therefore in using susceptibility values for the purpose of palaeoclimatic reconstruction.

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AEOLIAN RED CLAY IN CHINESE LOESS PLATEAU, EVIDENCES FROM MAGNETIC FABRIC AND ITS PALEOCLIMATIC SIGNIFICANCE

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The Red Clay, underlying the Quaternary loess-palaeosol sequence in the Chinese Loess Plateau, has a similar distribution to the overlying loess. The Quaternary loess-palaeosol sequence has a thickness of over 100 m in most areas of the Loess Plateau, for example, it is about 170 m at Xifeng, 135 m at Luochuan and 160 m at Baoji. In the last two decades the loess-palaeosol sequence has been intensively studied by scientists for reconstruction of Quaternary palaeoclimatic history and has provided major advances in our understanding of climatic evolution over the past 2.5 Ma. Magnetic susceptibility and grain size records from by these studies have confirmed their linkage to pedogenesis, or palaeoclimate. The magnetic susceptibility records from Xifeng and Luochuan have become standard palaeoclimatic proxy indicators which have been widely used for the correlation of palaeoclimatic signals between the continents and oceans.

This success with the loess-palaeosol sequence has encouraged scientists to look more closely at the Red Clay formation to see if a similar approach can extend the palaeoclimatic record back into the Pliocene. The Red Clay is a continuous deposit underlying the loess-palaeosol strata and exhibits many similarities, including many nodular pedogenic calcium carbonate layers (palaeosol structures) and a continental variety of xerophilous fauna but lacking the horizontal bedding. It was first referred to by Anderson (1923) as the Hipparion SP. Red Soil and was thought to have originated as an alluvial flood deposit, or by oxidation of lacustrine sediments. This water-lain origin of the Red Clay held favour until 1958, when Russian scientists included the Red Clay into the loess-palaeosol sequence as aeolian in origin (Kes 1958). This conclusion was generally ignored until magnetic fabric studies were applied by Liu et al. (1987, 1988). They studied the Red Clay in the upper part of the Xifeng section, successfully distinguishing water-lain (secondary) loess from wind-blown (primary) loess. Their results suggested the studied Red Clay profile to be aeolian in origin with palaeomagnetic ages between 2.5 and 3.4 Ma. Subsequent investigations have used additional approaches to confirm the aeolian origin of the Red Clay. Recently some new and more complete sections of Red Clay have been reported. Their detailed palaeomagnetic studies have confirmed earlier dates of 3.4 Ma for the upper part of the Red Clay in the Xifeng profile (Liu et al. 1987, 1988), extended downward to 5.0 Ma in Lantian near Xi'an (Zheng et al. 1991), to 5.2 Ma in Jiaxian (Ding et al. 1997), and have now been extended to 7.05 Ma (Ding et al. 1998) and 7.2Ma (Sun et al. 1998a) in Lingtai (also known as Pinglian) and 7.6 Ma in Xifeng (Sun et al. 1998b). As an aeolian deposit, Red Clay is of great significance for paleoclimatic change. For the much longer sections now known it is necessary to apply magnetic fabric analysis to determine the mode of deposition of the early Red Clay.

Our results demonstrate that the degree of alignment of magnetic grains within loess precipitated in different media — water and air, is different and that the two modes of deposition can be distinguished by magnetic anisotropy of susceptibility measurements. The Red Clay is characterised by aeolian magnetic fabric features (Fig.1). The aeolian deposits therefore started at least 7.6 Ma ago in Northern and Central China and record two important transitions of paleoclimatic significance: between the end of the Cretaceous Sandstone deposition and the start of the Red Clay accumulation at ~7.6 Ma, and the transition from the Red Clay to the overlying loess-palaeosol sequence at ~2.5 Ma. The Red Clay gradually spread toward the Southeast as the Cretaceous Sandstone emerged above water. Uplift of the Tibetan Plateau through critical threshold levels is inferred to relate to the appearance of the Red Clay, for reason that the age of the abrupt uplift of the Himalaya-Tibet Plateau to half its present elevation is estimated at between 7 and 8 Ma when the monsoon either started or intensified (Prell & Kutzbach 1992). Our study indicates that the Red Clay, like the overlying loess-palaeosol sequence, has a gradient in magnetic susceptibility from NW to SE matching the present-day summer monsoon pattern, probably indicating that the palaeomonsoon had started,or was already operative, at that time.

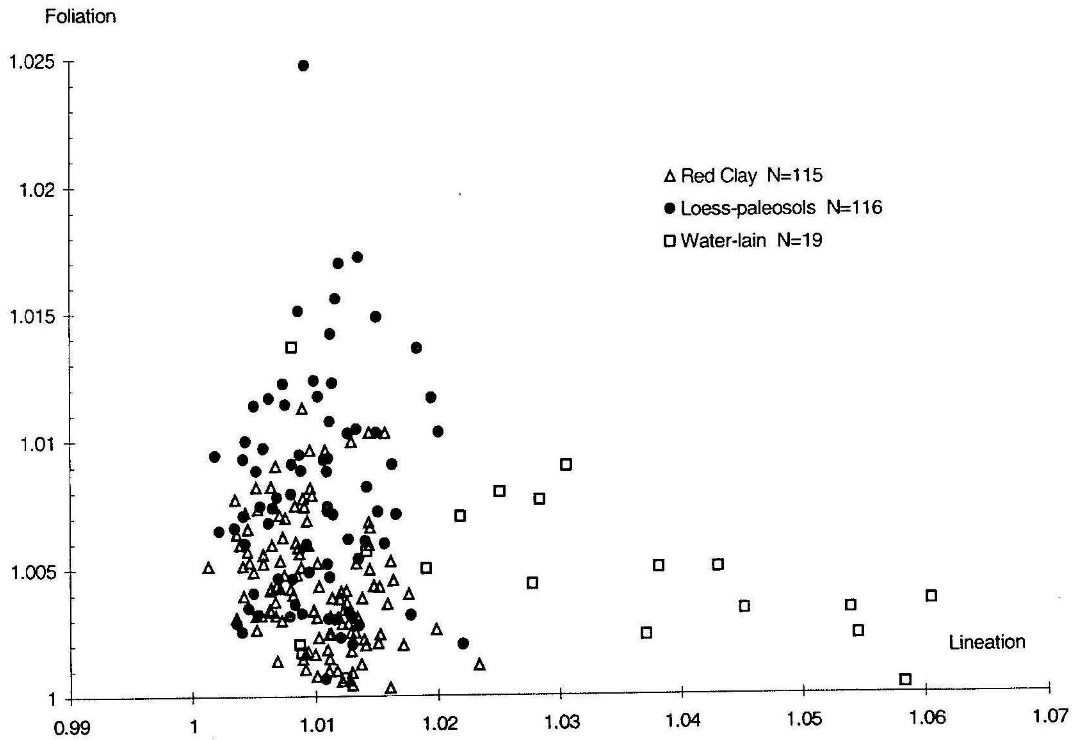

Figure 1. Distribution areas of lineation-versus-foliation parameters for wind-blown loes-palaeosols, redeposited water-lain loes, and the Red Clay. The Red Clay, like the overlying wind-blown loess, has aeolian characteristics.

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DETECTING FLYASH IN THE ENVIRONMENT USING A MAGNETIC FINGERPRINT: PRELIMINARY FINDINGS

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Flyash is produced as a by-product of fossil fuel combustion. During the combustion process, pyrite contained in the coal is transformed into iron oxides:

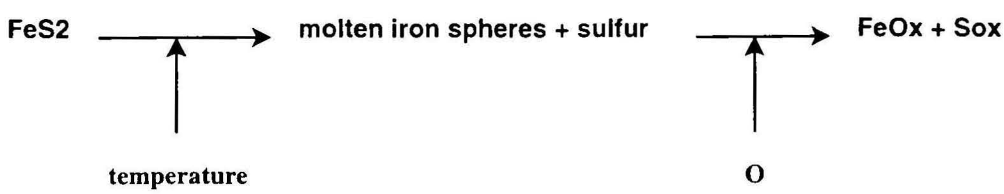

Figure 1. The origin of magnetic particles in Fly ash. (As from Flanders, 1999)

It is these iron oxides, in the form of magnetite and haematite, that are magnetic and allow flyash to be analysed magnetically.

Topsoil (O-layer), soil profiles and vegetation samples were collected from the area surrounding Eraring Power Station, Lake Macquarie NSW. These samples were analysed using low field susceptibility, frequency dependent susceptibility, ARM, IRM acquisition, SIRM and coercivity of remanence. Selected samples were also analysed using hysteresis loops and curie temperatures. Heavy metal analysis was performed on the samples to determine if any relationship exists between the presence of fly ash and heavy metals in the environment.

Flyash from the chimney filters at Eraring Power Station was used as a control sample for comparison with the soil and vegetation samples.

Soil profiles were analysed to determine the background soil contribution to the results of the topsoil samples. Susceptibility measurements of these profiles indicate magnetic enhancement of the topsoil. This occurs with the exception of one profile taken adjacent to the power station, where a second peak exists at a depth of approximately 8cm, above a layer of clay. SEM shows that this sample contains iron rich spheres. This may indicate the movement of fly ash through the soil profile, or suggest that the soil has been disturbed.

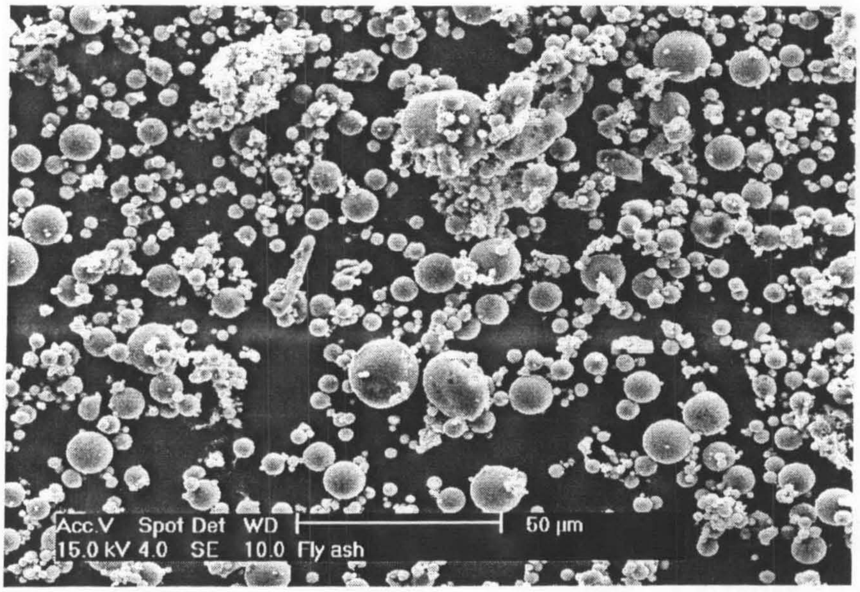

Figure 2. Flyash as seen under the Scanning Electron Microscope. Energy Dispersive X-Ray shows that some of these spheres are iron rich.

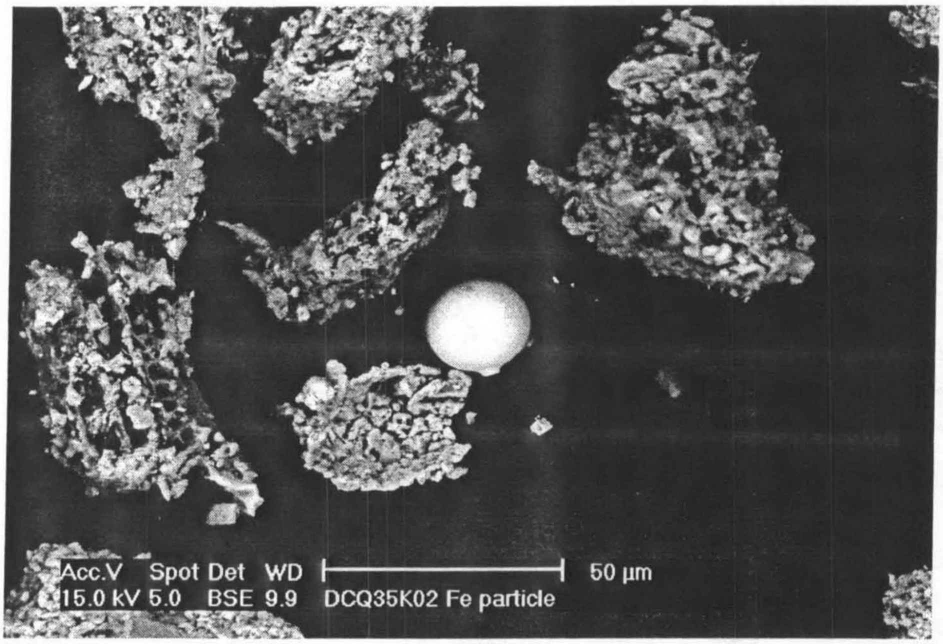

Figure 3. Iron rich sphere identified in particulate matter separated from leaves.

ROCK MAGNETISM AND THE DEEP BIOSPHERE

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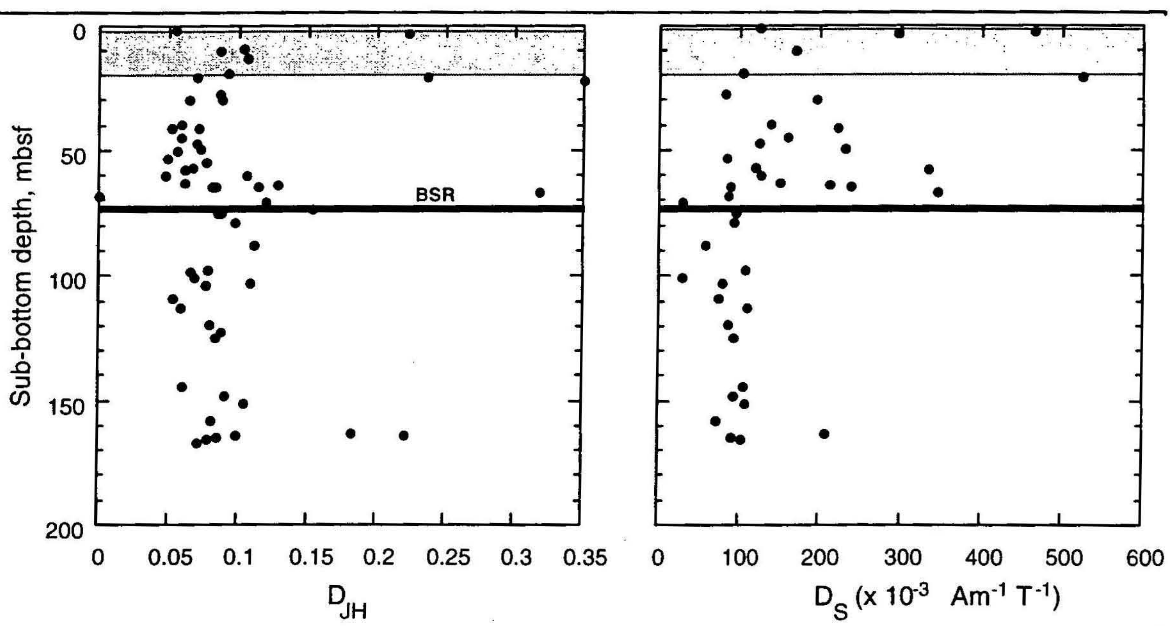
The significance of microbiological activity in the deep subsurface - the "Deep Biosphere" - has only recently been recognised. Much effort is currently being exerted to verify the presence of viable bacteria in sediments deep (up to a km) below the seafloor, and to interpret its consequences for sediment diagenesis, hydrocarbon maturation, and gas hydrate accumulation. Microbial populations involved in these processes deep in marine sediments form a significant proportion (10%, as a rough estimate) of the world's total biomass. Conventional microbiological studies of the deep subsurface rely on determinations of counts of viable bacteria in aseptic subsamples of drill cores, and on measurements of rates and styles of activity in cultures derived from these samples. Such studies, however, require elaborate coring and sampling protocols, are subject to issues of contamination, and represent only an ephemeral record of bacterial activity.

Magnetic minerals, on the other hand, are relatively robust to processes of core recovery, sampling, and storage, yet are known to be modified by subsurface bacterial activity. Rock magnetism has already been shown to preserve a record of bacterial activity associated with sediment diagenesis, fluid migration, and gas hydrate accumulation; current studies are investigating the relationship between bacterial metabolic processes and changes in rock magnetic parameters, with the aim of interpreting records of past bacterial activity from their "rock magnetic fossils".

Bacterial involvement in the reduction of iron oxides to iron sulphides within the zone of active sulphate reduction in the top 20 metres or so of the marine sediment column has long been recognised. Similar bacterially-driven magnetic diagenesis in more deeply buried sediments has only recently been recognised, in part because such sediments are often already strongly reduced. Rock-magnetic parameters, which respond to changes in mineralogy and grain size in the iron oxyhydroxide to pyrite reduction series, are useful proxies for this bacterial activity. Greigite (Fe_3S_4) production, in particular, appears to be closely linked to bacterial activity, and both intracellular and extracellular (dissimilatory) bacterial generation of greigite in sediments has recently been demonstrated. Greigite, like magnetite, is a ferrimagnet, with a high saturation remanent magnetisation. It is thus easily distinguished from pyrite, which is a paramagnet, and so supports no remanence. Greigite can also be distinguished from magnetite by a number of rock magnetic characteristics.

Recent studies of specially sampled ODP cores has established the presence of high populations of viable bacteria to at least 500 metres below seafloor. Samples from ODP Leg 146, on the Cascadia Margin, showed that bacterial populations were strongly enhanced within intervals of methane hydrate accumulation. Rock magnetic analysis of the same sequence established a close correlation between indices controlled by magnetite dissolution and greigite formation and the presence of gas hydrate. Two indices were found to be useful as markers of bacterial magnetic diagenesis: D_{JH} (= $\{J_r/J_s\}/\{H_{cr}/H_c\}$), which increases in response to growth of single-domain sized

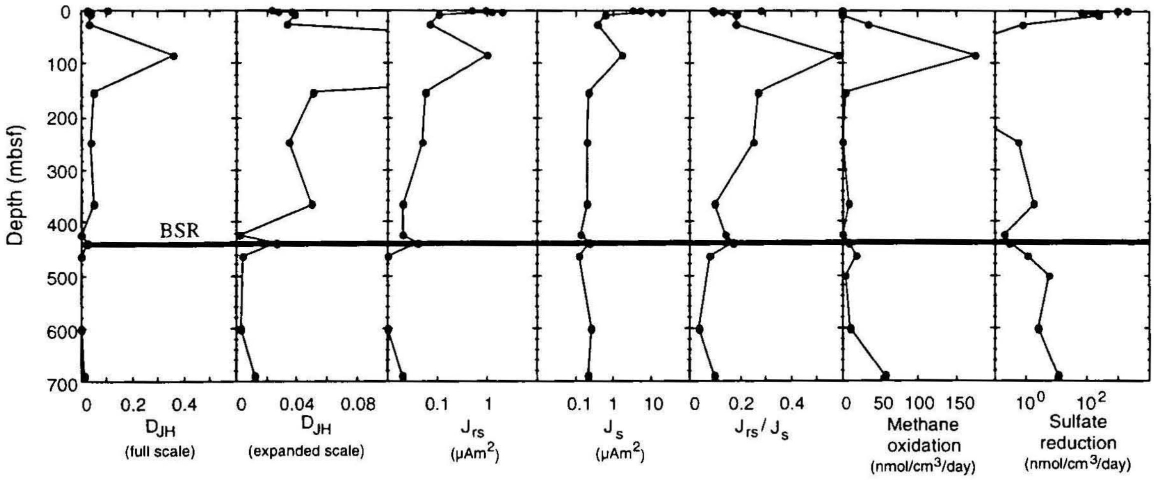
(~1 μm) ferrimagnets, and D_S (= {J_{rs}/k}/H_{cr}), which is higher for single-domain greigite than magnetite. Higher and more scattered values of D_{JH}, D_S, and J_{rs}/k occur in association with gas hydrate, suggesting growth of single-domain greigite (possibly from larger, multidomain magnetite that survived near-seafloor reduction, or from iron from silicate phases). These parameters decline sharply below the base of hydrate stability ("BSR"), suggesting further reduction of greigite to pyrite at this point; intriguingly though, the decline in D_{JH} at site 889 from Leg 146 does not occur at the BSR, but rather about 60 m lower, at a depth predicted by simple temperature-pressure history modelling to have been the former base of hydrate stability during the last glacial (a "fossil BSR"). Bacterial involvement in the generation of greigite in the gas hydrate zone was inferred from these results.



Leg 146, Site 892: relationship between rock magnetism and hydrate concentrations. Hatched region: anomalous near-surface hydrate. BSR: bottom-simulating reflector, marking hydrate accumulation at base of hydrate stability zone.

ODP Leg 164 was the first ocean drilling leg devoted entirely to the study of gas hydrates, and provided the opportunity for co-ordinated rock-magnetic and microbiological sampling, using splits of the same samples. A series of measures of vertical profiles of bacterial activity and metabolism could be compared with the resulting changes in rock magnetic parameters.

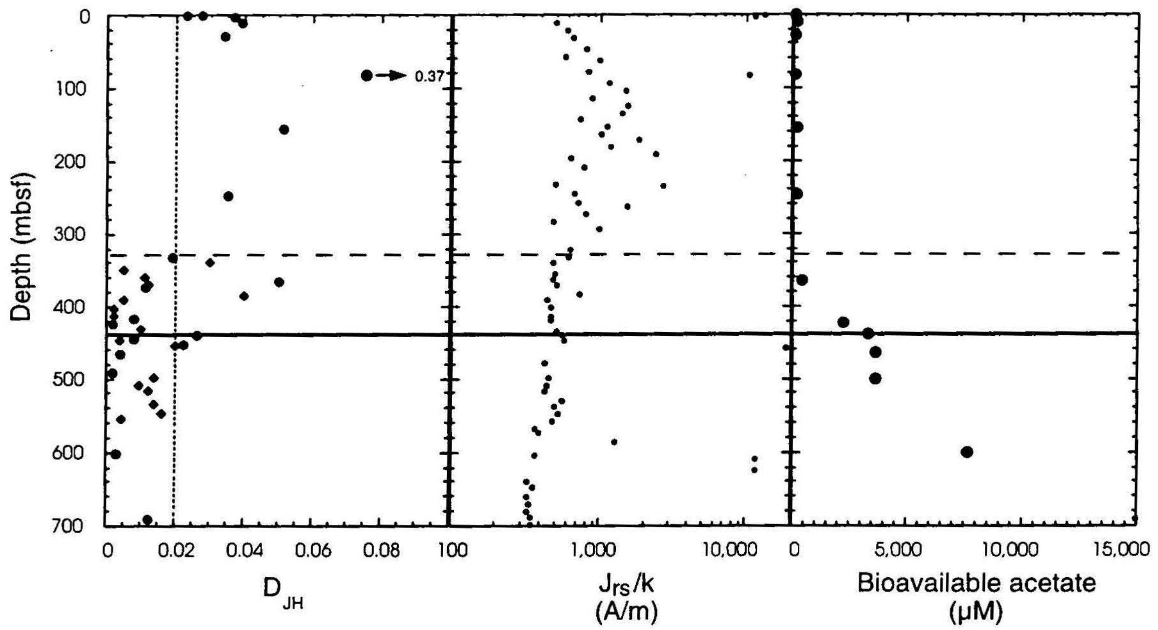
Results showed that bacterial sulphate reduction rates do not correlate with methane oxidation, implying that another electron acceptor must be involved. Methane oxidation does correlate closely with D_{JH}, however, down to the BSR. A large peak is present in both D_{JH} and methane oxidation in the bioturbated horizon at about 80 metres below seafloor. There are also corresponding peaks in J_{rs}, J_s, and the J_{rs}/J_s ratio, indicating growth of a new ferrimagnetic phase. The rock-magnetic peaks can be best explained by the growth of single-domain sized greigite from a paramagnetic precursor, presumably an iron silicate (glauconite?); reduction producing greigite accompanies oxidation of methane, with iron liberated from iron sulphides as the likely electron acceptor.



Leg 164, Site 995: Microbiological and rock magnetic parameters

A second, smaller peak in D_{JH} occurs immediately above the BSR, and is associated with the increase in methane oxidation at this depth. Methane oxidation rates continue to increase, however, in the free-gas interval below the BSR, where D_{JH}, J_{rs} and the J_{rs}/J_s ratio all sharply decrease. Decreases in all three parameters may be explained by further reduction of the greigite produced above the BSR to pyrite immediately below the BSR, as the BSR and accompanying hydrate and free-methane accumulations migrate upwards with continued sedimentation. Why should pyrite formation not occur until the free-gas interval? Greigite is a metastable precursor to pyrite, and its preservation may require restricted availability of H_2S. Sulphate reduction to produce H_2S is renewed in the incubated samples below the BSR, which presumably implies renewed sulphate reduction *in situ* below the BSR. The source of the sulphate is unclear, although it may reflect fluid migration towards the top of Blake Ridge below the trap at the BSR. Resulting H_2S generation may explain the decrease in D_{JH} below the BSR.

Combining data from all of the samples processed for rock magnetism from Leg 164 reveals a more complete picture of the evolution of the magnetic mineralogy. D_{JH} is low throughout the sequence, lower than for sites from the Cascadia margin (Leg 146), suggesting that reduction generally is more complete, with less surviving single-domain greigite or magnetite. D_{JH} decreases to below 0.02 below 460 metres below seafloor; this is close to the multidomain/superparamagnetic field on a Day plot, which is bounded by $D_{JH} = 0.0125$, suggesting that very few single or pseudo-single domain grains of magnetite or greigite survive. Conversely, D_{JH} is consistently greater than 0.02 above about 320 metres below seafloor. This corresponds to the interval on the profile of shipboard measurements over which there are scattered, elevated values for J_{rs}/k, above a logarithmically-declining background trend. This interval also corresponds to a zone of elevated values of bio-available acetate. Increased acetate availability will drive more bacterial activity, and presumably therefore increased reduction of iron phases. This may drive any remaining single-domain magnetite and greigite through to complete reduction to pyrite in some samples, resulting in the scattered very low D_{JH} values, and the reduction of J_{rs}/k to a background trend. Conversely, the local peak in D_{JH} and J_{rs}/k in the methane rich zone on either side of the BSR represents a renewed burst of single-domain greigite generation from a non-ferrimagnetic precursor; high methane availability may have "encouraged" bacteria to utilise oxidised iron in iron silicates.



Leg 164, Site 995: Effect on rock magnetic parameters of (a) appearance of bio-available acetate (dashed horizontal line) and (b) BSR (greyed horizontal line). Vertical dashed line indicates cut-off for SD/PSD grains.

The next step in the understanding of the relationship between bacterial activity and magnetic diagenesis is represented in an experiment currently underway, being conducted jointly by the Geomicrobiology Group at the University of Bristol and the PALM lab at La Trobe University. A slurry of bacteria, sediment, iron oxyhydroxide, sulphate, and organic feedstock, carefully proportioned to maximise the extent of reduction, has been "brewing" over the last 12 months, with samples taken for rock magnetic and sulphur isotopic analysis. Preliminary results confirm a suspicion gathered from the Leg 164 studies, that at high reduction states bacteria cycle sulphur backwards and forwards between pyrite and greigite. This result may have profound implications for bacterial concentration of metals in other sulphide systems, including ore sulphides.

PALAEOMAGNETIC DATING OF PHANEROZOIC WEATHERING IMPRINTS, MOUNT PERCY MINE, KALGOORLIE, WESTERN AUSTRALIA

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Archaean basement rocks at Mt Percy gold mine, in the eastern Yilgarn Craton, have been deeply weathered in a tectonically stable, near-surface environment, possibly for much of the Phanerozoic. Secondary iron oxides in the weathered regolith acquired a chemical remanent magnetisation at the time they formed. Ages of weathering-induced magnetisation are estimated by comparison with the Australian Apparent Polar Wander Path (AAPWP). Resultant ages indicate, for the first time, that Cainozoic, Mesozoic and Paleozoic weathering imprints are recorded in regolith at a single site.

Geological setting

Mount Percy gold mine is located about 2 km northeast of the centre of Kalgoorlie, at the northern end of the Kalgoorlie-Kambalda greenstone sequence. Archean rocks at Mount Percy comprise ultramafic to mafic volcanics, sediments, doleritic sills and felsic porphyries, which occur in the hinge zone and steeply east-dipping limb of the Kalgoorlie Anticline (Johnston et al. 1990). The sequence is cut by a series of north-trending, west-dipping dextral faults. Primary gold mineralisation is largely confined to a series of irregular, mostly steeply dipping lenses within the porphyries and adjacent alteration zones. A thick "lateritic" weathering profile extends to depths of 50-60 m with minor oxidation extending to 100 m or more along fractures. The profile consists of lateritic duricrust and gravels, up to 5 m thick, underlain by about 15 m of mottled clays which grade down into an oxidised saprolite zone some 40-50 m thick (Butt 1998).

Samples and laboratory measurements

Specimens of oxidised saprolite were collected at six sites. Two sites (11 and 13) were porphyry saprolite; four sites (29, 31, 32, 33) were ultramafic or mafic saprolite. At each site the wall of the mine pit was cut back with a spade to expose a fresh, sub-vertical face. Small cube-shaped pedestals were carved with a sharp knife, onto which 6 cm^3 plastic boxes were carefully fitted. Before removal from the face, samples were oriented with a Brunton compass, corrected for local magnetic declination. Red-weathered materials were preferentially sampled as previous experience had indicated that they were likely to be hematitic, and hence carry a stable remanence (a detailed rock magnetic study of the samples is being undertaken by P. Mathe, CEREGE, and will be reported elsewhere).

Samples were subject to stepwise demagnetisation, using both thermal and alternating field (a.f.) techniques. A pilot study of sample behaviour indicated that thermal demagnetisation generally yielded more consistent results, and hence a.f. demagnetisation was used only for samples which were too friable for thermal measurements. Remanences were measured on an ScT 2-axis cryogenic magnetometer at the AGSO/ANU Black Mountain Palaeomagnetic Facility, Canberra. Magnetic susceptibilities were measured on a Digico bulk susceptibility bridge, to monitor possible mineralogical changes with increasing temperature. Characteristic Remanent Magnetisations were identified on orthogonal plots and directions calculated by Principal

Component Analysis (Kirschvink 1980).

Results

A summary of palaeomagnetic results from Mt Percy mine is given in Table 1. Representative vector component plots are shown in Fig.1.

Site 11: A well defined intermediate (IT) and high (HT) temperature component (Fig 1E) comprises both normal and reversed polarity specimens. The resultant pole intersects the Mesozoic segment of the AAPWP (Embleton 1981) in two places – indicating either a mid Cretaceous or a Jurassic age. The samples at site 11 contain both normal and reverse polarities, whereas the mid Cretaceous is characterised by normal polarity field directions only (e.g. Opdyke & Channell 1996). A Jurassic age is thus indicated.

Site13: Two magnetisation components are present (Fig 1B). The HT component yields a pole consistent with a Carboniferous age by comparison with the Palaeozoic AAPWP of Li et al. (1990). The LT component yields a pole that is statistically indistinguishable from a weathering overprint pole determined from Permian to Cretaceous sediments in the Perth Basin (Schmidt & Embleton 1976) – see Table 1. Comparison with the Cainozoic segment of the AAPWP (Idnurm 1985, 1994) indicates a late Miocene to early Pliocene age for the overprint pole, here assigned a nominal age of 5 Ma.

Site 29: Two magnetisation components are present (Fig 1A). The LT component is similar to the HT component at Site 13, and hence may be of Carboniferous age. The HT component yields a pole position which lies on the latest Cretaceous to early Palaeocene (60±10 Ma) part of the AAPWP of Idnurm (1985,1994). This pole is similar to the pole determined for the Morney weathering profile in the Eromanga Basin, southern Queensland (Idnurm & Senior 1978) - see Table 1.

Site 31: All specimens are of reversed polarity, and yield a well defined HT component (Fig 1C) that gives a statistically similar pole (and hence age) to the HT pole determined for Site 29. (i.e. 60±10 Ma)

Site 32: Specimens have four component magnetisations (Fig 1D; Table 1). The IT component is statistically indistinguishable from the Mesozoic IT/HT component identified at site 11. That this component is present in two adjacent, contrasting lithologies, supports the field interpretation that it is not a primary magnetisation component inherited from the rock, but rather is a secondary, weathering-induced overprint. One HT component yields a pole position well away from the Phanerozoic APWP, and may represent a primary magnetisation component inherited from the Archaean bedrock. The LT component also yields a pole away from the Phanerozoic AAPWP, and may represent a viscous component of no geological significance.

Site 33: A single, well defined HT component of normal polarity is present in all four specimens (Fig 1F), yielding an apparent mid-Tertiary age. The pole is similar to one of the HT components identified in five specimens at Site 32, but all components are close to the modern, normal field direction; a mining-induced origin cannot be ruled out.

Discussion and conclusions

Stratigraphic evidence for the ages of regolith deposits in the Kambalda area of the eastern Yilgarn was summarised by Clarke (1994) as follows:

9. Mid and late Eocene marine sediments occur in paleovalleys cut into older weathered regolith which is therefore of pre-mid Eocene age. Weathering profiles which later developed into the palaeovalley sediments are therefore of post-late Eocene age.
10. The headwaters of northward-flowing paleovalley drainage networks extend south to, and are truncated by, the present coast. If the headwater regions lay to the south, they must have been in Antarctica prior to the start of continental rifting in the Jurassic. The regolith into which the palaeovalleys were incised is therefore at least as old as Jurassic.

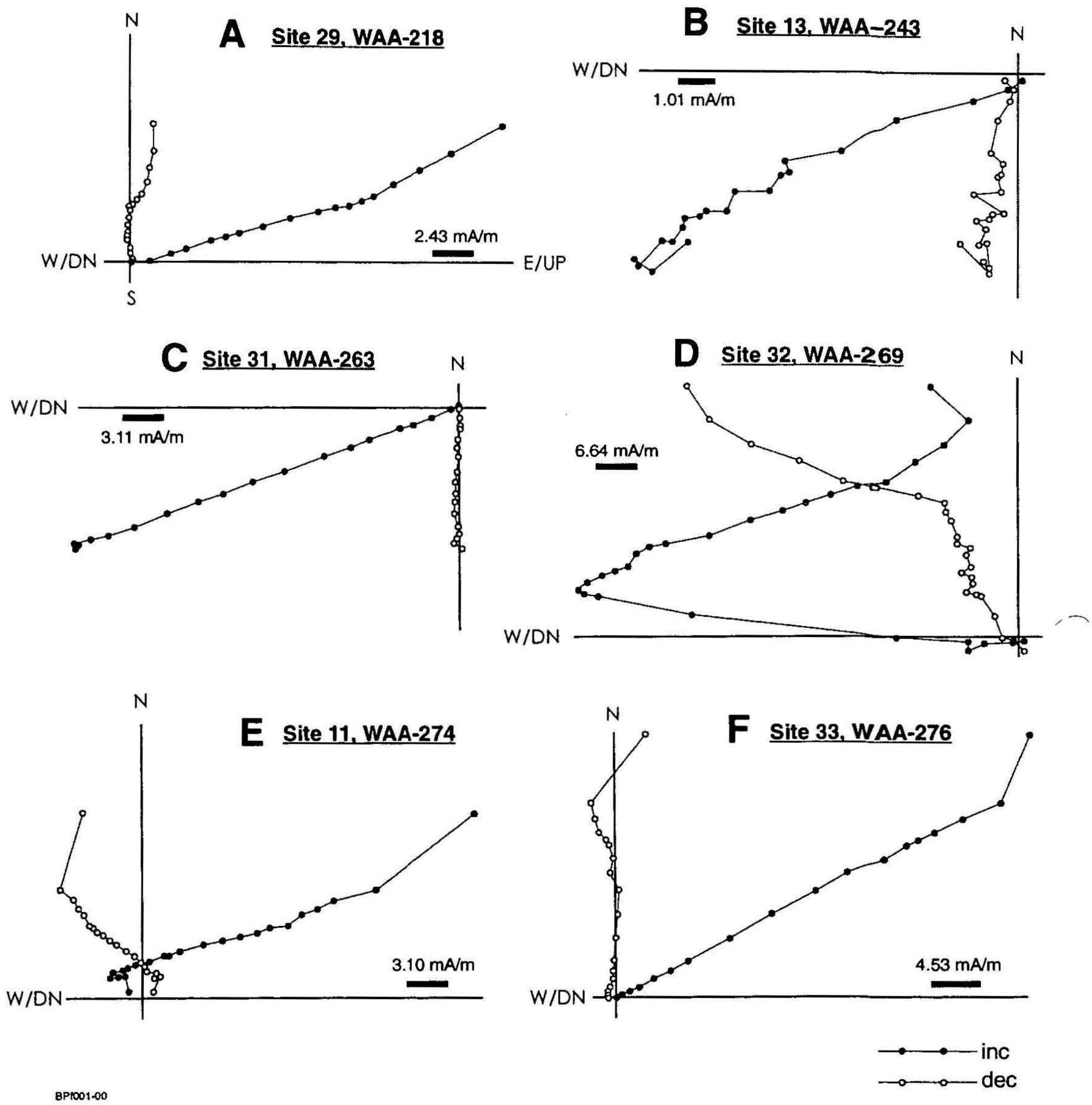

Figure 1. Representative orthogonal vector plots for specimens from Mt Percy.

The few published numerical age estimates for weathered regolith in the Yilgarn range from mid to late Tertiary: Oxygen isotope analyses of kaolinite in weathering profiles developed on granite at Coolgardie and Collie indicate a post-mid Tertiary age, i.e. less than 30-40 Ma (Bird & Chivas 1989). Bird et al. (1990) reported a K/Ar age of 4.87±0.06 Ma (early Pliocene) for alunite from"kaolinized Archean igneous and metamorphic rocks" near Kanowna. K/Ar and $^{40}Ar/^{39}Ar$ ages, range from 1.4 to 36 Ma, for potassium-bearing Mn oxides in weathering profiles across the Yilgarn Craton (Dammer et al. 1999).

The palaeomagnetic results imply that regolith weathering has been an ongoing, though not necessarily continuous process at Mt Percy since the Carboniferous. Palaeomagnetic ages of Cainozoic (5 and 60 Ma) and Mesozoic (Jurassic) weathering imprints are broadly consistent with other regolith age estimates from the Yilgarn Craton. Such imprints may represent periods of more intense and/or deeper weathering which are linked to major changes in climatic boundary conditions. It is unknown whether the regolith profile at Mt Percy has been continuously subaerially exposed since the Carboniferous, or has experienced episodes of burial and exhumation, such as documented using paleomagnetic and apatite fission track data in eastern Australia (e.g. O'Sullivan et al. (2000).

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TABLE 1: Summary of paleomagnetic results from weathered saprolite, Mount Percy mine, WA.

SITE	LOCATION (depth)	COMP[1]	N(+)[2]	REMANENCE DIRECTIONS[3] Decl.	Incl.	k	α_{95}	SOUTH POLE Long.	Lat.	K	A_{95}	AGE
	Mount Percy (121.5°E, 30.7°S)											
11	Mystery Pit (12 m)	IT,HT	19(5)	321.2	-68.0	45.3	5.04	164.8E	54.7S	45.3	5.04	Jurassic
13	Mystery Pit (35-40 m)	LT	9(0)	000.4	-56.1	20.0	11.79	107.9E	82.4S	13.4	14.61	5-10 Ma
		IT,HT	28(28)	200.6	62.2	101.1	2.72	076.8E	69.4S	53.3	3.77	Carb.
29	Union Club Pit (15-20 m)	LT	7(0)	021.8	-59.3	77.3	6.91	66.7E	69.9s	43.2	9.28	Carb?
		HT	7(0)	007.5	-73.6	375.5	3.12	113.7E	60.6S	134.1	5.23	60 Ma
31	Far East Porphyry Pit (20 m)	HT	12(12)	184.5	73.5	942.4	1.41	116.7E	61.2S	332.8	2.38	60 Ma
32	Mystery Pit (5-10 m)	LT	5(0)	295.9	-29.2	212.1	5.27	210.4E	30.0S	223.4	5.13	?
		IT1	4(0)	326.7	-66.1	53.1	12.72	164.4E	59.4S	28.4	17.54	Jurassic
		HT1	5(0)	015.5	-67.3	169.9	5.89	95.3E	67.3S	71.1	9.14	?
		HT	7(7)	320.4	83.4	205.5	4.22	292.7E	20.5N	55.5	8.17	Arch?
33	Mystery Pit (12 m)	HT	4(0)	009.7	-63.5	1247	2.60	96.4E	73.7s	532.7	3.98	?
	Perth Basin (Schmidt & Embleton 1976)											
PB	Permian to Cretaceous sediments	HT	128(?)					109.9E	82.7S		2.4	5-10 Ma
	Morney profile, Qld (Idnurm & Senior 1978)											
MP			37(17)	017.8	-68.3		2.4	118.5,	59.8		3.8	60 Ma

Notes: [1] N = number of specimens; (+) = number of specimens with positive inclination
[2] LT = low temp component; IT = intermediate temp component (<580°C); HT = high temp component (>580°C)
[3] k and K are Fisher precision parameters; α_{95} and A_{95} are semi-angles of 95% confidence.

PALAEOMAGNETIC CONSTRAINTS FOR THE BUILDING BLOCKS OF RODINIA

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Although there are several versions of the composition and configuration of the late Proterozoic supercontinent Rodinia (e.g. Hoffman 1991; Dalziel 1997; Weil et al. 1998), the main features are the same in all of them: Laurentia, the core of Rodinia, is surrounded by other blocks. East Gondwanaland, according to SWEAT hypothesis (Moores 1991) was connected to its W-SW margin, Amazonia - Rio de LaPlata craton(s?) and Baltica – to the E-SE margin, and Siberia – to the N margin (present-day orientation). The positions of other cratons – Kalahari, Congo/San-Francisco, West Africa, N. and S. China and others are less certain. The palaeomagnetic data provide quantitative constraints for the Precambrian palaeoreconstructions. We propose the following configuration of Rodinia (at *ca.* 1020 Ma) based mainly on palaeomagnetic data (Fig.1). Unfortunately, these data are distributed very non-uniformly in time and space. The majority of palaeomagnetic results for Rodinian times (roughly between 1000 and 750 Ma) came from Laurentia. McElhinny and McFadden (1999) did what seems to be the most reasonable analysis of these Laurentian data, and we have used their APWP as a framework for Rodinia reconstructions. Powell et al. (2000) analysed the APWP of Kalahari for 1100 - 1000 Ma and made the suggestion that this craton was attached to East Gondwanaland in Rodinia times - a position "reversed" with respect to other reconstructions with its Namaqua-Natal foldbelt facing away from the core of Rodinia. Unfortunately, there are no reliable palaeomagnetic data from Kalahari for younger Neoproterozoic times. Probably the next most valuable Neoproterozoic APWP is that of Baltica (e.g. Pisarevsky & Bylund 1998). The comparison of Grenvillian and Sveconorwegian Loops leads to that Baltica is not attached to E.Greenland (Dalziel 1997), but more to the south with the Rockall Plateau in between, which fits to the models of Park (1992) and Starmer (1996). The posititons of Amazonia and Rio de La Plata must correspondingly be shifted to the present south. The position of East Gondwanaland is mainly based on the palaeomagnetic results from Mount Isa and Stuart Dykes (Idnurm et al. 1995). Recent palaeomagnetic results from Siberia (Pisarevsky et al. 1997; Pisarevsky et al. 2000) together with new geochronological information (Rainbird et al. 1998), point in favour of Laurentia - Siberia fit suggested by Hoffman (1991) and supported by Pelechaty (1996). The few palaeomagnetic data from the Congo/San-Francisco craton support its closeness to Amazonia *ca.* 1000Ma, but with different orientation than in their Gondwanaland fit. The position of Western Africa is questionable – its pre-Rodinia attachment to Amazonia suggested by geological comparison contradicts the few available palaeomagnetic data.

Reconstructions made with the PLATES program from the University of Texas at Austin.

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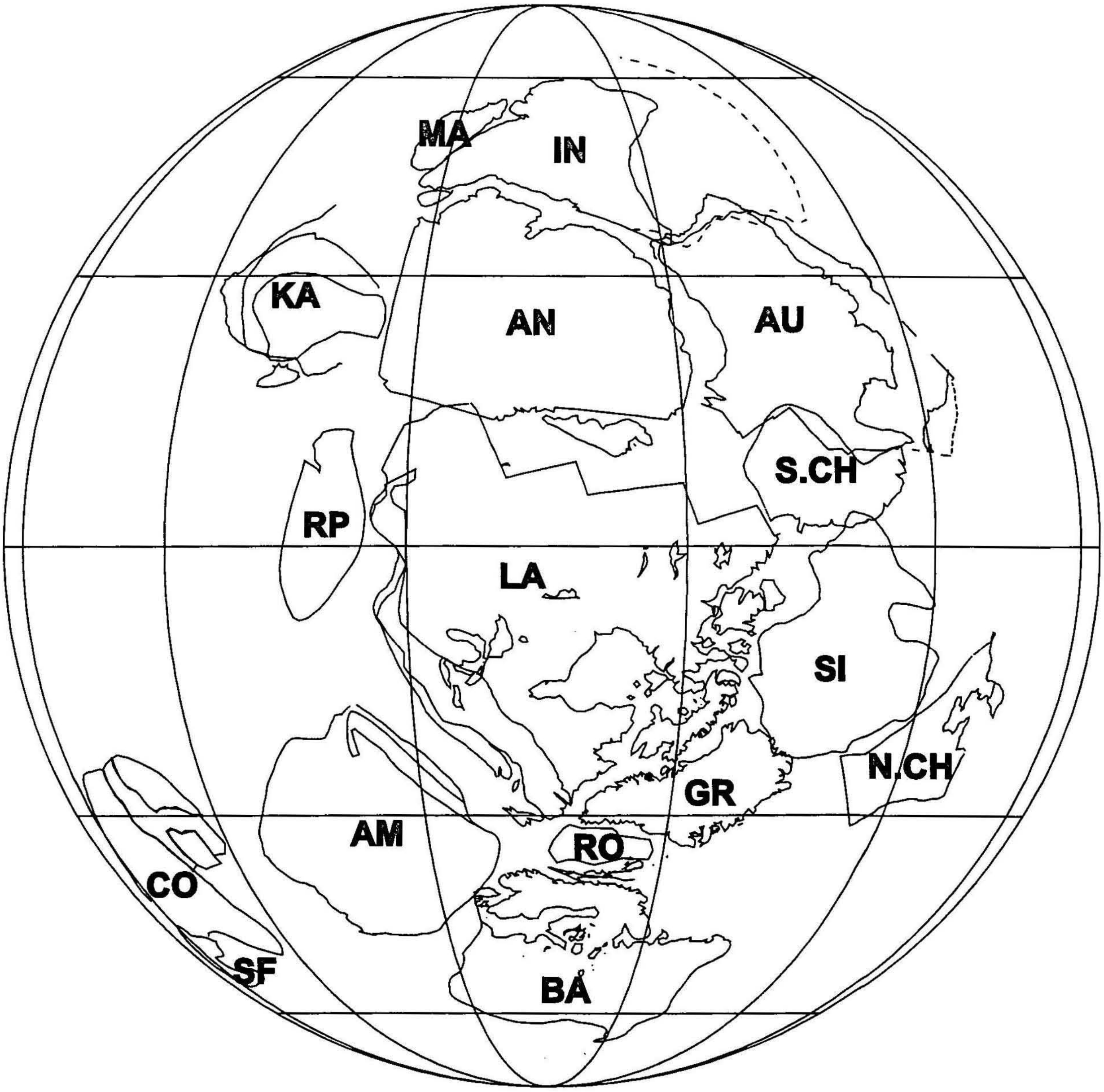

Figure 1 Rodinia at 1020 Ma. **AM** - Amazonia, **AN** - Antarctica, **AU** - Australia, **BA** - Baltica, **CO** - Congo, **GR** - Greenland, **IN** - India, **KA** - Kalahari, **LA** - Laurentia, **MA** - Madagascar, **N.CH** - North China, **RO** - Rockall, **RP** - Rio de La Plata, **SF** - San Francisco, **S.CH** - South China.

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STRATIGRAPHIC EVIDENCE FOR REDEFINITION OF THE BASE OF THE KIAMAN REVERSED SUPERCHRON

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Redefiniton of the base of the Kiaman was required after the age of the Paterson Volcanics, the unit originally used to define the base, was found to be late Visean rather than late Westphalian. Strata in the southern part of the Rocky Creek Syncline in northern NSW provide both the stratigraphic and geochronological evidence for the revised boundary. The succession investigated ranges in age from middle Visean to Westphalian, and comprises the Caroda Formation, Spion Kop Conglomerate, Ermelo Pyroclastics, Clifden Formation, Rocky Creek Conglomerate and Lark Hill Formation. The majority of these units are fluvial and volcanogenic, with parts of two of the conglomerates glacigene in origin. Ignimbrites are common in all except the Spion Kop Conglomerate and provide the bulk of palaeomagnetic data, as well as samples for SHRIMP zircon U-Pb dating using the SL13 standard.

The base of the Kiaman is defined within the Clifden Formation between the last unit with normal polarity, the Wanganui Andesite Member (319.2 ± 3.2 Ma), and the first widespread reversed overlying unit, the Peri Rhyolite Member (317.8 ± 2.8 Ma). Two other ignimbrites have a bearing on the exact location of the boundary. The Glen Idle Rhyolite Member, which is reversed, is located 400 m beneath the Peri Rhyolite in the lower part of the Clifden Formation, but has an outcrop length of 1.25 km, compared with 100 km for the Peri Rhyolite. Reversal may have taken place slightly earlier than the record within Peri Rhyolite. A single outcrop of an unnamed red ignimbrite in an area of faulting and poor outcrop on the Barraba-Boggabri road could, from air photo interpretation, be stratigraphically younger than the Peri Rhyolite. The red ignimbrite has normal polarity. However, no other red ignimbrites with normal polarity occupy a comparable stratigraphic position, and the mineralogy resembles that of basal parts of the Wanganui Andesite. In the absence of further evidence, we take the base of the Kiaman Reversal between about 318 and 316 Ma or within the upper part of the Namurian Stage of Europe, the only region with which the Australian late Carboniferous can be correlated. Reinterpretation of the palynofloral record of the Maritimes region of eastern Canada suggests that the 318-316 Ma interval may coincide with that between the tops of the N6 and N8 Normal Zones in Nova Scotia. The Kiaman Reversal is younger than the base of the type non-marine Pennsylvanian in the Central Appalachians, USA, but cannot be related with the mid-Carboniferous boundary now taken as the base of the Pennsylvanian Subsystem of the Carboniferous.

SECULAR VARIATION FROM ITALIAN LACUSTRINE AND MARINE SEDIMENTS: CORRELATING RECORDS OF ENVIRONMENTAL CHANGE

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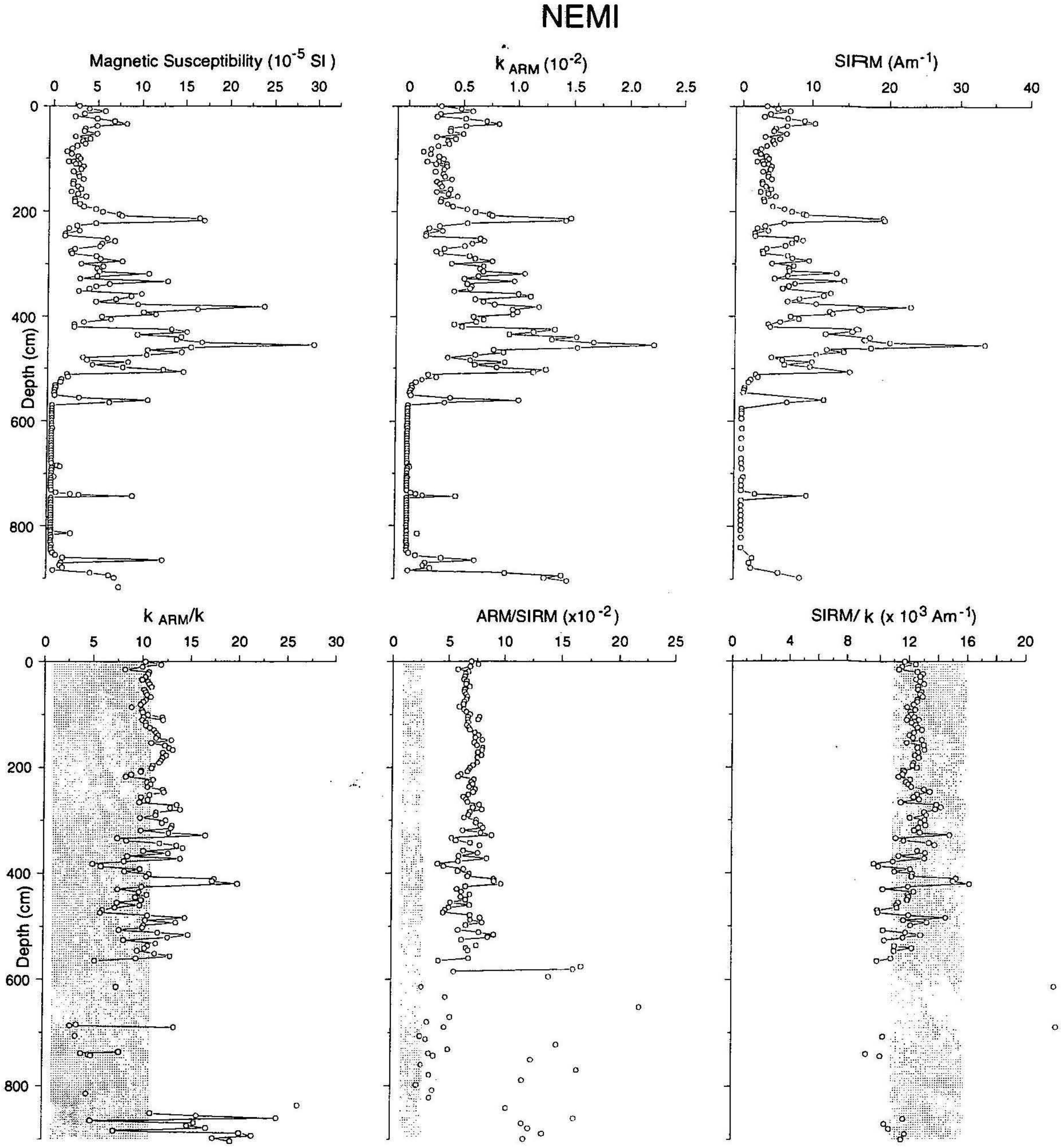
In spite of the potential problems associated with the acquisition and retention of remanence in sediments, the often semi-continuous nature of their accumulation makes them prime targets for studies of long-term trends in secular variation. The Holocene provides us with an excellent opportunity to investigate the fidelity of these sedimentary archives. Not only are chronologies easier to establish, such studies also allow us to investigate the influence on palaeomagnetic records of environmentally-moderated variations in magnetic mineralogy.



Here I will present Holocene secular variation and environmental magnetic data from sediment cores collected in Lakes Albano and Nemi, and in the shallow water off the East Coast of Italy. These records were obtained as part of the recent PALICLAS (PALaeoenvironmental analyses of Italian Crater Lake and Adriatic Sediments) initiative, a multi-disciplinary investigation focused on the Late Glacial and Holocene climate of Central Italy. Secular variation curves were established to provide correlations between the two areas and as independent support for the radiocarbon and tephra-based chronologies. Complementary rock magnetic measurements were used to investigate the origin of the sedimentary remanence at each site and to provide environmental magnetic data as support for the other climate-proxy data.

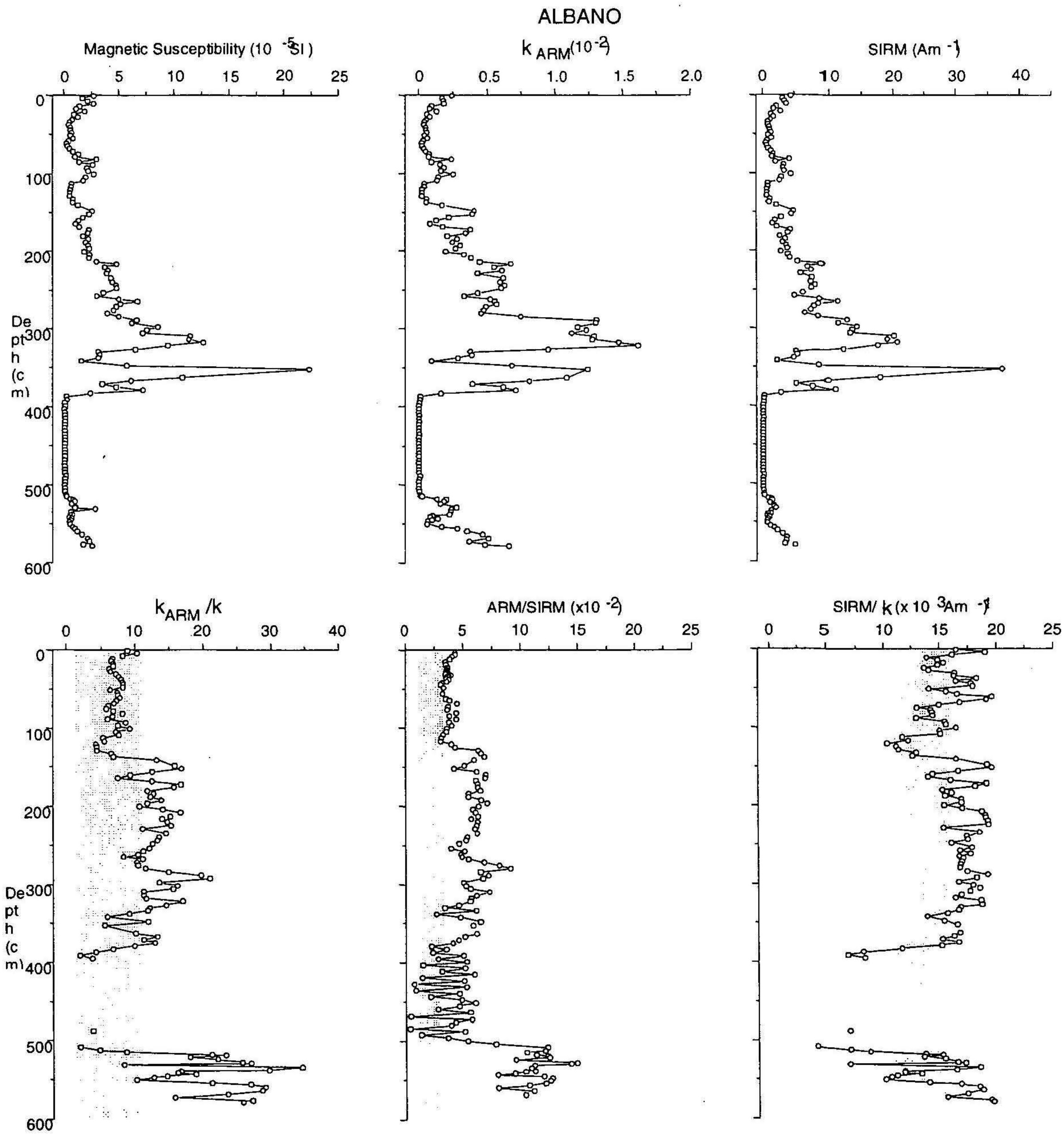


Figure 1. Rock magnetic data from lakes Nemi (opposite page) and Albano (above). The grey envelopes reflect the range of values displayed by modern catchment soils

The two lakes are separated by only a few km, both are hydrologically closed, and both catchments have identical rocks and soils. Consequently broad correlations can be established rapidly using magnetic susceptibility data, although additional magnetic analyses show that subtle differences exist between the magnetic mineralogy of the two lake cores (Fig. 1). This may reflect the different water depths of the two lakes or the different location of each core with respect to the respective lake margin. A tephra has been identified in both cores and has been identified as the 3670 BP 'Avellino' tephra of Somma-Vesuvio. The magnetic carriers in both cores are derived from two sources, most likely representing a detrital and authigenic (bacterial magnetite?) signal. The relative contribution of each component varies throughout both cores making them unsuitable for relative palaeointensity estimates. However stable palaeomagnetic directions can be obtained from the majority of the sediment in both cores, the only exception being a zone of reductive diagenesis present in both cores.

Rock magnetic data cannot provide a correlation between the Adriatic core and the lake cores. The Adriatic core contains a more regional record of environmental change whilst the lake cores will be heavily influenced by changes within their catchments. The dominant magnetic features in the Adriatic core are four peaks associated with tephra (Fig. 2). The oldest of these has been identified as the 'Avellino' tephra found in the lake cores. In common with the lake cores the magnetic carriers are attributed to varying contributions from a detrital and authigenic source. This again makes the core unsuitable for relative palaeointensity estimates, but stable palaeomagnetic directions are obtained from the whole core.

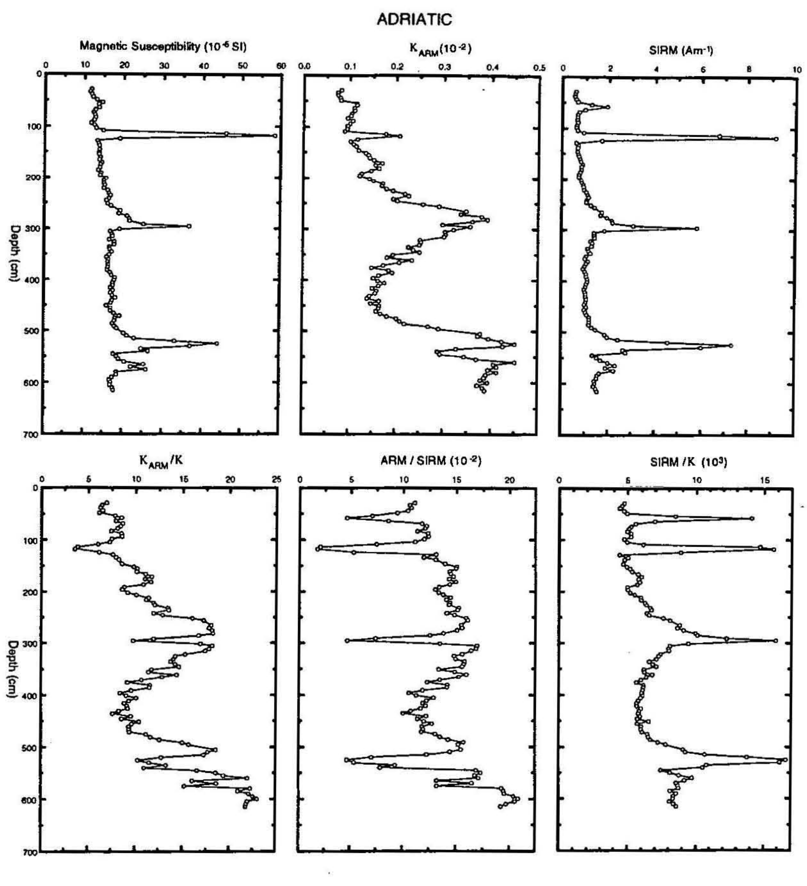


Figure 2. Rock magnetic parameters for the Adriatic core.

Figure 3 shows a correlation between the two lakes and the Adriatic based on the magnetic inclination. Also shown is the Lake Windermere (UK) Holocene record. In places the Lake Albano inclination seems too steep, and this is attributed to sediment disturbance during transport. However the disturbance has not been sufficient to totally distort this record, as can be seen from the correlation between the Albano and Windermere declination records.

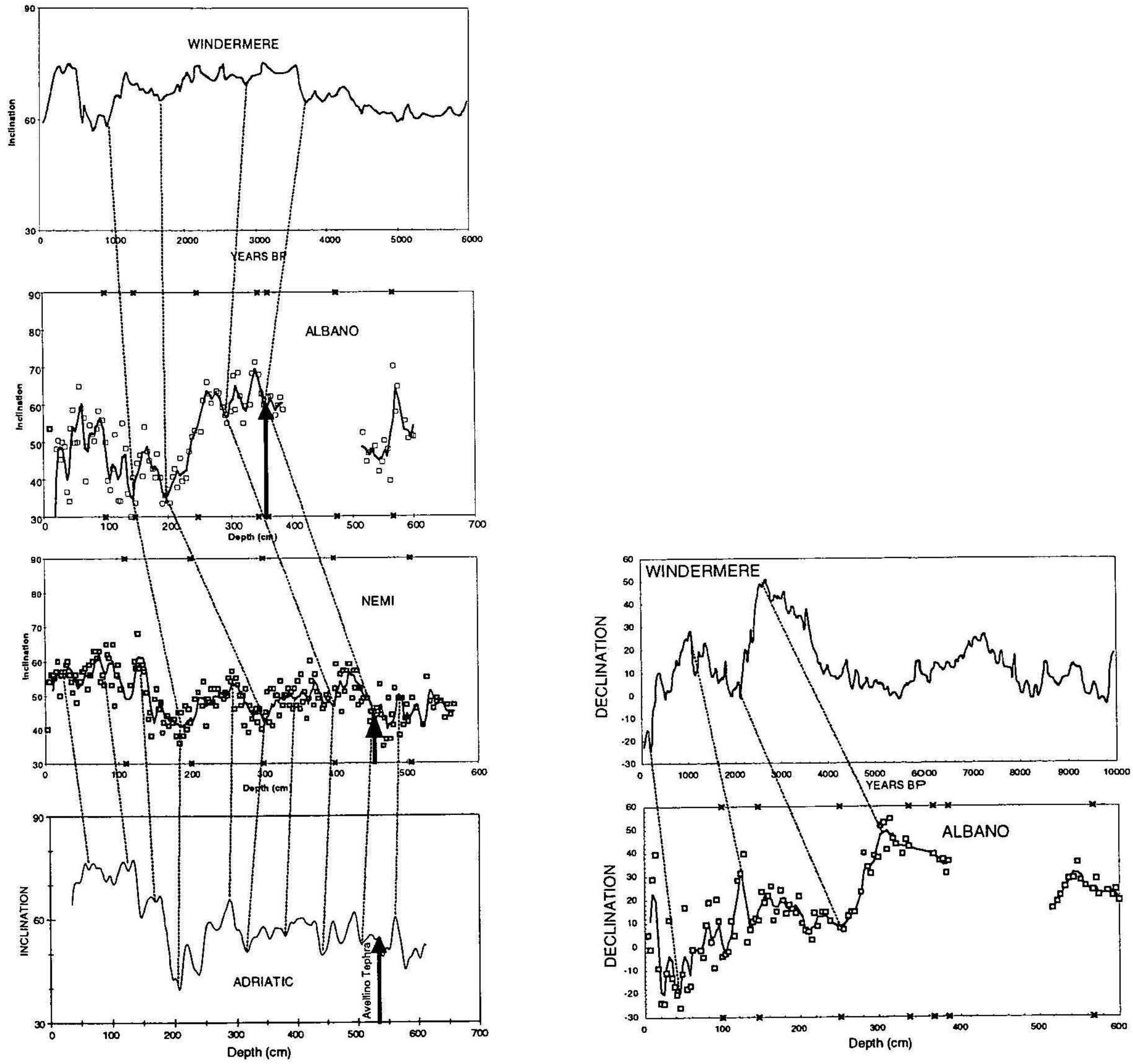


Figure 3. Palaeomagnetic correlation using inclination and declination records.

ENVIRONMENTAL MAGNETISM: WHAT IT IS AND WHAT IT DOES

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Environmental magnetism is a broad discipline with application in many areas of science. It utilises the fact that anthropogenic activities and natural environmental processes can modify the magnetic content of the atmosphere, hydrosphere and lithosphere. Using a range of standard, and typically rapidly applied, techniques, the chemistry, grain-size and concentration of magnetic minerals can be identified and related to environmental factors. In this way the magnetic minerals are providing a proxy record of these activities and processes. Although magnetic techniques can be applied and interpreted in isolation, they are far more effective when combined with additional diagnostic techniques that can be used to calibrate, or confirm, the magnetic interpretation.

Areas in which this discipline is prominent include the provision of climate change data, the sourcing of sediments in rivers, lakes and oceans, and the identification of pollutants in the environment. The first two areas are being addressed by other talks in this session, so for this introduction I will only touch briefly on these topics and concentrate on recent developments in the area of pollution studies. This will include examples from former Soviet block countries, in which environmental degradation is a serious health issue, and from the more advanced industrial nations in which it is a significant political issue. Hopefully the talk will illustrate the utility of magnetic techniques and promote their use as rapid tools for environmental monitoring.

PALAEOMAGNETISM AND ROCK MAGNETISM OF PALAEOPROTEROZOIC IRON-FORMATIONS: THE FRERE FORMATION, NABBERU PROVINCE, WA

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We are investigating the palaeomagnetism and rock magnetism of granular and banded iron formation from the ~2 Ga Frere Formation in the Earaheedy Basin, Nabberu Province, WA, as part of a global study of iron formations funded by ARC. The present study is the first palaeomagnetic and rock magnetic investigation carried out in the Nabberu Province. The palaeomagnetic data will help in understanding the palaeogeography of the iron formation, while the rock magnetic data will have application in exploration strategies in the Nabberu Province and elsewhere.

In 1999 we obtained oriented cores of unweathered granular and banded iron formation from the Frere Formation by drilling two diamond drill-holes each 120 m deep located near the Gunbarrel Highway 200 km east of Wiluna. The area selected for drilling is outside the zone of metamorphism that affects the northwestern part of the Earaheedy Basin. The holes were drilled on each limb of an anticline to enable a fold test to be conducted to constrain the timing of the remanent magnetisation. The rocks at the drill sites and regionally in the Earaheedy Basin are weathered to a depth of ~60 m, confirming that the drilling was essential to obtain fresh iron formation suitable for magnetic studies.

Anisotropy of magnetic susceptibility (AMS) measurements for the iron formation show a primary fabric indicating that the Frere Formation has escaped metamorphic effects in the area where we drilled. The AMS essentially reflects primary bedding planes with the minimum susceptibility axes defining poles to planes. The results can be used to accurately define bedding, which will assist in the execution of a fold test. In addition, the magnetic mineralogy of the Frere Formation was studied using a Variable Field Translation Balance. The predominant magnetic mineral is hematite but a small amount of magnetite also is present in some samples.

Palaeomagnetic results to hand imply an interesting relationship with the magnetic record for the Hamersley Iron Province. Based on demagnetisation so far, three components of remanent magnetisation can be recognised in the Frere Formation: one component is probably a viscous remanent magnetisation (VRM) close to the Earth's present field direction, and the other is an older component that is directed upward with an inclination of about –50° to the northwest. This ancient component is predominantly of one polarity and closely resembles that found in some iron-ores from the Hamersley Basin (e.g. Mt Tom Price) and as overprint magnetisations in the underlying Fortescue Volcanics. The interpretation of this magnetisation in the Earaheedy Basin and the similarity with Hamersley Basin magnetisations is in progress. A fold test on the remanence directions from the two limbs of the anticline we drilled has yet to be carried out so at this stage the relationship between the magnetisation and Stanley folding in the Earaheedy Basin is not known. Some samples alter chemically on heating producing magnetite which is prone to acquiring spurious remanence in the laboratory. Thermal demagnetisation will be completed by mid-year using an automatic low-field alternating field (AF) demagnetisation step, that has been added as an option to the 2G magnetometer acquisition program, prior to each measurement. It is hoped that this will erase spurious magnetisations acquired by the secondary magnetite.

DEVELOPMENT OF GONDWANA'S PALAEOZOIC APPARENT POLAR WANDER PATH

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This abstract borrows rather heavily from an earlier paper (Schmidt et al. 1993) but is justified since it is mainly an historical sketch and many of the issues addressed then are still current. I apologise if it seems a little dated but I've got a day-time job which precludes, or at least limits, these indulgences.

There would appear to have been a great deal of progress refining Gondwana's apparent polar wander path since the first compilation by Irving and Green (1958). However, the path is still known only rudimentarily. In a Gondwana reconstruction the Cambrian is somewhere near north Africa, the Permian is close to Australia and there is controversy concerning how the path gets from one to the other. Some workers prefer a simple path crossing Africa from the northwest to the southeast, discarding pole positions from the possibly allochthonous Tasman Fold Belt of eastern Australia. The implications of the different models are of major global palaeogeographic and tectonic significance. Some models suggest only small oceans between Laurentia and Gondwana throughout the Palaeozoic, while others suggest a wide oceanic separation existed in the Devonian-Carboniferous. There is an urgent need for reliable Palaeozoic palaeomagnetic poles from the Gondwana continents.

The first pole path compiled by Irving and Green (1958) is remarkable in that it was based on natural remanent magnetisations (NRM), that is, data without palaeomagnetic cleaning. There followed a path proposed by McElhinny et al. (1968) which was based on African data that showed the same general trend as the 1958 path. This confirmed the longevity of Gondwana, at least for the Palaeozoic. The next development was the allochthonous model of Embleton et al. (1974) and McElhinny and Embleton (1974) in which the then recent data from Middle Palaeozoic rocks of the Tasman Fold Belt were seen as evidence for displaced terranes. A disjunction was recognised between the Early Palaeozoic poles of cratonic Australia and the Mid-Palaeozoic poles from the Tasman. It is worth remembering that this model pre-dated the wide acceptance of allochthonous terranes, especially from the Mesozoic/Cainozoic Cordillera of North America. Next Schmidt and Morris (1977) pointed out that by using the anti-poles of the Early Palaeozoic poles, a continuous path could be constructed utilising all the data without a disjunction. This model advocated the opposite geomagnetic polarity for the Early Palaeozoic compared to that conventionally used, i.e. the 'reverse polarity option'. Another continuous path model proposed that retained the original polarity convention was that of Morel and Irving (1978). In essence, this model recognised the possibily (probability?) that there are gaps in the record and disjunctions are inevitable.

Klootwijk (1980) put forward a pole path which did not directly address the polarity problem, or the origin of the Tasman Fold Belt, but added considerable detail to the Early Palaeozoic. A period of pronounced overprinting was recognised during the Cambro-Ordovician Delamerian

Orogeny of South Australia yielding magnetisation directions not previously reported for the Australian Palaeozoic. Based on new data from the Tasman Fold Belt, Goleby (1980) produced a path with a loop similar to that of Morel and Irving's, adding support for an autochthonous Tasman Fold Belt. The reality of this loop was apparently confirmed by Klootwijk and Giddings (1988), although these workers maintain that it is the record of Kanimblan (mid-Carboniferous) overprinting throughout the southern Tasman Fold Belt.

Since 1988 there have been several more 'refinements' to the Gondwana Palaeozoic APWP. Based on geological considerations and the appearance of some new Silurian and Devonian data from Australia and Africa, Schmidt et al. (1990) supported the autochthonous model but added the caveat that there was a long segment of APWP in the Ordovician-Silurian time that is not represented by any reliable data. Bachtadse and Briden (1991) argue for a conservative pole path, ironically similar to the 1958 path, dismissing as suspect all poles from the Tasman Fold Belt rock units older than Carboniferous (at least in the context of Gondwana). Then, in a synthesis of global data, Van der Voo (1992) proposed a "filtered" path which nevertheless recognises an autochthonous Tasman orogeny but differs from the previous paths in detail, particularly the segment over which the path is interpolated.

More reliable pole positions of Late Ordovician and Early Silurian age are required to discriminate between the various models for Palaeozoic APWP of Gondwana. Results from the Black Hill Norite (Schmidt et al. 1993) suggest that the Early Ordovician pole position, immediately following the Delamerian Orogeny, was near the African Bight rather than northeast of Africa. This raises the spectre that some Australian Cambrian pole positions which plot nearby may have been overprinted during the Delamerian Orogeny. More recently Clark (1997, and this volume) and Roberts and Geeve (1998, and this volume) have produced a number of critical poles from north Queensland and southern New England which go some way to resolving two important issues. Poles from the former study relate to the 'reverse polarity option', which they appear to support, while poles from the latter study provide irrefutable evidence for rotations of blocks within the New England Orogen. This has important consequences for the alternative pole path suggested by Klootwijk and Giddings (1988, Klootwijk this volume).

Resolving these issues is crucial to be able to use the APWP for solving geological problems such as tectonic rotations, age dating and recognising thermal and orogenic events. Although Australia's research effort in this discipline is increasingly challenged, palaeomagnetism remains one of the few techniques with which to tackle tectonic problems. As long as students continue to be attracted to palaeomagnetism (see Anderson [2000], and this volume) I believe that through dedication and perseverance we will have some answers to Palaeozoic APWP questions within the next few years.

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UNRAVELLING THE MULTICOMPONENT MAGNETISATION OF THE NEOGENE MARINE SEDIMENTS OF NEW ZEALAND

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Introduction

New Zealand contains many thick sequences of Neogene sediments, which were originally deposited on the continental shelf but have since been tectonically uplifted and now outcrop on land. Such sequences have been central to the development of a biostratigraphic framework for temperate southern latitudes, with chronological control almost invariably dependent on the correlation of a magnetostratigraphic record with the geomagnetic polarity timescale (GPTS). To this end, palaeomagnetic studies have been carried out on many key sections in both North and South Islands.

Interpretation of the natural remanent magnetisation (NRM) of these sediments is however notoriously difficult, with most published magnetostratigraphic logs including many sites from which neither the direction nor polarity of characteristic magnetisation can be deduced with confidence. The main reasons for this difficulty are:

- The NRM is very weak, typically 10^{-5} - 10^{-4} A/m,
- Secondary components frequently overprint the primary magnetisation
- Thermal instability of the clay minerals in the sediments limits the temperature to which thermal demagnetisation experiments can be conducted, and therefore the extent to which the various components of magnetisation can be separated.

In the course of a new study of the sediments of the Wanganui River Valley and other river valleys of the Wanganui Basin, some unusually well defined demagnetisation data have been obtained. These together with new and existing rock magnetic data, have enabled

- a systematic characterisation of the multi-component nature of the NRM,
- formulation and evaluation of different theories for the acquisition of remanence
- consistently reliable identification and determination of the primary component of NRM.
- construction of a new magnetostratigraphic record for the Pliocene-Pleistocene sequence of the Wanganui River valley
- re-interpretation of the ten-year old palaeomagnetic dataset for the Turakina River valley sediments (McGuire, 1989) and correlation of the magnetostratigraphy with the GPTS.

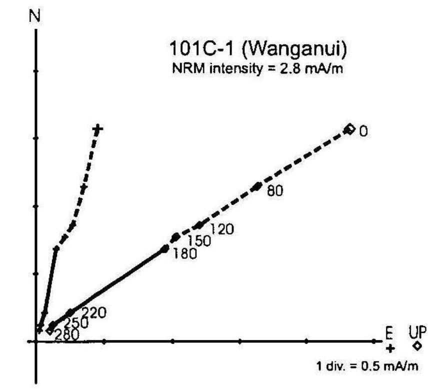
Characterisation of the Natural Remanent Magnetisation.

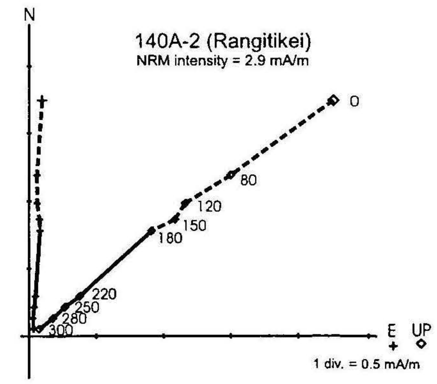
Figure 1 illustrates the progressive thermal demagnetisation of a selection of specimens. In general it is possible to recognise three components of magnetisation:

Figure 1 *(opposite page)* Vector component plots for progressive thermal demagnetisation of selected specimens from the sediments of rivers of the Wanganui Basin, illustrating Class A, B and C behaviour, as described in the text. Demagnetisation temperatures are shown alongside points on the vertical component of magnetisation for each specimen.

CLASS A specimens: two components of NRM:

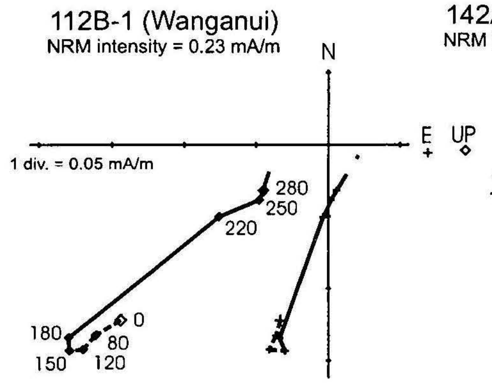
- small - moderate low blocking temperature component.
- intermediate Tb component well resolved and trends to origin
- no high Tb component.

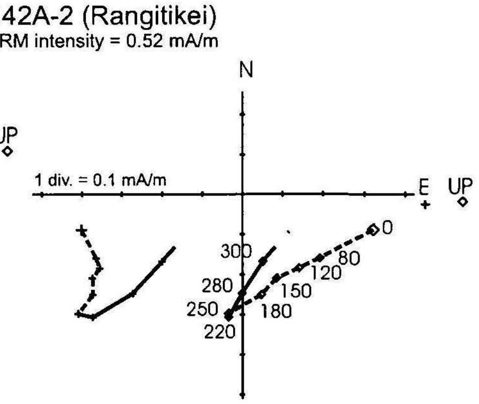




CLASS B specimens: three components of NRM:

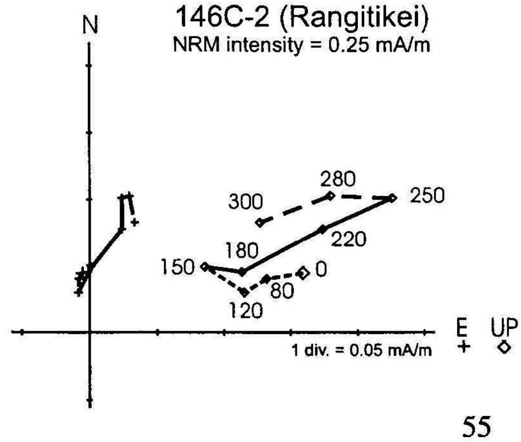
- small - moderate low Tb component
- intermediate Tb component well resolved
- small high Tb component, usually poorly resolved below

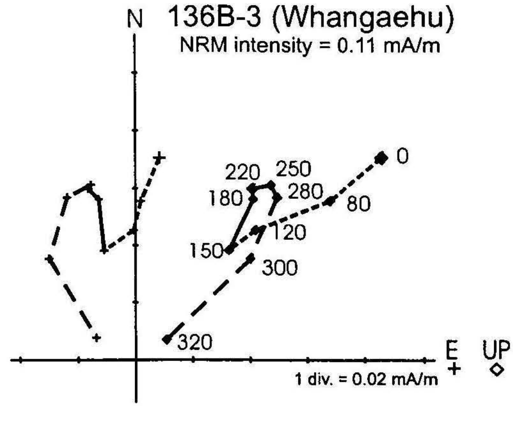




CLASS C specimens: three components of NRM:

- moderate - large low Tb component
- small intermediate component, often poorly resolved





1. A low blocking temperature (T_b) component that is lost below about 150°C. This component is usually of normal polarity and is close to the present day field direction.
2. A component residing in grains with T_bs above 150°C. Occasionally this is the sole remaining component and trends towards the origin of the vector component plot. More often it is identifiable up to about 250°C, and is underlain by another component.
3. A a third, high T_b component can usually be identified or inferred from the failure of the intermediate T_b component to demagnetise towards the origin of the vector component plot.

The following classification system was devised to describe the degree to which the various components are developed:

Class A: Relatively intense NRM's. The remanent vector shows little change in direction with demagnetisation: after removal of the low T_b component, the plots trend towards the origin. e.g. 101C-1, 140A-2. The NRM is almost all lost by 300°C.

Class B: Specimens 112B-1and 142A-2 are typical of a large number of specimens that lose two components of magnetisation up to about 250°C, but which bypass the origin, indicating a third, underlying component, in grains of higher T_b. The low and mid T_b components almost certainly correspond to the two components identified in Class A specimens. The high T_b component is additional.

Class C: The high T_b component reaches further down the blocking temperature spectrum, so that the three components are clearly identified, and all three can be estimated by principal component analysis (PCA). A large proportion of specimens show evidence of three components, but 146C-2 and 136B-3 are unusual in that they overlap very little.

Two theories have been proposed to explain the acquisition of these three components of remanence:

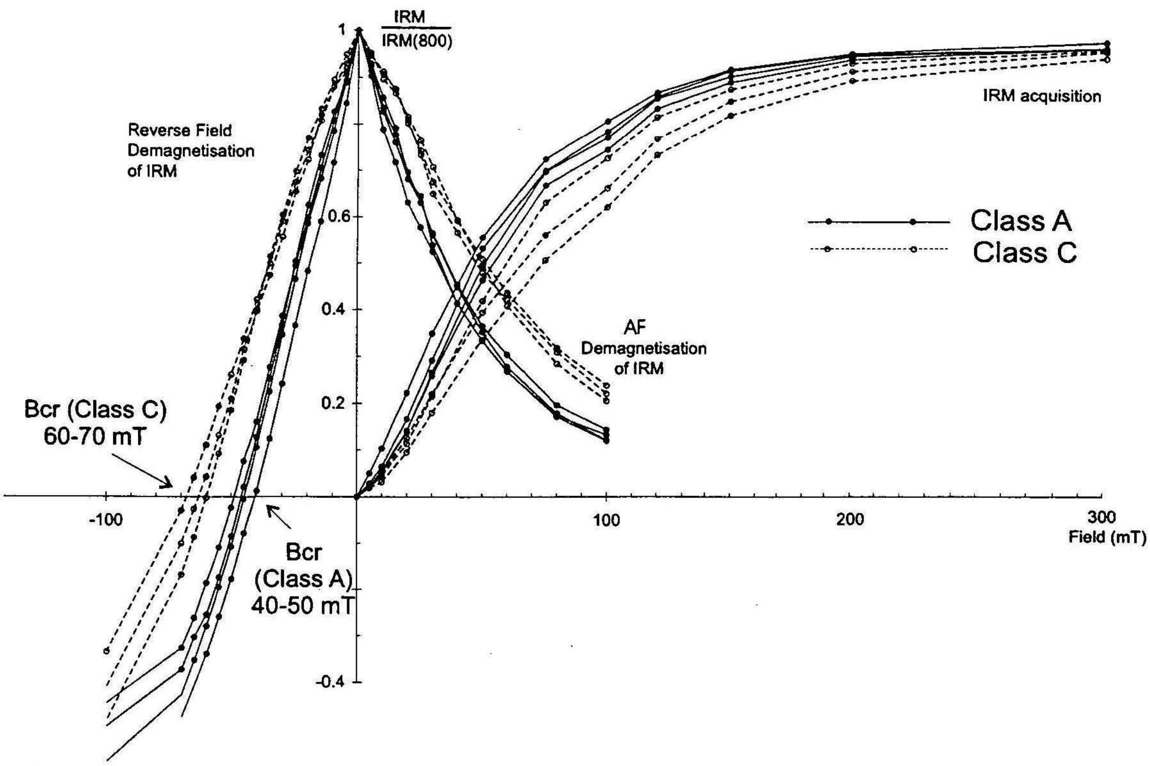
TVRM – burial - primary. In which the low T_b component corresponds to a thermoviscous component (TVRM) of recent origin; the intermediate component is a secondary component acquired as grains reblock during uplift after burial at an elevated temperature; and the high T_b component is all that remains of the primary detrital remanence,

TVRM – primary – CRM In which the three components correspond respectively to a TVRM as above, the remnant of the primary detrital magnetisation and a secondary component acquired during the authigenic growth by crystallisation of grains of a new magnetic phase.

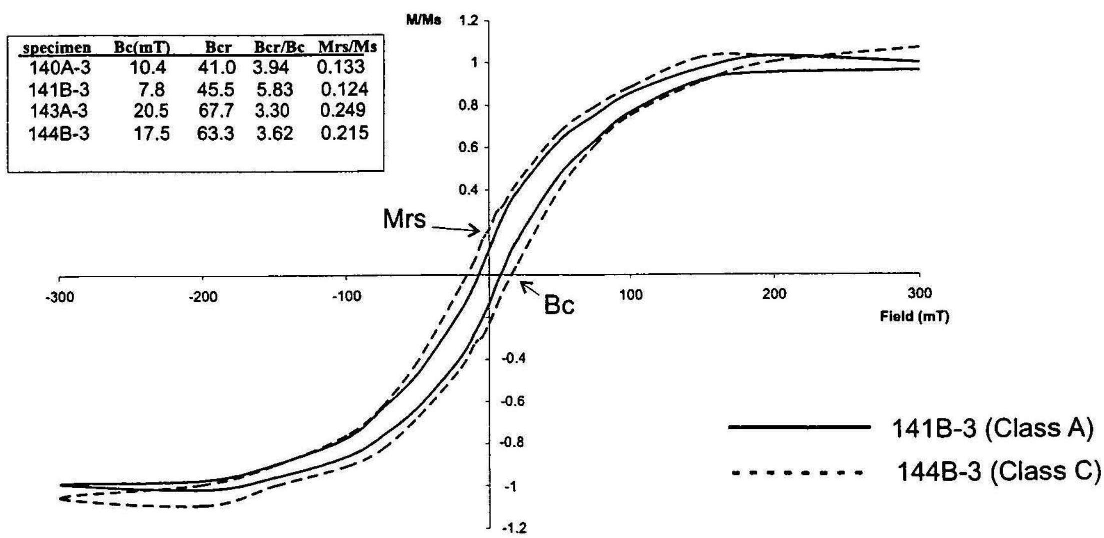
It is critical to distinguish between these two mechanisms, since for many class B and C specimens they lead to different "primary" polarities. The spectrum of remanence bearing grains should provide a means of discriminating between the two mechanisms. The TVRM – burial – primary theory only a single population of detrital ferrimagnetic grains. In the TVRM – primary – CRM theory, the CRM is carried by a second authigenic phase. Rock magnetic investigations were undertaken to test this possibility. Plots showing the acquisition of isothermal remanent magnetisation (IRM), backfield demagnetisation of IRM and alternating field (AF) demagnetisation of saturated IRM, and hysteresis loops are shown in Figure 2.

- The IRM of Class C specimens saturates much more slowly with increasing direct field
- The coercivity of remanence, B_{cr}, (the direct field required to reverse a saturated

(a) **Rangitikei Sites:** IRM acquisition, Back IRMs, AF Demag of IRM(800mT)



(b) Rangitikei sites: hysteresis curves (after paramagnetic correction)



specimen	Bc(mT)	Bcr	Bcr/Bc	Mrs/Ms
140A-3	10.4	41.0	3.94	0.133
141B-3	7.8	45.5	5.83	0.124
143A-3	20.5	67.7	3.30	0.249
144B-3	17.5	63.3	3.62	0.215

Figure 2 Results of rock magnetic experiments for selected specimens. (a) acquisition and demagnetisation of isothermal remanent magnetisation for specimens from sites along the Rangitikei River; (b) hysteresis curves for two typical Rangitikei sites, and tabulated parameters for two class A specimens (140A-3, 141B-3) and two class C specimens (143A-3 and 144B-3).

IRM)of Class C specimens is consistently about 20mT, or 50%, higher than for Class A specimens.

- The median destructive field (MDF) is in general about 20 mT or 50% higher for class C than for Class A specimens.
- The hysteresis loop for specimen 144B-3 (Class C) is much broader than that for 141B-3 (Class A). A comparison of B_{cr}/B_c and M_{rs}/M_s ratios indicates that Class C specimens contain a much bigger proportion of small single domain (SD) particles.

Conclusion and Summary

The data described above indicate that the NRM's of Class A and Class C specimens are dominated by different populations of ferrimagnetic grains. Class A specimens have relatively high intensity NRMs, carried by low-intermediate blocking temperature grains. Laboratory induced remanences show a soft coercivity spectrum, characteristic in shape of a single grain population.
Class C specimens have generally weaker NRM's, with a component carried by higher blocking temperature grains. There is considerable evidence of higher coercivity grains in laboratory induced remanent magnetisations.

This is readily explained in terms of the TVRM - primary - CRM mechanism for remanence acquistion: Class C specimens have developed by dissolution of much of the original, low Tb detrital ferrimagnetic mineral, some of which is still present in Class A specimens. This is accompanied by growth through crystallisation of small grains of another phase, resulting in stable single domain grains with high coercivities and blocking temperatures. The TVRM – burial – primary model was rejected firstly, because it implies a single grain population, whereas the evidence suggests two, and secondly because there is no geological or tectonic evidence for the sediments having been reheated to a sufficient temperature to explain the intermediate Tb component as a partial TRM.

In some previous studies the highest blocking temperature component has tacitly been interpreted as the primary magnetisation. The present study implies that this may have resulted in the wrong geomagnetic polarity being assigned to sites. Recently, the entire Turakina River dataset of McGuire (1989) has been reinterpreted on the basis of the TVRM-primary-CRM theory. The interpretation of many sites remains unchanged (Class A and A-B behaviour), however there are clusters of generally Class B-C or C sites for which the polarity interpretation has been reversed. Whereas the original polarity zonation was inconclusive, the new record is quite unambiguous, its correlation with the GPTS is excellent, and in agreement with all available biostratigraphic constraints.

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