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PALAEOMAGNETISM IN AUSTRALASIA: DATING, TECTONIC, AND ENVIRONMENTAL APPLICATIONS

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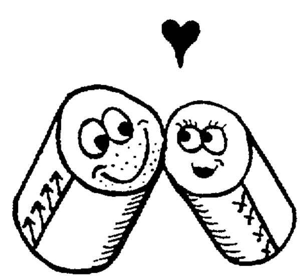

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Old Developments in Palaeomagnetism; what's left to do?

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"Old" Palaeomagnetism discovered what more "important" geophysical disciplines denied or failed to predict. The major discoveries were as follows.

. For the Earth: geomagnetic polarity reversals, properties of the palaeosecular variation, polar wandering, the first quantitative evidence for continental drift and, hence, the start of serious discussion about mantle convection. It has proved to be a vital tool in studying tectonic movements and displaced terranes.

. For the Moon: the existence of a primaeval dipole magnetic field, its exponential decay from 4 b.y. to 3.2 b.y., the existence of an iron core, reorientations of the Moon with respect to its axis of rotation and the presence of a primaeval lunar satellite system - a clue in the understanding of planetary formation by accretion.

. For meteorites: their remanent magnetization gives evidence for an early solar system magnetic field - the key to the venerable angular momentum problem - and from the SNC meteorites possible evidence of an early Martian magnetic field, now hardly detectable.

What will new "state of the art" palaeomagnetism achieve? Predictions by geophysicists rival those of economists! But a shopping list might include:

(1) Search for periodicities in Recent secular variation, especially by lake sediments.
(2) Extensive study of the palaeosecular variation in the Pacific as compared with the non-Pacific hemisphere.
(3) Further development of archaeomagnetism, both palaeodirections and palaeointensities.
(4) Search for trends in the palaeointensity of the geomagnetic field over an appreciable fraction of Earth's life.
(5) Palaeointensity of lunar rocks especially to investigate the apparent rise in the lunar field prior to its maximum 3.9-4.0 b.y. ago.
(6) There is a great need to clarify "shock" magnetization experimentally and theoretically and whether it is important in terrestrial impact craters and the SNC meteorites.
(7) The fundamental question of relative movements within Pangea prior to the Wegener break up needs intensive study.

In the search for new sections and sites where the transition fields during reversals in the last part of Cenozoic times may be followed with increasing accuracy, the desirability of obtaining a few in earlier times for comparison of the VGPs path should be remembered.

In the study of plate motions prior to the Wegener break up, the important question of True Polar Wandering should be also emphasized.

New Developments in Rock Magnetism

Ronald T. Merrill
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Rock magnetism is currently undergoing a revolution that, ultimately, will alter all theories for remanent magnetizations. Few palaeomagnetists seem aware of this revolution, and still fewer seem to believe that it will impact their work. The purpose of this talk will be to describe this revolution, without resorting to complicated mathematics, and to suggest ways in which some of the standard procedures used in palaeomagnetism are likely to be transformed during the next decade.

Statistical Analysis of Palaeomagnetic Data

Phil McFadden
Australian Geological Survey Organisation

Palaeomagnetic data are highly dispersed over a restricted space. As a consequence, palaeomagnetism is heavily dependent upon statistical analyses in order to extract the relevant information from the basic data. The primary questions that are still asked of the data areas follows

- What was the true mean direction for this magnetization, and with what precision have I been able to estimate it?
- What is the age of this magnetization?
- Are these two magnetizations drawn from the same population?
- And, because of the nature of statistics, how meaningful are my tests?

The choice of an underlying distribution for the basic data, the value of computer-intensive techniques, the classification of tests, and the fold test will be discussed in the context of these questions.

Global Palaeomagnetic Database: update to 1992

Michael W. McElhinny
Gondwana Consultants

At the Vancouver General Assembly of the IUGG in 1987, Division I of IAGA decided to embark on a plan to establish several databases in palaeomagnetism and rock magnetism. Because of the previous regular publication of Pole Lists in the *Geophysical Journal*
, a Global Database for Palaeomagnetic Directions and Pole Positions was the first to be established. Through contributions from 10 countries the Global Palaeomagnetic Database (GPMDB) was set up by Jo Lock and myself using the *Oracle* relational database management system for IBM compatible PCs. This project was successfully completed in July 1991 in time for the Vienna General Assembly of IUGG. The GPMDB (Version 1.4 of July 1991) contained all global data up to the end of 1988 from published literature and included 5705 results from 2182 references.

A four year update that includes all global data to the end of 1992 is now finalised (Version 2.2) and contains nearly 7000 results from about 2700 references. As a result of feedback from Version 1.4, a new, more sophisticated Menu has been developed that makes operation much easier and provides a standard summary output. There is now little requirement for users to know the SQL database language. A brief resume will be given of the new operational features of the Global Database.

On Integrating Palaeomagnetism and Geochronology

Michael McWilliams
Stanford University

There has always been a close historical connection between palaeomagnetism and geochronology, for an undated palaeomagnetic result is seldom very useful. This statement is particularly true for K/Ar geochronology, for which the results depend upon a thermally activated diffusion process with an activation energy similar to that of the TRM blocking process.

Recent technical improvements have made it possible to obtain precise $^{40}Ar/^{39}Ar$ ages from quite small and quite young samples in a matter of a few hours. It is now routine to analyse single crystals of Quaternary sanidine or biotite or single fragments of basalt by laser fusion, and plagioclase separates or whole rock basalts with a mass of only 10 to 100 mg and as young as 0.3 Ma have been successfully dated using an ultraclean resistance furnace. With careful attention to experimental issues such as the close monitoring of neutron fluence and system blank, experimental precision approaching 0.1% is routinely reported by several laboratories. Apart from the obvious goal of obtaining better ages for palaeomagnetic poles, the importance of this increased precision and speed to palaeomagnetism are best illustrated with a few examples.

Polarity Timescale The 0-83 Ma portion of the Harland et al. [1989] polarity timescale contains 196 polarity intervals, the majority of which are less than $5*10^5$ years in duration. If an accuracy of 0.1% can be consistently achieved for the ages which constrain the timescale, all but 7 (96%) polarity intervals could be resolved, as compared with perhaps 50% using convential methods. This observation has not escaped notice, and several groups (including ours at Stanford) are working to refine and recalibrate the timescale using high resolution $^{40}Ar/^{39}Ar$ geochronology. A clear outcome of the first round of studies is that the 0-4 Ma K/Ar calibrated timescale is in error by as much as 7% in some places, and the Miocene part of the timescale may be in error by as much as 1 Ma at 15 Ma.

Tilt or Translation? $^{40}Ar/^{39}Ar$ and fission-track data are becoming increasingly important to the interpretation of palaeomagnetic results from batholithic terranes for which palaeohorizontal control is not available. Palaeomagnetic inclinations from the Coast Ranges of British Columbia and the Peninsular Ranges Terrane in Alta and Baja California have been interpreted to indicate large poleward translation, but an alternative hypothesis is that these large terranes have been systematically tilted since acquiring their magnetization. In this instance the anomalously shallow inclinations record tilt, not transport. Our new $^{40}Ar/^{39}Ar$ and fission-track data from the Peninsular Ranges Terrane indicate that while some tilt has occurred, the shallow inclinations do indeed reflect large poleward motion.

Direct Dating of MORB Radiometric dating of MORB is difficult because the samples recovered from deep sea drilling are often highly altered, and the alteration has disturbed the K/Ar system by potassic alteration and gain/loss of Ar. $^{40}Ar/^{39}Ar$ geochronology has been the most successful method widely applied to MORB, but even its application has been hampered by the low K content and small amounts of suitable material recovered. We have studied small amounts of plagioclase from ODP samples in the Pacific and Sea of Japan, yielding promising results with precision approaching 0.5%. If the promise of these initial experiments is borne out in future studies, it should be possible to directly calibrate spreading rates and marine magnetic anomalies by investigating samples from ODP and DSDP cores.

'Ground-Truth' in Aeromagnetism

Colin V. Reeves
Australian Geological Survey Organisation

Abstract

One of the unkowns in the interpretation of magnetic anomalies is the magnetic properties of the source rocks. These can, however, be measured independently and at a cost which is small compared with the cost of carrying out an airborne survey. A systematic programme of rock-property measurements, linked to geological mapping in new aeromagnetic survey sheet areas, could develop into a valuable resource for all those using geophysical map data of Australia. Some examples from Africa are used to illustrate these points.

Introduction

One of the most fruitful approaches to the interpretation of potential field anomalies is to generate the model of a source body which could, in theory, replicate very closely a given anomaly observed in the field. The fundamental problem of non-uniqueness is usually reduced to manageable proportions by independent a priori information, geological reasonableness or even plain common sense. In the best tradition of scientific investigation, the method then leads to a hypothesis which (a) serves to explain all existing data and (b) may be tested by future experiment. The result consists of a set of parameters which define the position and geometry of the source body in three dimensions plus a value for the physical property contrast which sets the body apart from its host environment. Unless there is good reason to the contrary, economy of hypothesis dictates that the causative body is assumed to be physically uniform and of simple - but geologically plausible - geometry.

The above paragraph encapsulates the process by which we attempt to acquire knowledge and understanding of three-dimensional geology by way of carrying out and interpreting potential field surveys at - or above - the earth's surface. Producing a geophysical anomaly map - of which an aeromagnetic map is perhaps typical - involves carrying out a series of observations from which a contour presentation or image may be produced more-or-less unequivocally; an independent group of observers should arrive at a map which is essentially identical.

The interpretation of that map or image is equivocal because the solution to the three-dimensional geological problem is under-determined by the two-dimensional observation set in the x,y plane. One approach to reducing the uncertainty is obvious - the magnetic properties of rocks can be determined from measurements made at outcrop sites and on hand specimens returned to the laboratory. For some reason this approach is sadly neglected almost universally, even though useful data may be collected at a fraction of the cost of carrying out an airborne survey.

Rock magnetism and the magnetic interpreter

Rocks exhibit magnetisation either because it is induced by the present-day geomagnetic field (induced magnetisation) or because they have inherited a permanent magnetisation from some event in their geological past (remanent magnetisation). Induced magnetisation is, by definition, in the direction of the present-day earth's field which can be known to the interpreter simply by looking at world charts of total magnetic field, inclination and declination. Only the magnetic susceptibility remains to be determined. Remanent magnetisation, on the other hand, can be in any direction, given the apparent polar wandering for the site, the frequent reversals of the geomagnetic field during the geological time-spans over which remanent magnetisation can be preserved and the thermo-tectonic history of the site. The interpreter encountering remanent magnetisation needs to discover a magnitude and direction of magnetisation for which, in general, he has no reasonable control.

For a typical dipping body with (near-)infinite strike length there is additional ambiguity in that present-day magnetic inclination, body-dip and remanent magnetisation all contribute to the position of the anomaly curve shape within the family of curves which covers all possible anomalies for a given body-geometry (Reeves, 1989). In other words, remanent magnetisation may be confused with body-dip for a given inclination of the inducing field. When there is no good reason to the contrary, interpreters are forced to assume only induced magnetisation. Counter-indications are usually limited to severe cases where no reasonable body-dip can account for the shape of the observed anomaly. Even this situation can be solved by the expediency of assuming 'reversed magnetisation'.

Some support for the predominance of induced magnetisation in magnetic anomalies comes from a systematic study of some 30 000 specimens collected in northern Scandinavia and analysed in a joint project of the geological surveys of Norway, Sweden and Finland (Henkel, 1991). The average Konigsberger ratio for all these samples was about 0.2.

Usually, aeromagnetic surveys are carried out at the forefront of an exploration programme, before significant 'ground-truth' studies have started. Furthermore, they find particular application in those areas where the bedrock geology is obscured from direct examination by cover rocks or weathering. The aeromagnetic interpreter therefore seldom has a great deal of ground truth of any sort to fall back on, let alone laboratory measurements of oriented specimens. The interpreter needs to preserve a broad perspective and, as with most types of geophysics, be opportunistic where a more holistic approach to his subject can be taken.

In the case of Australia, where reconnaissance aeromagnetic survey coverage nears completion and a new generation of more detailed surveys is under way, the opportunity for initiating a systematic sampling programme in sheets areas selected for detailed survey should not be missed. If sampling follows preliminary compilation of the aeromagnetic data, the main rock units which generate magnetic anomalies can be identified from the anomaly maps and then visited for field sampling. The essential parameters to measure would be magnetic susceptibility and total NRM (magnitude and direction). Selected anomalies which betray remanent magnetisation could be treated in more detail. It is conceivable, for example, that intrusions could be dated from their paleo-pole position or that other facts which might assist in the interpretation of the geological history of a sheet area could be revealed. Together with density measurements, such an exercise would build into a solid physical-property data-base for all interpreters of Australian geophysical map data. The advantages of linking this with any on-going age-dating programme are fairly clear (BMR, 1992).

Some examples from Africa which I came across in earlier projects may serve to demonstrate the point.

Botswana

An impressive swarm of basic dykes, seen only very locally in outcrop due to the cover of Kalahari Sand, was revealed by the aeromagnetic survey of Botswana (Reeves, 1978). While the bulk of anomalies suggested normal induced magnetisation, others could only be modelled by 'reversed' magnetisation. The shape of 'normal' and 'reversed' anomalies was later found to be consistent with remanent magnetisation acquired at the time of emplacement (mid-Jurassic), implying at least one magnetic reversal during the period when emplacement was taking place (Reeves, 1989).

Ivory Coast

About 70 small, circular anomalies were revealed by the aeromagnetic survey of Ivory Coast (Grant et al., 1980). Some of these anomalies coincided with known vertical metabasic intrusions. Anomaly shapes were consistent with a vertically-oriented remanent magnetisation; some of the bodies showed the direction oriented vertically upward, others vertically downward. The age of the intrusions is known to be about 1900 Ma when African apparent polar wander paths show west Africa to be close to the magnetic pole. Again, at least one magnetic reversal occurring during the period of emplacement is consistent with the observations.

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Magnetic petrology: Application of integrated rock magnetic and petrological techniques to geological interpretation of magnetic surveys

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Interpretation of magnetic surveys in terms of geology is hampered by poor correspondence between broad lithological categories and magnetic properties, and by lack of knowledge of the geological factors that influence the magnetisation of rocks. Magnetic petrology is the integrated application of rock magnetic and conventional petrologic techniques to identify and characterise the magnetic minerals in rocks. This information elucidates the factors that produce, alter and destroy magnetic minerals and thereby influence the bulk magnetic properties of the rocks and their associated magnetic anomalies. Improved understanding of magnetic petrology is therefore essential for maximising the geological information that can be obtained from magnetic anomaly patterns.

Magnetic interpretation is essentially an inversion process, whereby magnetic anomaly patterns are analysed to produce an interpreted source distribution and the sources in turn are interpreted in terms of geological entities, such as rock units, alteration zones and structures. The fundamental problem of magnetic interpretation arises because this inversion of magnetics to geology is highly ambiguous. The non-uniqueness of source geometry associated with a given anomaly is a well known problem of magnetic modelling (quantitative interpretation), which can be ameliorated by constraining the class of possible models. Constraints can be imposed a priori, on the basis of geological plausibility for example, or, preferably, can rely on additional information from drilling, other geophysical methods, or from magnetic property measurements. Similarly, the ambiguity in inferring the geological nature of the sources (qualitative interpretation) can be reduced by a better understanding of the relationships between magnetic properties of rocks and geology.

This paper discusses the application of magnetic petrology to improving geological interpretation of magnetic surveys and illustrates some general findings with case studies.

Subdivision of eastern Australia into crust with different cratonization history using gravity and magnetic anomalies

Peter Wellman
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Eastern Australia (Tasman Orogenic System and northern Queensland) can be subdivided into geophysical domains. Each domain is thought to represent a unit with the same cratonization history, within a domain gravity and magnetic trends are sub-parallel, and these trends differ in direction from adjacent domains. At the boundaries between domains there is a broad zone where the younger of the two domains reworks the margin of the older domain. Aeromagnetic anomalies show that this reworking distroys the induced and remanent magnetization of the rocks of the older domain, generally resulting in a band of non-magnetic rock. However in some cases the reworking results in prograde metamorphism which forms new magnetic minerals and a higher ?induced magnetization. These reworked zones form as much as one quarter of the crust. This model has important implications for Australian palaeomagnetism. The pattem of geophysical domains is a major constraint on possible models for the cratonization history of eastern Australia. The pattern of reworked zones between geophysical domains should be taken into account in palaeomagnetic sampling, because in these zones it is unlikely that any remanent magnetization will be preserved that is older than the cratonization of the adjacent younger domain.

Rock Magnetism and Geophysical Interpretation of the Black Hill Norite, South Australia

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Igneous rocks found associated with Kanmantoo Group and Adelaide Supergroup metasediments in the southern Adelaide Foldbelt can be considered to be pre-tectonic or related to the Delamerian Orogeny (either early or syn-tectonic) or post-tectonic. Typically the pre-tectonic and syn-tectonic igneous rocks tend to be granitic and are found within the foldbelt west of the Palmer-Milendella fault zone. The known post-tectonic intrusives are bimodal (though again granitic rocks predominate) and form part of the western margin of the basement to the Murray Basin.

The western margin is very poorly exposed and exposures are restricted to the extremely limited outcrop of a few granitoid tors and the Black Hill Norite. Most basement features have been identified mainly on the basis of regional aeromagnetic maps in combination with gravity data, borehole control, sparse seismic profiles and of course the known outcrops. Specific magnetic anomalies have been correlated with exposed A-type granites, gabbros, metasediments (possible Kanmantoo Group or Adelaide Supergroup equivalents) and possible volcanics (Brown and others,1988; Rajagopalan,1989; Bontenakel,1992).

The exposed intrusives are undeformed and their intrusion is believed to have marked the cessation of the Delamerian Orogeny. The granites and gabbros may have originated through extended fractionation of basaltic magmas. They appear to be compositionally and spatially distinct from the deformed, pre- and syn-tectonic granites found in the Adelaide Foldbelt (Sandiford and others,1992; Turner and others,1992a,1992b). The bimodal post-tectonic igneous suite suggests a period of extensional tectonics very shortly after the close of the Delamerian Orogeny. The earliest example of this later stage mafic activity is a diorite dyke which cuts a deformed granodiorite pluton at Reedy Creek and itself has a very weak fabric suggesting intrusion near the very end of the deformation. Magmatism increased with the intrusion of several plutons at Black Hill which consist of undeformed, layered gabbros. Slightly later than these intrusives are a series of basaltic dykes which cut the Black Hill and Mannum plutons.

The Black Hill complex comprises several large layered plutons with a continental tholeiitic nature. The Black Hill Norite (Wegmann,1980) is a major but poorly exposed mafic intrusion to the east of the Mt. Lofty Ranges north of Mannum in South Australia. The Norite probably intruded Kanmantoo Group metasediments. The Black Hill Norite is not metamorphosed and observed deformation is restricted to discrete shear zones and is therefore regarded by Turner (1991) as effectively post-tectonic. Milnes and others (1977) report a *Rb-Sr* biotite-whole rock isochron from the Black Hill gabbros which gave and age of 487 $\pm$ 5 *Ma* and they also gave a *K-Ar* date on the biotite of 486 *Ma* indicating there has been no significant thermal pertubation subsequent to crystallization. A seven point *Nd-Sm* mineral-whole rock isochron (Turner,1991) yielded an age of 489 $\pm$ 10 *Ma*. The undeformed Early Ordovician Black Hill intrusive is evidence of major mantle-dirived mafic activity following the Delamarian Orogeny.

Geophysical data available for the area include gravity data collected by SADME and students (Kennedy,1989; Turner,1991) and aeromagnetic data from a survey flown by the BMR (150 metre main terrain clearance, 1500 metre line spacing, 55 metre sample spacing). On these maps, it is apparent that the Black Hill Norite is associated with an unusual magnetic anomaly. For a vertical funnel-shaped source at this latitude we would expect a major magnetic high to the north and a much smaller low to the south. The principal magnetic axis (or high-low axis) should trend north-south though this would be affected by the elongation direction of the source. The Black Hill anomaly on the contrary is associated with a major low to the north-east and a slightly reduced high to the southwest with the principal axis oriented approximately NE-SW. The anomaly amplitude exceeds 3000 *nT*. There are at least two similar anomalies in the vicinity: on to the west indicating a smaller pluton - the Cambrai pluton and another larger one to the southwest - the Central pluton. The Black Hill pluton is the only one which is partly exposed. Remanence is obviously indicated here and the combination of the age of the intrusive and its undeformed state suggest that it could be a good palaeomagnetic recorder of the Ordovician pole position.

Kennedy (1989) carried out a gravity survey over the Black Hill and Cambrai plutons. Both plutons are associated with residual gravity highs (6 *mGals* and 5 *mGals* respectively). Kennedy interpreted the sources to be funnel-shaped an extending to a depth of around 3-3.5 *km*.

Very little work has been carried out on the magnetic properties of this intrusion despite its obvious significance. Wake-Dyster (1974) used a vertical field magnetometer to measure the direction of the NRM. Though his measurements were scattered he gave the mean estimates of the declination and inclination of the remanent magnetization as 212^0 and 23^0 respectively. He could not measure intensity by this method though he indicates that the remanent intensity is of the same order as the present earth's field. He calculated the north palaeomagnetic pole position to be 53^0S and 19^0E.

Schmidt and others (this volume) have recently collected and measured the magnetization of the Black Hill Norite. The Black Hill Norite displays a very stable remanent magnetization with the following properties: declination = 210^0, inclination = 10^0, and a Koenigsberger ratio of between 8 and 10. Outcrop susceptibility measurements ranged from $2000\text{-}4000*10^{-5}$ *SI* units.

The available gravity and magnetic data have been interpreted using the rock property information. The magnetic data were reduced to the pole (resultant vector declination and inclination are approximately 211^0 and -5^0 respectively). The reduced-to-the-pole magnetic anomalies matched the shape of the residual gravity anomalies. All three intrusions appear to be elliptical in cross-section and the Cambrai pluton trends E-W while the Black Hill pluton and the Central pluton trend NE-SW. This is consistent with the trend of the gravity anomalies and the principal axes of the magnetic anomalies. The Cambrai pluton is the smallest (spatial extent of 6 km^2), the Black Hill pluton is next (20 km^2) and the central pluton is the largest (25 km^2).

The opaque minerals (Turner,1991) found in the Black Hill Complex include pyrite, hemo-ilmenite and magnetite (sometimes with exsolved hercynite). The magnetite and ilmenite are found as separate phases. The ilmenites are *Ti*-rich while the magnetites contain very little titanium. The total amount of opaques present can exceed 5% though the typical value is nearer 2%. Magnetite is sometimes found exsolved out of biotite and clinopyroxene. The known amount of relatively coarsegrained (and therefore multidomain) magnetite present is sufficient to explain the high magnetic susceptibility but is unlikely to be the dause of the stable and intense remanence. Data on grain size are not available and additional probe work is planned to investigate the possibility of the presence of single domain magnetite grains.

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Polarity Reversals, Cooling Magmas and Aeromagnetic Anomalies

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Aeromagnetic anomalies over intrusions often exhibit complex patterns that are usually explained by multiple intrusions and complex geometry. Often, however, the cause may simply be due to polar reversals.

Consider a magma cooling from above the Curie point of constituent magnetite. In the case of a simple body with an upper surface approximating a dome or semisphere, there would be a wave front at the Curie point that would that would contract with time. The net result would be an onion ring pattern of normal and reversed remanent magnetism with thickness and occurrence depending on cooling rate and the relevant geological time. With subsequent exposure (slice the top off the onion) a circular pattern of normal and reversed magnetism should be evident. Magnetic surveys over intrusions have recorded complex anomalies which could be explained by such effects.

Model studies of vertical cylinders and spheres with concentric zones of reversed magnetism have been carried out. The responses are quite complex and often lack the circular symmetry of the source, especially in mid latitudes. It becomes evident that very detailed palaeomagnetic measurements would be required to model the response of irregularly shaped intrustions.

There are several such complex magnetic anomalies which may exhibit remanent magnetism and, perhaps, polarity reversals in the Charters Towers region. Most of these anomalies have irregular shapes but there is one circular anomaly that is particularly suited to test this hypothesis.

Oriented samples were collected from a granitic intrusion that coincided with this anomaly. Unfortunately this intrustion is, for the most part, deeply weathered so that a collection of a representative suite was not possible. The limited data, however, tended to confirm the existence of a polar reversal.

More detailed measurements are necessary to provide information for conclusive modelling. Nevertheless, delineation of such reversals in intrusions can only lead to a better understanding of their properties and, by extension, their relationships with surrounding rocks and possible mineralisation.

Palaeomagnetic tests of tectonic models of the Tasman Fold Belt during the Palaeozoic

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The Tasman Fold Belt is a Phanerozoic fold belt occupying the eastern third of Australia, and has a preserved width of more than 1000 km — the same width as the modern cordillera mountains of western USA. There are no known Precambrian rocks in the Tasman Fold Belt on mainland Australia, although Neoproterozoic metamorphic and sedimentary rocks outcrop in Tasmania, which is the on-strike continuation of the western half of the Tasman Fold Belt. The structural trends of the Tasman Fold Belt trend broadly northerly, and cut across the older Proterozoic trends in the immediately adjacent Precambrian rocks to the west.

Within the Tasman Fold Belt, three fold belts have been defined, which, from west to east, are the Kanmantoo, Lachlan and New England Fold Belts. The tectonic histories of these belts overlap in time but become progressively younger to the east. Thus, orogenic movements in the Kanmantoo Fold Belt were largely completed by the Cambro-Ordovician, in the Lachlan Fold Belt by the mid-Carboniferous, while the New England Fold Belt was not stabilized until the mid-Cretaceous. The Lachlan Fold Belt has a common Ordovician history throughout, but, in the Silurian to mid-Devonian, the eastern Lachlan Fold Belt is different from the western section.

Tectonic models of the Tasman Fold Belt have ranged from its growth in passive margin and back-arc settings adjacent to Gondwanaland to accretion of exotic terranes. The presence of a Precambrian thinned continental basement to parts of the outcropping Cambrian and Ordovician mafic volcanics and sediments has been suspected, but not proven, on isotopic grounds. Large-scale (≥100 km) transcurrent movements have been postulated for parts of the Lachlan and New England fold belts. Recently, the position of Tasmania in the Tasman Fold Belt has come under closer scrutiny, with postulates ranging from its being exotic in the earliest Cambrian (Powell 1990), to parts of it having been emplaced by transcurrent movement in the Devonian (Glen et al. 1992) or even as late as since the Middle Jurassic (Elliot & Gray 1992).

Palaeomagnetic evidence can address only some of these competing hypotheses. First, there is now mounting evidence that Australia-Antarctica and Laurentia were in a SWEAT-like configuration (Moores 1991) from at least 1050 Ma until 720 Ma, after which Laurentia began to rotate away from east Gondwanaland producing the palaeo-Pacific Ocean (Figure; Powell et al. 1993a). An ocean-floored Tasman Fold Belt could date from around 700 Ma, as by ~580 Ma there was a wide separation between Laurentia and East Gondwanaland. In the Adelaide region, the breakup event is marked by the unconformities at the base of the Umberatana Group, with the Warrina Supergroup representing the intra-Rodinian epicontinental supersequence preceding separation. The overlying Heysen Supergroup, of which the Umberatana is the lower group, represents a supersequence formed on the trailing continental edge of the growing palaeo-Pacific Ocean in which the Kanmantoo Group is likely to have been deposited.

There is no reliable palaeomagnetic constraint on the position of the mainland portion of the Tasman Fold Belt until the Early Devonian, when the Snowy River Volcanics pole gives good constraint on the position of the eastern Lachlan Fold Belt. Unfortunately, there is no reliable palaeomagnetic pole of the same age from cratonic Australia so that whether there is any rotation between the eastern Lachlan Fold Belt and cratonic Australia at that time has not yet been tested palaeomagnetically.

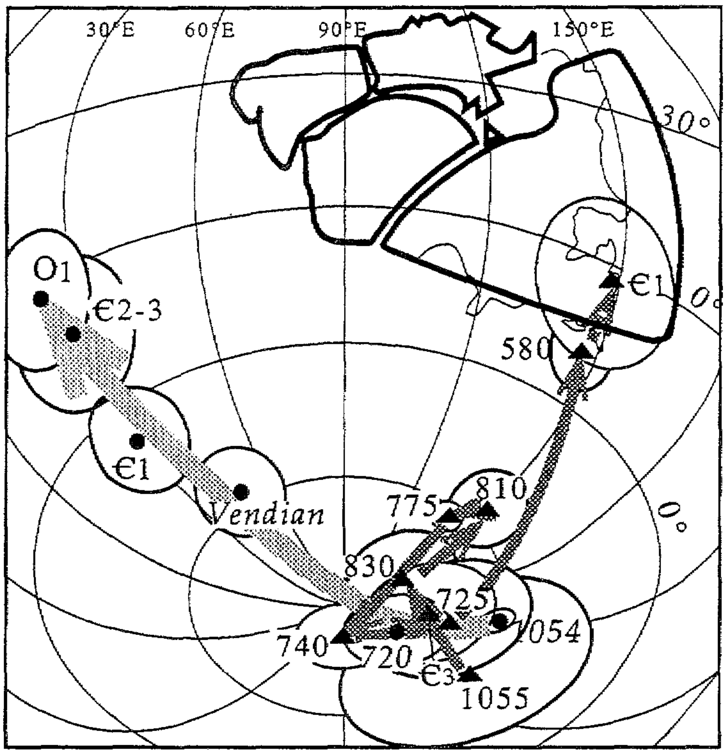

Figure 2. Neoproterozoic to Cambrian APWPs for Proto-East Gondwanaland and Laurentia rotated to their Rodinian configuration. Mean poles, with 95% confidence intervals, are shown as for Proto - East Gondwanaland and triangles for Laurentia, with 95% confidence intervals shown. Australia and Antarctica are rotated to India in its present-day coordinates using the parameters in Powell et al. 1988, and Laurentia is rotated to India by 166° about a pole at 56°S, 21°W. Inferred Neoproterozoic edges of eastern Australia and Antarctica are along the Tasman line and the Transantarctic Mountains (Dalziel, 1992), respectively. Lambert equal-area projection centered at 30°S, 90°E.

The next set of palaeomagnetic data relating to the Tasman Fold Belt comes from the mid-Devonian to Early Carboniferous interval, for which there are several key poles in both the fold belt and the craton (Chen et al. 1993, this volume). The palaeomagnetic data from the Tasman Fold Belt all come from the Lambian overlap assemblage, so it is not surprising that the data follow a common apparent polar wander path (APWP). As has been pointed out by Li et al. (1989) and Chen et al. (1993) there was rapid drift of Australia towards the South Pole during the Carboniferous, so that during the mid-Carboniferous Australia moved from tropical to near-polar latitudes. The details of this rapid drift remain to be documented, but potentially offer an APWP against which the postulated displacement of parts of the New England Fold Belt can be tested.

There is no reliable Permian palaeopole from cratonic Australia, but the earliest Triassic palaeopoles from the New England Fold Belt in northern NSW are not greatly different from the Late Carboniferous ones, permissive of an interpretation that Australia did not move much with respect to the South Pole in that interval.

Preliminary palaeomagnetic results show that Western Tasmania appears to have been in its present position with respect to Gondwanaland by the Late Cambrian (Li et al. 1993, in prep.), although the accuracy of the constraint is such that minor movements (up to a few hundred km) could not be detected. Taken together with geological argument that the Mathinna Group is the on-strike continuation of the Melbourne Trough succession (Powell & Baillie 1992; Powell et al. 1993b), the evidence is that Elliot and Gray's (1992) reconstruction for Palaeozoic Tasmania is untenable.

In summary, despite relatively abundant palaeomagnetic data in some time intervals, there is really very little palaeomagnetic constraint on possible tectonic models in the Early Palaeozoic before the eastward spread of the Lambian overlap assemblage. In the Carboniferous, there is a phase of rapid polar wander which is potentially good for testing models of orogen-parallel translation and rotation in the New England Fold Belt, but more work needs to be done on defining the reference APWP.

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Terrane Definition in the Lachlan Orogen: Palaeomagnetic Tests

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Introduction

Palaeomagnetics has made a major contribution to the understanding of orogenic belts around the world, by its ability to recognise the amalgamation and accretion of allochthonous terranes and by its ability to recognise rotations within orogenic collages and cratonic regions.

The Palaeozoic Lachlan Orogen of southeastern Australia stands out as one significant orogenic belt in which palaeomagnetism has not played any significant part in its interpretation. Why is this? There are three possible explanations:

1) there is a Mesozoic thermal and/or chemical overprint which, by resetting the palaeomagnetic compass, frustrates the ability to document Palaeozoic displacements.
2) the Lachlan Orogen is an abnormal orogen. Its assembly did not involve any terrane movements or block rotation above the palaeomagnetic detection limit.
3) palaeomagnetic studies have been applied to relatively young rocks in the orogen, which formed after major tectonic terrane accretion and block rotation.
4) there is no well defined early Palaeozoic polar wander path for the Australian craton which can be used as a yardstick with which to compare data from the orogen.

A combination of points 1) and 3) are probably the main reasons for the lack of significant palaeomagnetic input to our understanding of the Lachlan Orogen. It probably also fair to say that point 4) may be also relevant here, especially since some of the data are obtained from the orogenic belt itself. If one believes Scheibner (1985) and Coney et al. (1990), that all rocks outboard of the Late Proterozoic crystalline basement (ie Tasman Line) may be suspect (ie may have been displaced from their areas of formation - the concept of being presumed guilty until innocence is proven), then one should not use rocks from the orogenic belt to constrain the craton APWP. I certainly do not believe point 2) above, as I now elaborate.

The Lachlan Orogen

The Lachlan Orogen is in some ways an anomalous orogen - different from the classical collisional orogens of the Appalachians and Cordilleras, or the younger Western Alps and the Himalayas. It is a convergent margin orogen that formed by a oblique compression that was resolved into a combination of east-west compression (that led to meridional folding, thrusting and cleavage formation with some conjugate faulting) and north-south (or NNE-SSW) compression that led to (near)latitudinal folding, cleavage formation and thrusting in addition to strike-slip faulting along existing meridional faults (Glen 1992). Such an deforming environment would be conducive to internal block rotations as well as along-strike movements of terranes. However these terranes would need not be exotic or as easily recognisable as the classic terranes that make up the accreted part of the Cordilleras or even the Appalachians.

Terranes in the Lachlan Orogen

The Narooma terrane

This small terrane occurs around Batemans Bay and Narooma on the south coast of NSW (cf Powell 1983, Leitch and Scheibner 1987). Reinterpretation of stratigraphy in the Narooma area (Lewis and Glen 1991, Glen et al. in prep) indicates a mafic volcanic basal part which grades up into a chert-rich sequence and then into overlying argillites. The Narooma Terrane is thus a classic oceanic terrane, similar to some terranes (eg Marin Headland) in the North American Cordillera. Palaeontological work by Ian Stewart (Monash University, Stewart and Glen 1991) indicates that around Narooma, the chert sequence ranges in age from Late Cambrian into Late Ordovician. Farther north near Batemans Bay, Bischoff and Prendergast (1987) obtained Middle Cambrian fossils from limestone clasts in the basal basaltic unit at Burrewarra Point and Late Cambrian to Early Ordovician from the chert sequence at Melville Point.

This Cambrian to Ordovician history recorded by the Narooma Terrane is in marked contrast to relations elsewhere in the Lachlan Orogen, where rocks of the same period consist of a Cambrian greenstone/chert sequence in central Victoria and either a volumetrically major Lower Ordovician turbidite sequence overlain by Late Ordovician black shales or a volumetrically minor variable volcanic/limestone sequence. Stratigraphic differences thus indicate the separate nature of the Narooma Terrane.

A terrane must be fault bounded. Bounding faults between the Narooma Terrane and the Lower Ordovician Adaminaby Group have been mapped and inferred in the Narooma area (Lewis and Glen 1991, Glen et al. in prep). However, the boundary between these units at Melville Point has previously been reported as conformable. This inconsistency needs to be resolved. Two possibilities are that either there is an, as yet, unrecognised bedding-plane fault at Melville Point, or the terrane boundary lies farther west, and that the turbidites adjacent to the cherts are part of the Narooma terrane as well.

The Melbourne-Mathinna Terrane

This allochthonous terrane in the Southwestern belt of the Lachlan Orogen was proposed by Glen et al. (1992) to solve several major problems. The main one was the Lower Ordovician to mid-Silurian similarity in stratigraphic history between rocks in this belt, situated in central Victoria (lying between the Avoca Fault on the west and the Mount Wellington Fault Zone in the east) and to a lesser extent in northeastern Tasmania, and rocks in the Eastern belt of the Lachlan Orogen exposed in eastern NSW and East Gippsland in Victoria. Such a similarity could not have developed with the belts in the present positions, since they have been separated since the Late Ordovician by the Central Belt (=Wagga Omeo zone).

This problem was resolved by suggesting that the Melbourne-Mathinna terrane originally lay c. 450 km south of the eastern belt, and amalgamated with the rest of the Lachlan Orogen in the latest Silurian to mid-Devonian.

Such a solution also solved several other vexing problems, viz, the jog in the pattern of Ordovician granitoids along the eastern edge of the Delamerian Orogen, the lack of any proximal foreland basin on the eastern side of the Delamerian Orogen (except in northwestern NSW and in western Tasmania) the simple deformation pattern in the terrane, and particularly, the great width of Ordovician turbidites across the Lachlan, which Glen et al. argued was more apparent than real because of doubling-up caused by insertion of the Melbourne-Mathinna Terrane.

The Central Belt

Glen et al. (1992) suggested that the Central belt in the Lachlan Orogen was another strike-slip terrane because it is bounded by major dip-slip and strike-slip faults and because its deformation style from the Late Ordovician to Carboniferous indicated consisted north-south compression. The amount of movement of this terrane is unknown.

The problem of the Ordovician shoshonitic volcanics

A shoshonitic volcanic/shale/limestone association occurs in six separate belts of volcanics spread across the Eastern belt of the Lachlan Orogen. These volcanics were mainly formed from the Late Ordovician to Early Silurian although components were active from the Early Ordovician. There is some controversy about the tectonic significance of these volcanics - did they represent an island arc (Molong Arc) subsequently dispersed by later deformation - or were they formed by some other process (see Scheibner 1989 and Wyborn 1992 for discussions)?

Significantly, shoshonitic volcanism largely overlapped with deposition of turbidites and a starved black shale facies in marine basins east and west of the volcanic belts. Although there is some limited interfingering of arc detritus with the more quartz-rich detritus typical of the turbidites, there are places where coeval turbidites show no sign of any volcanic input. Contacts in these areas are possibly faults. In such cases, there is a probability that the volcanic rocks represent a separate terrane from that represented by the turbidite-shale sequence (Glen 1992).

Palaeomagnetic Input

Postulating terrane models for the Lachlan Orogen is one thing (the hardest!). Testing them is another. One of the best potential tools in this regard is palaeomagnetism.

I would thus like to suggest that there be a real concerted application of palaeomagnetism to the Lachlan Orogen. To do this, several things are needed:

1) a good APWP for the Australian craton that does not include data from the orogenic belt.
2) tests devised to see whether it is possible to see through Mesozozic overprints. The conglomerate and fold tests are the obvious ones.
3) a palaeomagnetic project focusing on Ordovician and Cambrian rocks, testing both for along-strike movements of terranes as well as for block rotations. Three elements need to be considered. The shoshonitic volcanics and their basement, the turbidite association and the Narooma terrane. Such a project would make an important contribution to existing NGMA studies on the Lachlan Orogen .

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Tectonic problems in the New England Orogen and Bowen-Sydney Basin system

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Palaeomagnetic studies could contribute to our understanding of the tectonic evolution of the New England Orogen and Bowen-Sydney Basin by addressing several current problems, some of which are:

1. Early to Middle Devonian rocks in the Tamworth Belt are currently interpreted as part of an oceanic island arc system, with some debate as to the polanty. Equivalent rocks in Queensland are considered to be part of a continental margin volcanic arc system. What is the relationship between the two arc systems ? Where was the island arc system located in relation to the continent (Lachland) ?

2. During the Late Devonian to Late Carboniferous, the New England Orogen was dominated by a convergent plate margin system, with west-directed subduction at the continental (Lachland) margin. Are the more quartzose metasedimentary rocks of the Shoalwater and Beenleigh blocks accreted terranes or simply part of the accretionary wedge ?

3. The latest Carboniferous to earliest Permian is a time of plate reorganisation in the New England Orogen. Continental margin magmatic arc activity ceased in the western part of the orogen and was replaced by volcanism related to extension and initiation of the Bowen-Sydney Basin system. What is the relationship of the plate reorganisation to the magnetic overprinting that occurred at this time and is widespread in eastern Australia ?

4. In the Early Permian, the magmatic arc relocated to the eastern part of the orogen. The Camboon Volcanic Arc is probably of continental margin affinity, whereas the volcanics in the Gympie Block are island arc tholeiites. Is the Gympie Block an accreted terrane and, if so, at what time was it accreted to the Australian continental margin ?

5. In the mid-Permian, oroclinal bending has been inferred, involving about 500 km of southward (relative to craton) translation of part of the accretionary wedge. This interpretation was based on structural geology, and the oroclines are clearly seen in the aeromagnetic data. Anisotropy of magnetic susceptibility measurements show that the magnetic fabric is related to the mesoscopic cleavage in the deformed rocks. Can palaeomagnetism help constrain the oroclinal bending model ?

6. The Bowen-Sydney Basin system evolved in a back-arc setting simultaneously with the Early Permian arc volcanism and the oroclinal bending. Is there any evidence for strike-slip movements between the basins and the orogen during the early phase of basin history ? Can the later foreland loading phase of basin history be related to collisional events (including possible docking of exotic terranes) and major shortening in the orogen ?

Uraniferous quartz - hematite breccias at Mt Painter (South Australia): Palaeomagnetic dating of hydrothermal activity

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Palaeomagnetic measurements indicate that the uraniferous Radium Ridge Breccias near Mount Painter in the northern Flinders Ranges of South Australia have been magnetized twice, both times in the Permo-Carboniferous. The palaeomagnetic south pole for one remanence was estimated as 165.1^{0}E, 65.7^{0}S (A_{95}=11.5^0). The direction for the other remanence was not well defined; however samples collected from diamictite bodies within the breccias gave 133.9^{0}E, 33.1^{0}S (A_{95}=6.9^0) as the probable pole for the overprint. The latter is similar to overprint poles published from central Australia, which are generally attributed to the Alice Springs Orogeny (Fig.1).

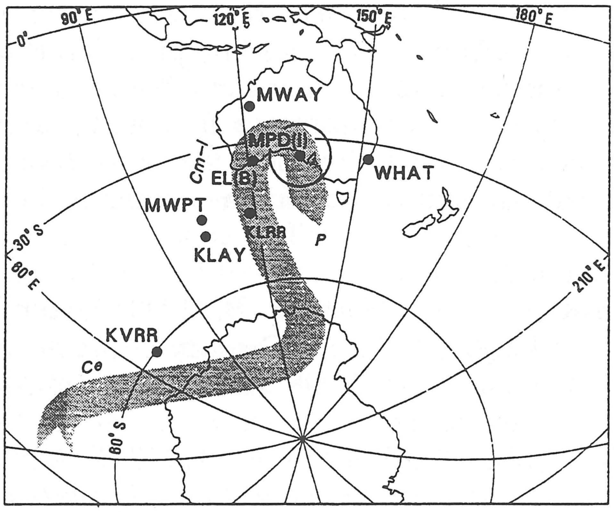

Fig. 1 Diamictite pole MPD(I) for intermediate temperature component compared with overprint poles from central Australia (Li et al., 1989). (From Idnurm and Heinrich, 1993, fig. 11).

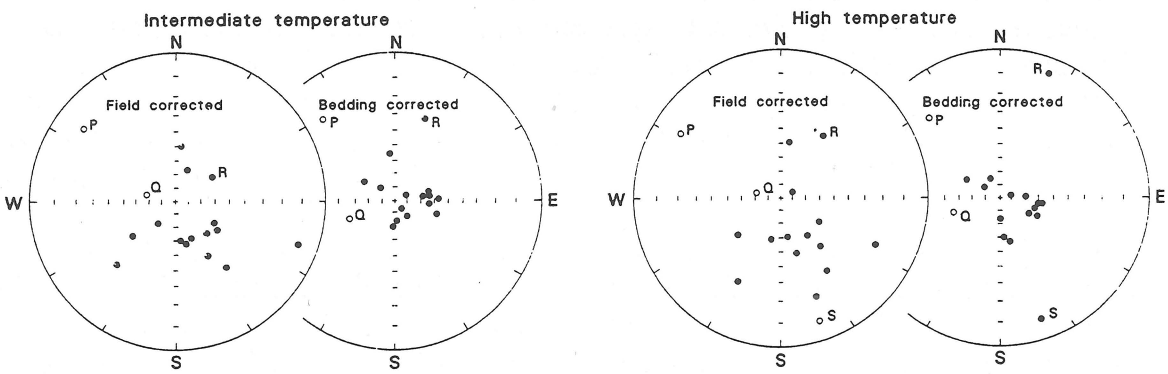

Fig. 2 Equal angle stereo projections showing intermediate and high unblocking temperature directions for fine-grained siliceous sinter. Increased clustering of directions as a result of bedding-correction provides evidence at 99% confidence level for a primary, pre-folding, magnetization of the youngest unit in the Mount Gee Sinter. Open (closed) circles denote upper (lower) hemisphere. (From Idnurm and Heinrich, 1993, fig. 4b).

Magnetization directions interpreted as Permo-Carboniferous were obtained also from the Mount Gee Sinter (a quartz-hematite-rich chemical sediment which overlies the Radium Ridge Breccias) and from U-mineralized hematitic ironstone bodies within the breccias. The magnetizations of both units were probably coeval with the younger magnetization of the Radium Ridge Breccias. A positive fold test (Fig. 2) demonstrates that the remanence of the sinter is primary, thus indicating a major hydrothermal event in the Permo-Carboniferous.

It is not clear by how much this event postdates the deposition of the underlying Radium Ridge Breccias and hematitic ironstone. The latter may be Ordovician or older if earlier monazite U-Pb data are correct, and may have been formed by granite-related hydrothermal fluids. In that case, the older remanence in the breccias is also an overprint. Epithermal sinter formation and chemical (rather than purely thermal) resetting of the remanence in the underlying breccias were probably due to deep circulation of oxidised fluids during Permo-Carboniferous tectonic activity. Chemical reaction of these fluids with pre-existing magnetite-bearing ironstones may have been responsible for uranium mineralization during the Permo-Carboniferous. This interpretation is consistent with published textural, isotopic and fluid inclusion data, but an older age for the uranium concentration, as a primary part of the ironstone formation, cannot be excluded. Alternatively, if the monazite data are discarded, the entire hydrothermal process including iron, uranium and silica deposition could have occurred in the Permo-Carboniferous.

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Early Palaeozoic APWP of Gondwanaland: The Delamerian Revisited

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Superficially, a comparison of Australian Palaeozoic apparent polar wander paths (APWP) since the first compilation of Irving and Green (1958) suggests that there has been a great deal of progress. However, the Palaeozoic APWP for Gondwanaland is still known only rudimentarily. In a Gondwanaland 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. The implications of the different models are of major global palaeogeographic and tectonic significance. Some models suggest only small oceans between Laurentia and Gondwanaland throughout the Palaeozoic, while others suggest a wide palaeo-Atlantic existed in the Devonian-Carboniferous.

Figure 1 shows how the path with respect to Africa has evolved with time. Figure 1a is redrawn after Irving and Green (1958) re-cast in a Gondwanaland framework with respect to Africa. The path shown in Fig. 1b was proposed by McElhinny et al. (1968) and while it was based entirely on African data it showed the same general trend as the 1958 path. The next development (Fig. 1c) 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 a displaced terrane. 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 (Fig. 1d). This model advocated the opposite geomagnetic polarity for the Early Palaeozoic compared to that conventionally used. Another continuous path model proposed which retained the original polarity convention was that of Morel and Irving (1978) (Fig. 1e). 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, but added considerable detail to the Early Palaeozoic (Fig. 1f). In particular 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 Goleby (1980) produced a path with a loop similar to that of Morel and Irving's, adding support for an autochthonous Tasman Fold Belt (Fig. 1g). The reality of this loop has been confirmed by Klootwijk and Giddings (1985), although these workers maintain that it is the record of Kanimblan (Mid-Carboniferous) overprinting throughout the southern Tasman Fold Belt (Fig. 1h).

Since 1985 there have been two more "refinements" to the Gondwanaland Palaeozoic APWP. Based on geological considerations and the appearance of some new Silurian data from 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. This segement is dotted in Fig. 1i.

Finally, in a synthesis of global data Van der Voo (1992) proposed a "filtered" path which nevertheless recognises an autochthonous Tasman but differs from the previous paths in detail, particularly the segment for which no data exists.

At this stage there does seem to be a majority consensus on general features of the Gondwanaland Palaeozoic APWP, although fine details and their timing is not agreed on. To summarise the present position it is fair to say that there are three schools, in order of numerical superiority;

(1) **the autochthonous school** (CSIRO and North American workers) who accept that the Tasman Fold Belt formed basically in-situ and that the Mid-Palaeozoic path for Gondwanaland contains a loop, although there are no reliable data points for the earlier south trending segment,

(2) **the allochthonous school**, represented by European workers who still prefer a path similar to the 1958 path (Bachtadse and Briden, 1991) and who dismiss all poles from the Tasman Fold Belt older than Carboniferous,

(3) **the AGSO school** that believes that many of the pole positions that define the Mid-Palaeozoic loop are actually related to Carboniferous Kanimblan overprinting and the real Mid-Palaeozoic path is well to the north (in an African reference frame).

It is extraordinarily difficult to acquire reliable palaeomagnetic data from Early Palaeozoic rocks from Gondwanaland for a variety of reasons. These include remagnetisation associated with tectonic processes, the presence of an ancient regolith with attendant problems from weathering, lightning and poor outcrop. Thus the following preliminary account is unusual in that we report results from an Early Palaeozoic intrusion that has not been overprinted in the least since the time of formation.

Mafic intrusions that occur in the Adelaide Geosyncline date from various stages of the Delamerian Orogeny with some being pre- to syn-tectonic and others being post-tectonic. We have collected samples across the range of tectonic settings and preliminary rock magnetic results correlate well with their respective tectonic histories. The Black Hill Norite is a post-tectonic gabbroic body with a well constrained age at 487 ± 5 Ma, i.e. Early Ordovician. The rock has a high magnetic susceptibility of 0.050 SI (~4000 uG/Oe) and a strong remanence, 4.5 Am^{-1} (4500 uG), giving rise to a pronounced aeromagnetic anomaly (see Shanti Rajagopalan et al. this volume). The remanence comprises a single component which is extremely stable with a median destructive field of 200 mT (2000 Oe). While such extreme stability is rare, it has been reported from other post-tectonic mafic intrusions where it has been found to arise from very fine grained magnetite exsolved in pyroxene and plagioclase. The petrology and rock magnetic properties suggest that the rock could not have been overprinted since its time of emplacement. The mean direction is Dec = 210^0, Inc = 10^0 (a95 = 4^0) with a preliminary palaeomagnetic pole position at 50^0S, 9^0E (dp = 2^0, dm = 4^0). Preliminary palaeomagnetic data from other Cambro-Ordovician mafic intrusions in South Australia reflect their degree of deformation and alteration. The most deformed dykes have "paramagnetic" susceptibilities and retain very little magnetite. The remanence of these dykes is carried mainly by haematite and shows little within sample consistency in direction. The results from the deformed intrusions serve to emphasise the significance of the palaeomagnetic result from the Black Hill Norite.

If the Black Hill Norite result is substantiated by further work, it suggests that the Early Ordovician pole position, immediately following the Delamerian Orogeny, was near the African Bight as plotted in Figs. 1i and j, rather than northwest of Africa (Fig. 1f). In addition, we would argue that this pole position rules out the the AGSO model (Fig. 1h), since the pole falls close to the Devonian segment of that APWP. Nevertheless, we need more pole positions of Late Ordovician and Early Silurian age to discriminate between the two main models for Palaeozoic APWP of Gondwanaland.

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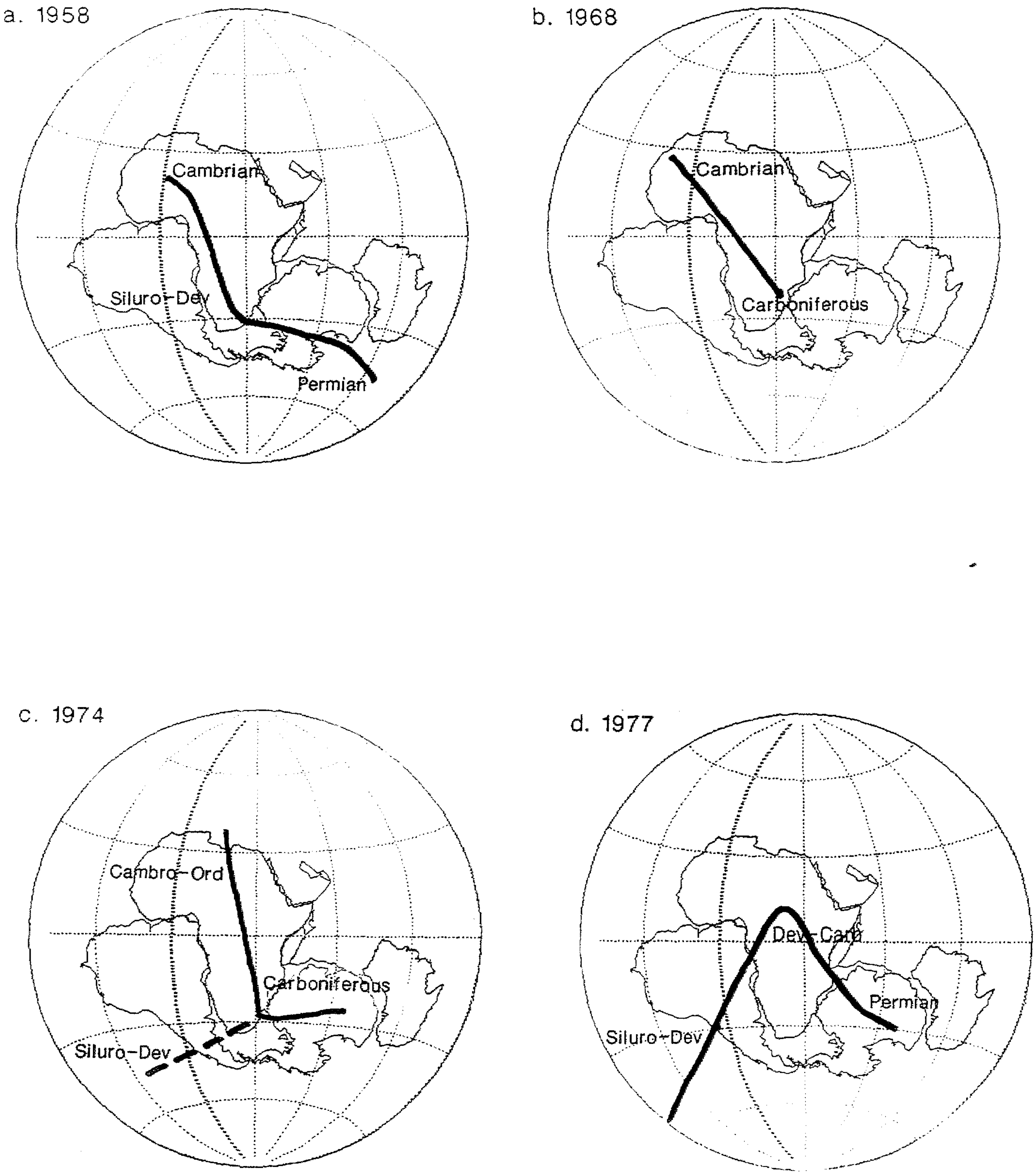
a. 1958
Cambrian
Siluro-Dev
Permian
b. 1968
Cambrian
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c. 1974
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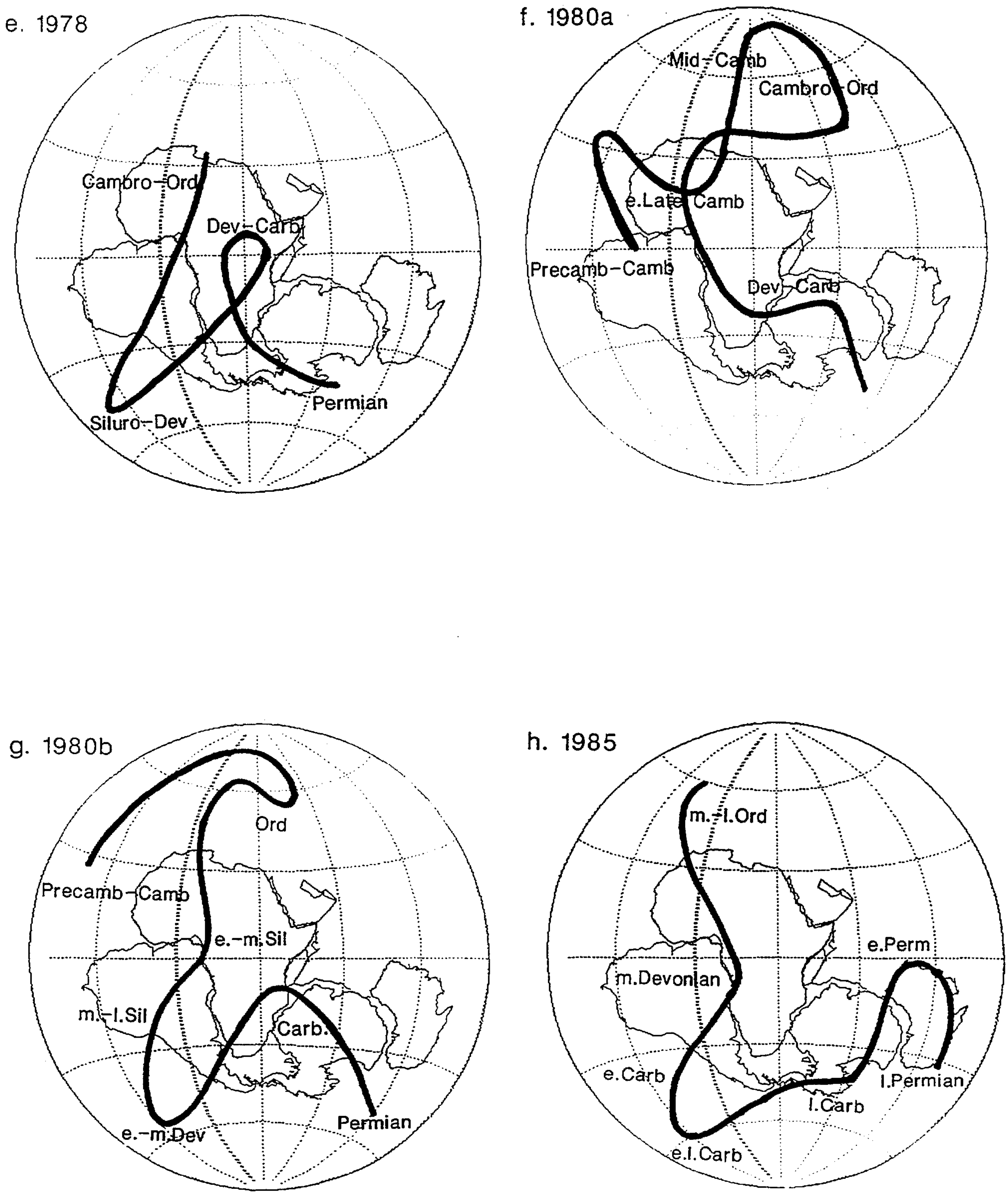
d. 1977
Dev-Carb
Permian
Siluro-Dev


e. 1978
Cambro-Ord
Dev-Carb
Siluro-Dev
Permian
f. 1980a
Mid-Camb
Cambro-Ord
e.Late Camb
Precamb-Camb
Dev-Carb
g. 1980b
Ord
Precamb-Camb
e.-m.Sil
m.-l.Sil
Carb.
e.-m.Dev
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h. 1985
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m.Devonian
e.Perm
e.Carb
l.Permian
l.Carb
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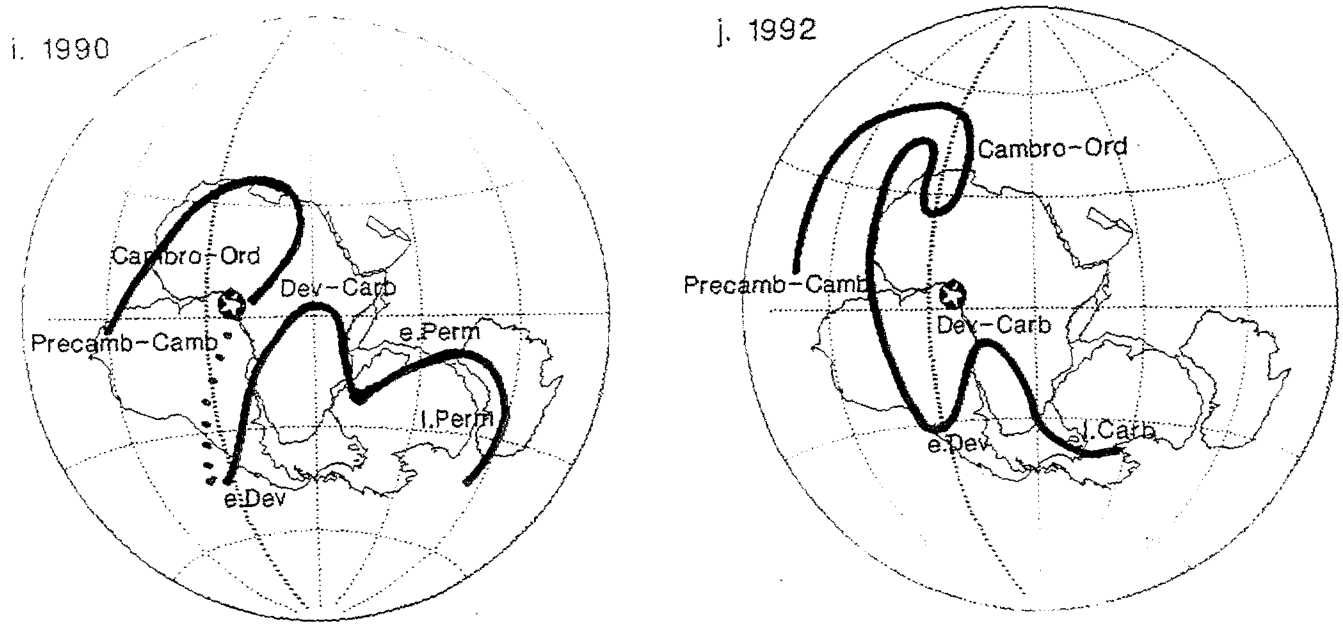

Fig. 1 Palaeozoic APWP models proposed for Australia and Gondwanaland;
(a) Irving and Green (1958) based on Australian data,
(b) McElhinny et al. (1968) based on African data,
(c) the allochthonous model of the Tasman Fold Belt given by Embleton et al, (1974) and McElhinny and Embleton (1974),
(d) the autochthonous model given by Schmidt and Morris (1977) after invoking the polarity option for Cambrian and Ordovician poles (which plot on the obscured hemisphere for this projection),
(e) the "Y" path of Morel and Irving (1978) introducing the Siluro-Devonian loop and implying an autochthonous Tasman Fold Belt,
(f) after Klootwijk (1980) showing the Delamarian overprint poles of Cambro-Ordovician age,
(g) after Goleby (1980) showing similarities with the loop path,
(h) after Klootwijk and Giddings (1985) re-calibrating the age of the loop,
(i) Schmidt et al. (1990) using only reliable data and emphasising the missing link (Ordovician-Silurian segment dotted), and
(j) Van der Voo (1992) sythesising reliable data from all Gondwanaland continents.
The star in (i) and (j) is the preliminary pole from the 487 Ma Black Hill Norite reported here - the missing link?

A New Palaeomagnetic Quality Filter: Implications for Gondwanan Palaeozoic Apparent Polar Wander Path

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The quality of available palaeomagnetic data varies greatly for diverse reasons, e.g. the lack of stepwise demagnetization for most of the early results, and the degrees to which the palaeohorizontal and age of a remanent magnetization are constrained. It is therefore critical that each data set be evaluated carefully before being used to investigate tectonic implications.

Existing quality filters can be generalized into two types based upon the way in which they work. Incremental schemes (or point systems), such as those described by McElhinny & Embleton (1976) and Van der Voo (1990), set out a number of parallel criteria, with the quality of a palaeopole being measured by the number of criteria it meets. Stepwise schemes (e.g. Briden & Duff, 1981) on the other hand, assign reliability criteria with a range of priorities. The quality of a palaeopole is assessed on a step-by-step basis, with a palaeopole proceeding to a higher quality level only if it passes each step.

Table 1 present a stepwise quality filter modified from Briden & Duff's (1981) scheme,

Table 1. Palaeomagnetic data quality filter

Criteria	*Pole quality and usefulness*
(1) All specimens have been subjected to demagnetization using one or more demagnetizing techniques, i.e. thermal, alternating field and chemical demagnetizations. Magnetic remanent components have been distinguished. (2) Results (experimental) fully documented.	*No* —→E pole (Unacceptable)
↓*Yes*	
(1) Reasonably large sample: ≥3 sites (or ≥12 samples) in sedimentary rocks, ≥3 layers of lava flows or dykes (with a minimum of 3 samples from each flow or dyke). (2) Reasonable precision ($a_{95} \leq 30^{o}$). (3) A presumption of tectonic coherence with the craton or tectonic block concerned. (4) Paleohorizontal not suspect; Palaeohorizontal determined either by fold test or other geological test; or, structural correction makes no significant change to the remanent direction.	*No* —→**D** pole (Questionable)
↓*Yes*	
(1) Sufficiently large sample: ≥6 sites, or ≥24 samples for sedimentary rocks, ≥6 layers of intrusives or dykes. (2) Moderate to high precision ($k \geq 10$ & $a_{95} \leq 16^{o}$). (3) Age of magnetization established within a period or 60Ma, whichever is smaller.	*No* —→**C** pole (Acceptable, but use with caution)
↓*Yes*	
Age of magnetization established within an epoch for the Phanerozoic or 30Ma, whichever is smaller.	No —→**B** pole (Reliable - key pole)
↓*Yes* A-class pole (Best pole - key pole)	

with some of the criteria in Van der Voo's (1990) scheme being incorporated. This scheme is more stringent than the Van der Voo scheme, and it gave palaeohorizontal control higher priority than age control.

The Palaeozoic apparent polar wander path (APWP) of Gondwanaland was reassessed using the A- to C-class poles. Whereas the A- and B-class poles (i.e. the key poles) are used as "anchors" on the APWP (Fig. 1), C-poles are only of subsidiary value in defining the APWP mainly because of their poor age constraints (for clarity, C-poles are not shown in Fig. 1).

It should be emphasized that no data-filtering process can be totally objective, and that all the data were assessed based on the reported information. Even the quality of the key-poles may be challenged by later work (results from the Early Silurian and early Late Devonian ring complexes from Africa, for example).

The proposed APWP indicates that East and Wast Gondwanaland did not join together until the mid- to Late Cambrian. Although the drifting history of Gondwanaland may have been complicated in detail during the Cambro-Ordovician period as indicated by the proposed hairpins, northern Africa nevertheless remained at a polar position during that time interval. Palaeomagnetic constraint for the Silurian period is still poor, but well-established palaeoclimatic information indicates that the South Pole migrated from northern Africa to South America during the Early Silurian. This is consistent with assigning an earliest Silurian age for the controversial Tumblagooda Sandstone pole.

The Late Devonian-Early Carboniferous APWP is well constrained by key poles to migrate from east South America to central Africa. However, key poles are needed to define the mid-Carboniferous path between central Africa and East Antarctica

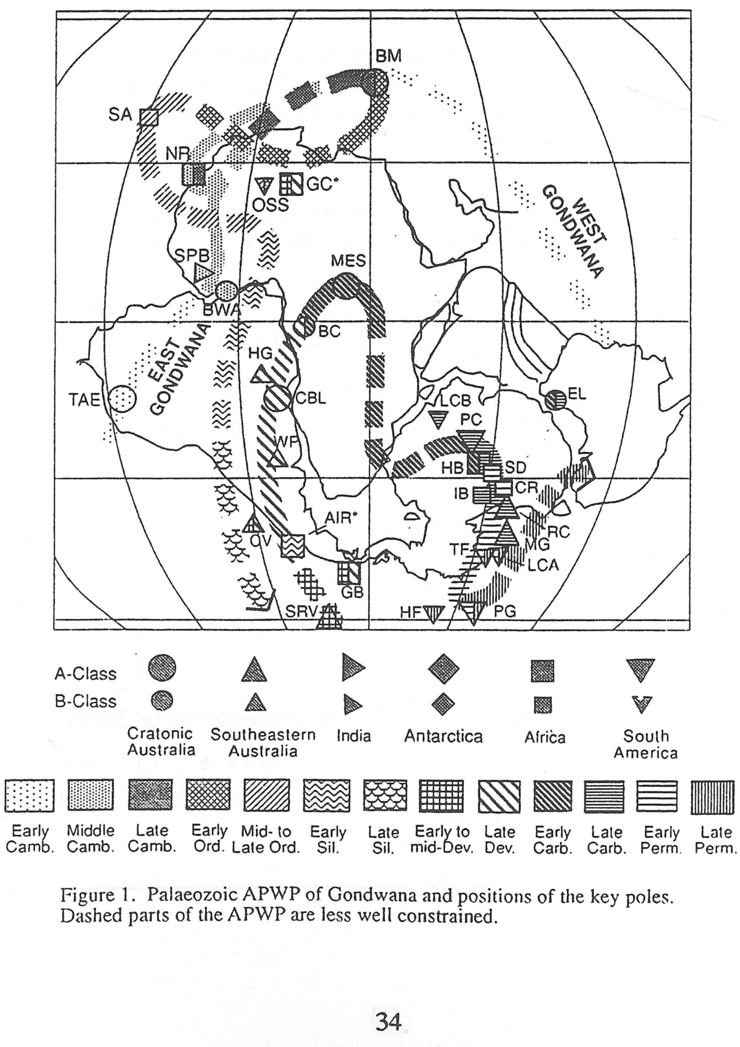

Figure 1. Palaeozoic APWP of Gondwana and positions of the key poles. Dashed parts of the APWP are less well constrained.

The Dilemma of Australia's Late Palaeozoic Pole Path: Y-Front or G-String?

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Gondwana underwent considerable rotations during the Late Palaeozoic, resulting in large-scale latitudinal movement of its eastern, Australian, rim. The Australian Apparent Polar Wander Path (APWP) can offer, therefore, a high resolution record that may be crucial in unravelling key geological problems of regional and global importance such as: extent of the mid-Carboniferous Kanimblan deformation, mode and timing of accretion of New England terranes, extent and timing of Australia's Carboniferous polar drift, mode and timing of the Gondwana-Laurentia convergence, and extent and cause of global remagnetization and isotopic resetting during the Kiaman Reversed Polarity Interval.

Unfortunately, definition of the Australian Late Palaeozoic APWP has continued to be contentious ever since Morel and Irving's (1978) Gondwana-wide **Y-path** was challenged by Goleby's (1980) alternative Australian path. The latter was based on a string of pole positions from the Lachlan Fold Belt now known as the G-poles (**G-string**). From the mid 1980s onwards, these two opposing concepts have been pursued, with various modifications, by palaeomagnetists from on the one hand, the CSIRO and University of Western Australia (e.g. Schmidt et al.,1990; Li et al.,1990; Powell et al.,1990; Thrupp et al.,1991; Schmidt and Lackie,1993), and, on the other hand AGSO (e.g. Klootwijk,1988; Klootwijk et al.,1992; Klootwijk and Giddings,1988,1993). Though recent studies have considerably extended the database of Late Palaeozoic poles, the debate shows little sign that a common opinion may be reached any time soon. The depth of the controversy may be apparent from the widely different interpretations that the two groups reached from a joint key-study of the Mount Eclipse Sandstone from the Ngalia Basin. This difference poses some fundamental questions on the soundness of palaeomagnetic interpretation methods, in particular whether the opposing views suffer from the re-enforcement syndrome?

The two opposing views on Australia's Late Palaeozoic pole path are compared in figure 1. A generalized APWP representing the progression of pole paths previously proposed by Schmidt, Li, Powell and others (Fig.1C, SLiP-path) is compared with an alternative path proposed by Klootwijk and Giddings (Fig.1D, KG-path). The SLiP-path and the KG-path both show Middle Palaeozoic pole positions that are distal to Australia and proximal Late Palaeozoic pole positions, and both paths imply that Eastern Gondwana moved during the Carboniferous from equatorial to near-polar latitudes. Timing of this movement is currently not better defined than between latest Visean and the Kiaman Superchron. Preliminary results from ignimbrite successions in the Hunter-Myall region suggest that a considerable part of this movement may have occurred between extrusion of the Nerong Volcanics and the Paterson Volcanics, that is between about 340 and 330 Ma based on preliminary SHRIMP zircon ages (Jon Claoué-Long, pers. comm. 1993). This is all that the two paths have in common.

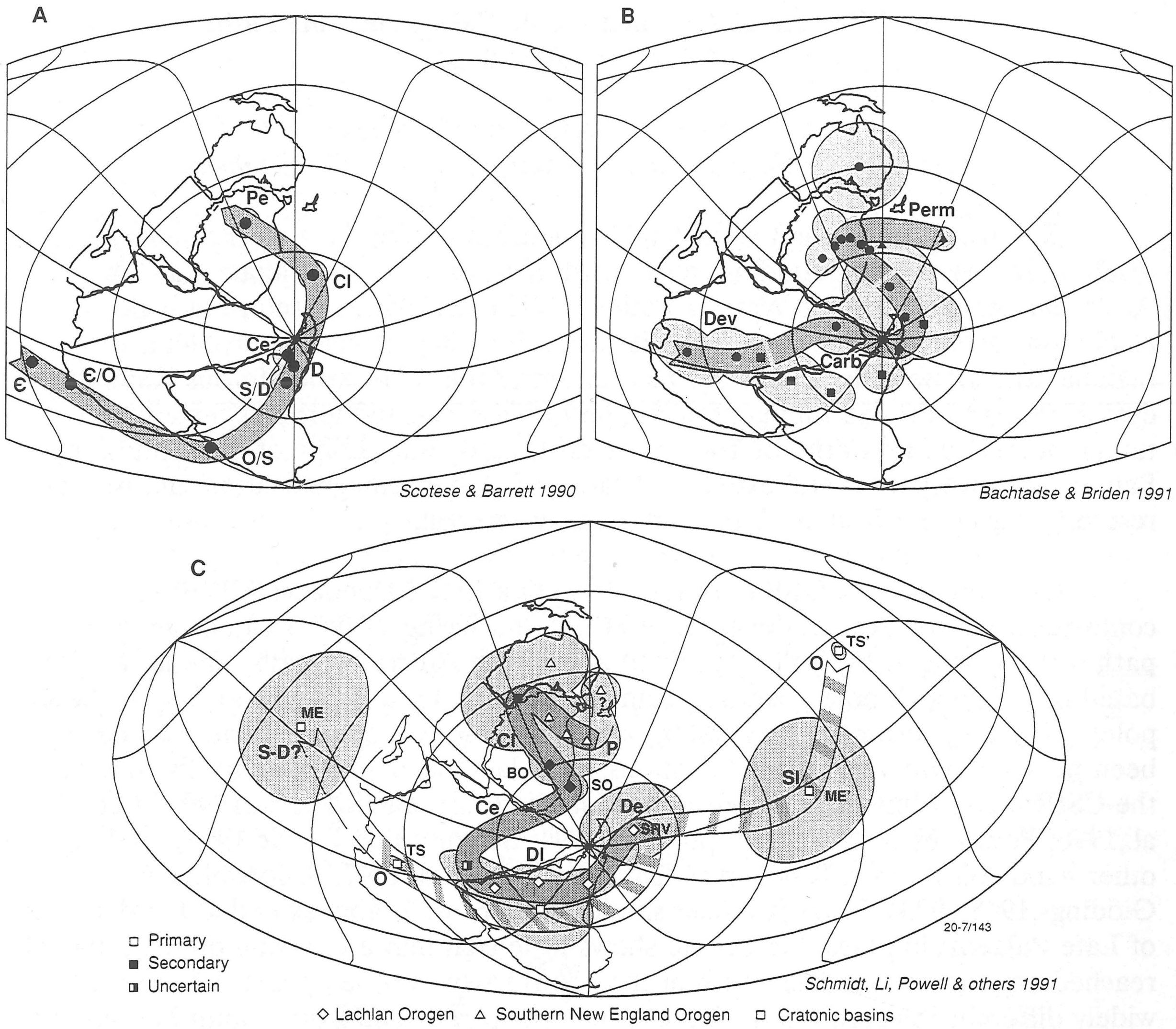
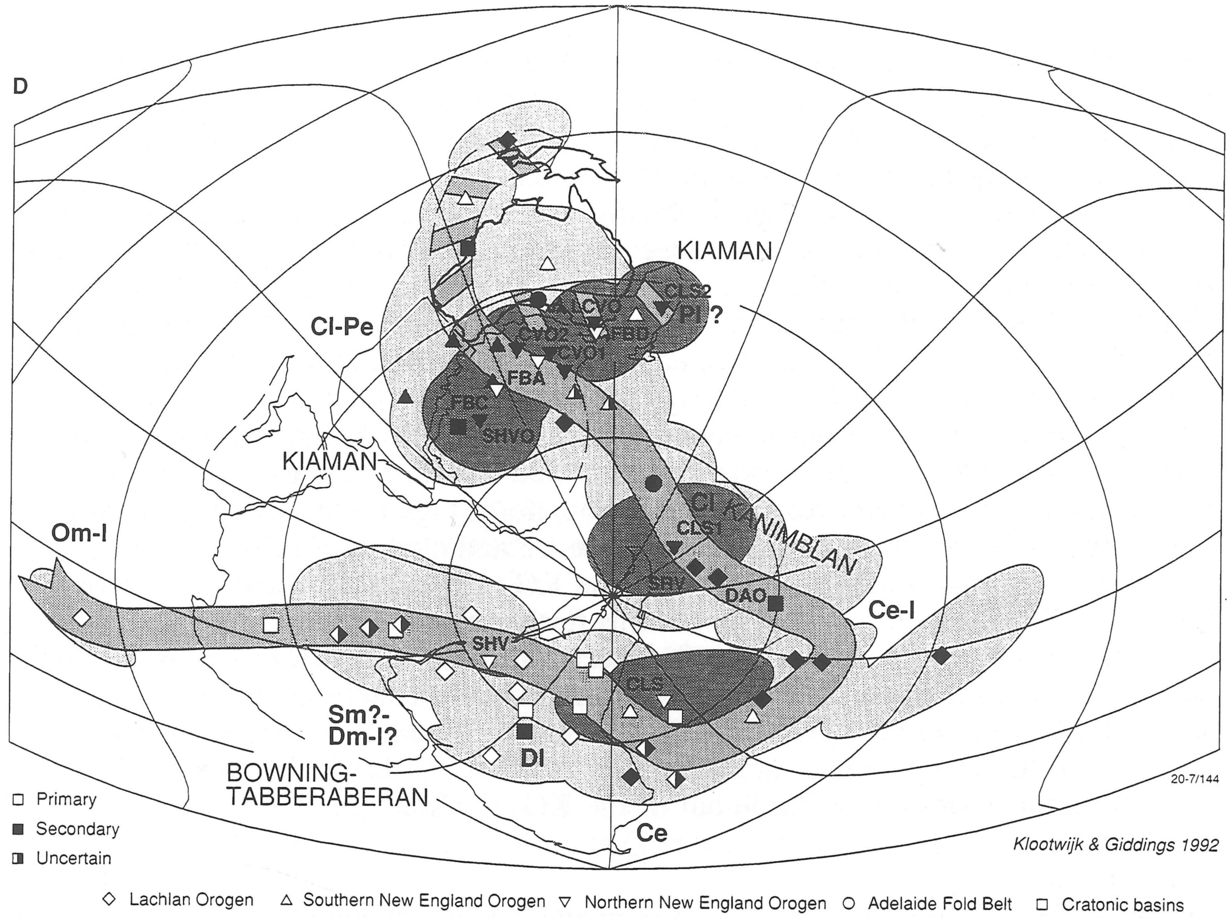


Fig.1 Generalized Late Palaeozoic apparent polar wander paths. A) Gondwana APWP proposed by Scotese and Barrett (1990), based on lithological indicators of climate of the Gondwana continents. B) Gondwana APWP proposed by Bachtadse and Briden (1991), based on palaeomagnetic data from Africa (full dots), Australia (squares), and Madagascar (triangles). C) Compilation of previously proposed Australian APWPs (SLiP-path, after Schmidt et al.,1986,1987,1990; Li et al.,1989,1990,1991; Thrupp et al.,1991). Two versions are shown for the pre-Devonian part of the APWP, based on antipoles of the Mereenie Sandstone (ME) and the Tumblagooda Sandstone (TS). SRV: Snowy River Volcanics; SO: ibid, overprint; BO: Buchan Caves Limestone overprint. D) Alternative Australian APWP (KG-path, after Klootwijk,1988; Klootwijk et al.,1992), SRV: Snowy River Volcanics, DAO: Dandenong Volcanics, CLSO1: Star of Hope Formation volcanics. Recently obtained pole positions from northeastern Queensland (Klootwijk et al., 1993) are distinguished by medium-shaded ellipses. Oblique Aïtoff projections. Gondwana reconstruction after Lawver and Scotese (1987), with Australia in its present-day position. Only poles with α_{95} or E_{95} values less than 20º have been plotted in figures C and D. See tables 9 (SLiP-paths) and 10 (KG-path) in Klootwijk et al. (1993) for data details.



A crucial difference between the two paths is the westward and clockwise Devonian-Early Carboniferous loop of the SLiP-path against the eastward and counterclockwise Late Devonian-Early Carboniferous loop of the KG-path. The westward loop implies Middle Devonian to Early Carboniferous re-eopening of an oceanic basin between the northwest African margin of Gondwana and the southern margin of Laurentia/Armorica, but such a re-opening is not supported by a variety of regional geological observations. The KG-path, in contrast, advocates continuing Gondwana-Laurasia contact during Devonian-Carboniferous.

Another crucial difference between the SLiP-path and the KG-path is the interpretation of the pole position from the Early Devonian Snowy River Volcanics (Fig.1C,D: SRV). This pole has a positive foldtest (Schmidt et al.,1987). The SLiP-path assumes folding to have occurred during the Middle Devonian Tabberabberan Orogeny, and interpretes the magnetization as primary. However, the SRV-pole position falls between poles for the Star of Hope Formation volcanics and the Dandenong Volcanics (Fig.1D), which are both of Late Devonian-Early Carboniferous extrusion age. A primary Early Devonian origin for the SRV-magnetization is, therefore, highly unlikely. It is far more reasonable to assume that the middle Carboniferous Kanimblan orogenic event also has affected the Snowy River Volcanics. We, therefore, interpret the three comparable pole positions (Fig.1D: SRV, CLSO1, DAO) as Kanimblan overprints, and interpret the SRV-magnetization as the pre-folding Kanimblan conjugate of directionally-close post-folding overprints in the Snowy River Volcanics and the overlying Buchan Caves Limestone (Fig.1C: SO,BO, Schmidt et al.,1987).

Two recently proposed pole paths for Gondwana provide further support for the KG-path. These are an APWP based on lithological indicators for the Late Palaeozoic Gondwanan climate (Fig.1A, Scotese and Barrett,1990), and an APWP based on reinterpretation of Gondwanan palaeomagnetic data in terms of Carboniferous overprints (Fig.1B, Bachtadse and Briden,1991). Although there are considerable differences in detail between these three APWP's (Fig.1A,1B,1D), their overall common characteristics distinguish them as a group from the SLiP-path (Fig.1C). These include roughly similar trajectories, counterclockwise rather than clockwise loops, lack of polar movement during the Silurian-Devonian, a middle to Late Carboniferous remagnetization age for the SRV pole, and absence of a Devonian-Early Carboniferous westward excursion. The Early Carboniferous eastward excursion is a feature unique to the KG-path, and its reality and extent need further determination. Preliminary results from Carboniferous ignimbrites successions from the southern Tamworth Belt support its existence and also show evidence for poles which position considerably to the east of the KG-path's eastward loop as shown in figure 1D. Whether, and to what extent this further eastern position may be indicative for counterclockwise rotations of the southern Tamworth Belt relative to the craton still has to be established. Pending this determination it may be questioned whether some of the poles on the apex of the SLiP-path's westward loop may represent antipoles to the KG-path's eastward loop, or in other words whether the SLiP-path's Y-front masquerades as the inside-out of the KG-path's G-string.

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Permian Remagnetisations and the Defornation of the New England Fold Belt

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The New England orogeny caused remagnetisation which is ubiquitous in sediments and very common in igneous rocks of all ages (Klootwijk & Giddings 1988). However, some rocks have been remagnetised whilst being folded, capturing a snapshot of the development of folding at that time. This new aspect of the palaeomagnetic data offers an opportunity to exploit the remagnetisation to gain a better understanding of the structural evolution of the orogen.

In light of the widespread remagnetisation, other aspects of the palaeomagnetic data from New England require re-evaluation. The apparent polar wander path (APWP) of Australia (Fig. 1) indicates rapid movement from low to high palaeolatitudes between the Early Carboniferous and the Late Carboniferous, with Australia moving from low latitudes through to high latitudes (Irving 1966, Schmidt 1988). Recent SHRIMP ion microprobe dating of zircons from Carboniferous volcanics of the southern New England Orogen (Roberts et al 1991) has meant a review of this part of the APWP. As rapid as the Carboniferous polar shift was thought to be (Schmidt 1988), the older date for the high latitude Paterson Volcanics (referred to as Paterson Toscanite in some references) now compresses the time available for Australia's shift into an absurd few Myr. While not disputing the new date for the Paterson Volcanics, the widespread remagnetisation and updating of older rock sequences during the Permian may be responsible for this paradox.

Palaeomagnetic studies of volcanic and sedimentary units within the southern New England Orogen show a northward migration of remagnetisation of the Orogen with time during the Permian. The magnetisation of some rock units is brought into best agreement after only partial tilt correction. This is interpreted as indicating remagnetisation during folding. Thus, after partial bedding correction nine sites in the Late Devonian/Early Carboniferous Kiah limestone yield a mean direction of Dec = 125.3^0 , Inc = 83.7^0 (α_{95} = 5.5^0), and a pole position at Lat = 38.0^0S, Long = 162.3^0E (A_{95} = 10.0^0). The Permian Werrie Basalt was magnetised before folding and required full tilt correction yield a site mean direction of Dec = 158.0^0, Inc = 74.4^0 (α_{95} = 11.5^0), and a pole position at Lat = 57.2^0S, Long = 170.3^0E (A_{95} = 20.2^0). The Visean Nerong/Gilmore Volcanics appear to have acquired a complicated remanence that is not related simply to the geological structures.

Figure 1 shows the current APWP for Australia from the Early Devonian to the Triassic. Large latitudinal movement of Australia is indicated from low palaeolatitudes in the Late Devonian/Early Carboniferous, as shown by the Worange Point (WP) and Hervey Group (HG) poles, to high palaeolatitudes in the Permian, as shown by the Early Permian Mount Leyshon pole (MTL). The Seaham Formation (referred to as Main Glacial Stage) pole (Irving 1966) falls quite close to the Early Permian MTL and northern Drummond Basin volcanics (DCV) poles suggesting an Early Permian age of magnetisation for the Seaham Formation rather than a primary Visean/Namurian age for the magnetisation. As well, the pole for the Paterson

Volcanics (Irving 1966), which is now known to be 330 Ma old (Roberts et al 1991), falls close to the SB pole, rather than the Late Devonian/Early Carboniferous HG and WP poles which would be expected if the Paterson Volcanics retained a primary magnetisation. Thus, it is possible that the Paterson Volcanics have been remagnetised after Australia had moved to higher palaeolatitudes or as with the Nerong/Gilmore Volcanics, the Paterson Volcanics acquired a non-representative remanence.

The pole for the Kiah Limestone (KL) falls on the Early Triassic section of the APWP while the Werrie Basalt pole (WB) falls off the APWP, although its α_{95} is quite large (~20). Rotation of the Werrie Syncline and Tamworth Anticline in the Hunter-Bowen Orogeny (Collins 1991) may explain the dissimilarity of the poles with the APWP. Also, imprecise knowledge of the palaeohorizontal of the flows could result in the "rotation" of the poles from their "correct" position. The palaeomagnetic results obtained from the Werrie Basalt, Kiah Limestone (this study) and the Seaham Formation (Irving 1966) show that the time of remagnetisation of those units appears to have migrated from the southeast to the northwest.

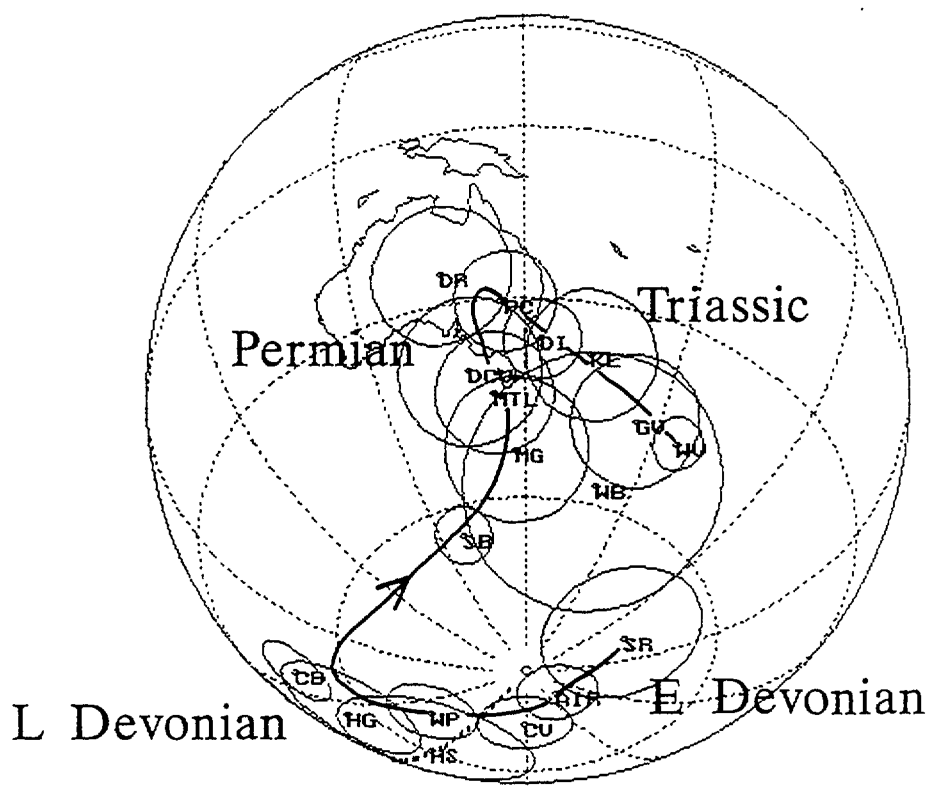

Figure 1. Apparent polar wander path (APWP) for Australia from the Devonian to Jurassic. HS, Hermannsburg Sandstone, Li 1988. AIR, Ring complex, Hargraves et al 1987. CV, Comerong Volcanics, Schmidt et al 1986. WP, Worange Point Formation, Thrupp et al 1991. HG, Hervey Group, Li et al 1988. CB, Canning Basin, Hurley & Van Der Voo 1987. SB, SV Snowy River Volcanics/Buchan Caves Limestone overprint, Snowy River Volcanics, Schmidt et al 1987. MG, Main Glacial Stage (Seaham Formation), Irving 1966. MTL, Mount Leyshon diatreme, Lackie et al 1991. DCV, Conway-Bimurra volcanics, Lackie et al 1992. DR, DI, Dundee Rhyodacite, Dundee Ignimbrite, Lackie 1989. PC, Patonga Claystone, Embleton & McDonnell 1980. WB, KL, Werrie Basalt, Kiah Limestone, this study. WV, Western Victorian Basalt, Schmidt 1976a. GV, Garrawilla Volcanics, Schmidt 1976b. Plot type: orthographic. Centre of plot 45^{0}S, 150^{0}E.

The results from the Seaham Formation show a positive fold test indicating that magnetisation occurred pre-folding. The pole position of the Seaham Formation suggests a Late Carboniferous/Early Permian age of magnetisation. Data from the Werrie Basalt also shows that magnetisation has occurred prior to significant tilting of the flow units. Data from the Kiah Limestone in the south of the Belt indicate that magnetisation occurred just before or at the beginning of folding. This is similar to the Werrie Basalt result.

The Kiah Limestone results from the north of the Belt indicate that magnetisation was acquired at various stages of folding. In the mid to Late Permian, meridional folds developed throughout the Tamworth Belt producing the Werrie and Gloucester Synclines and the Timor Anticline (Collins 1991). If folding is synchronous within the Tamworth Belt then the Permian remagnetisation event progressively moves from the southeast in the Early Permian to the northwest in the mid to Late Permian. It can also be argued that if remagnetisation across the Tamworth Belt is synchronous, then folding of the belt has progressed from the northwest to the southeast although this is not favoured on geological grounds.

The sequence of events are depicted in figure 2, where in the southeast remagnetisation occurs in the flat lying units, while further to the north, the remagnetisation occurs at the initiation of folding, while even further to the north, remagnetisation is synfolding in age. As a consequence of the time of remagnetisation of the units and thus attitude of the strata, the present measurable remanence varies from steep inclinations in the north to shallower inclinations in the south.

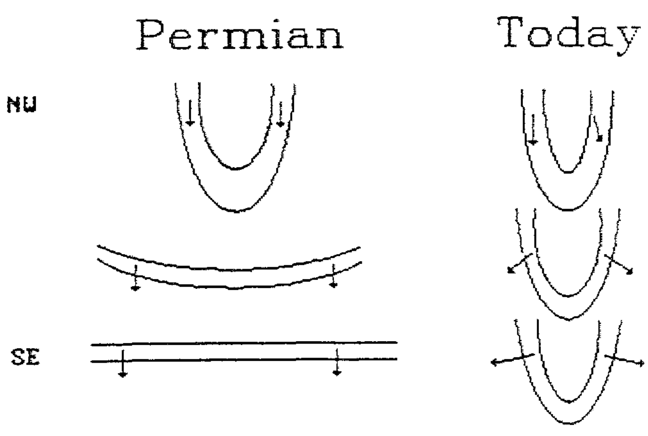

Figure 2. The LHS diagram depicts the relationship between the degree of folding and remagnetisation within the Tamworth Belt during the Permian. In the SE, remagnetisation occurs pre-folding, while progressively further to the northwest remagnetisation occurs during greater degrees of folding. The RHS, shows the relationship of the remanence of the units with respect to the structure of those units. Note, that in the south (Seaham Formation) the remanence of the sediments is dissimilar between limbs (because its a pre-folding remanence) while in the north (northern Kiah Limestone samples) the remanence is close to parallel between limbs (reflecting the syn-folding remanence).

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Revision of the Australian Late Devonian to Early Carboniferous APWP

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Palaeomagnetism of the Early Carboniferous succession of the Mount Eclipse Sandstone in the Ngalia Basin, the latest Devonian succession of the Brewer Conglomerate in the Amadeus Basin, and the Late Devonian limestones in the Canning Basin, has been investigated. Six magnetic remanences were identified from the studied 869 samples from 36 sites and 33 diamond drill-cores: (1) a present geomagnetic field overprint, (2) a drilling-induced remanence acquired during industrial drilling, (3) a mid- to Late Carboniferous syn-deformational overprint acquired during the Alice Springs Orogeny, (4) a Visean primary remanence, (5) a latest Devonian primary remanence and (6) a late Frasnian - early Famennian primary remanence. The primary origin of the last three remanences was demonstrated by either a fold test, or combination of a syn-depositional stylolite-breccia test, a block test and a polarity test. They provide three high-quality poles with good palaeohorizontal and magnetization-age constraints for Australia: a Visean pole (MES) at 38.2°S, 54.4°E with A_{95} = 8.1°, a latest Devonian pole (BC) at 47.1°S, 041.0°E with A_{95} = 6.4° and a late Frasnian - early Famennian pole (CBL) at 58.5°S, 033.3°E with A_{95} = 9.0°. The CBL pole was calculated combining the results from this study and selected data from Hurley and Van der Voo's (1987) study.

The late Frasnian - early Famennian CBL pole from the Australian craton agrees with the Famennian HG pole (Li et al., 1988) and the late Frasnian - Famennian WP pole (Thrupp et al., 1991) from southeastern Australia (Fig. 1), implying that the Lachlan Fold Belt was amalgamated to the Australian craton by late Frasnian. The revised APWP implies that the Australian continent occupied equatorial or low-latitude positions from Middle Devonian to Visean. It also implies a high rate of continental drift (~20 cm/yr) for Gondwanaland during the Late Devonian and mid-Carboniferous.

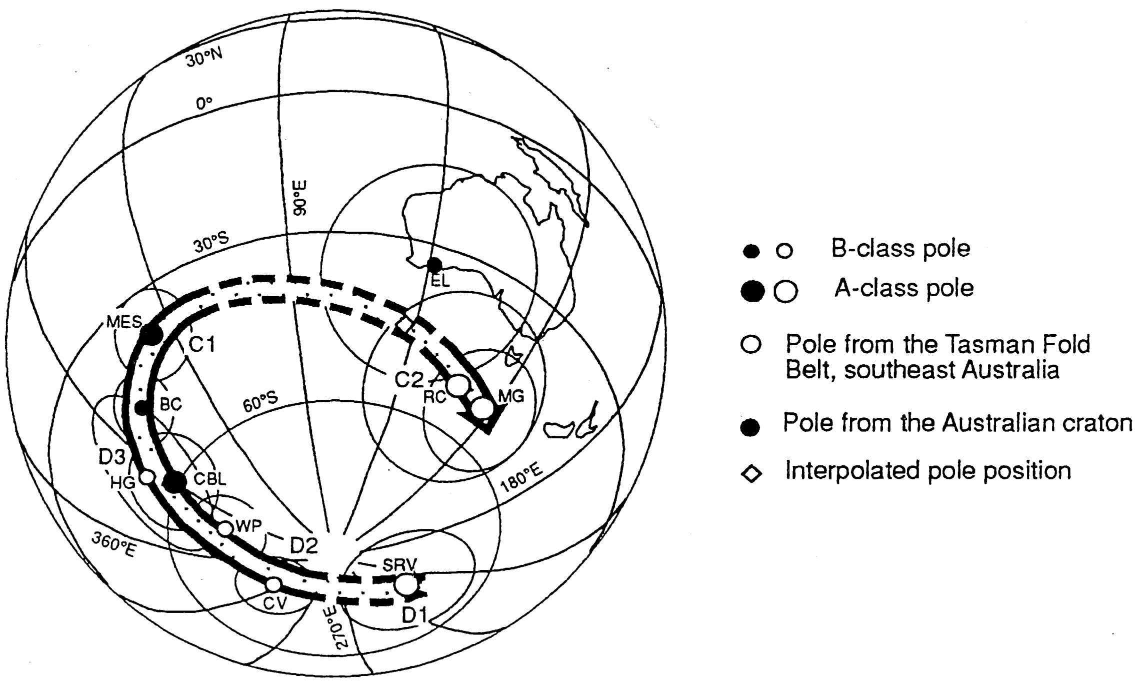

Figure 1. Revised Devonian - Carboniferous APWP for Australia based on A- and B-class poles. Equal-area stereographic projection. The continous parts of the path are more reliable than the dashed parts. D - Devonian, C = Carboniferous, 1 = early, 2 = middle or late and 3 = late.

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Palaeomagnetic results from the Moonbi and Walcha Road plutons and the surrounding hornfelses, New England Batholith, N.S.W.

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I-type granitoids of the Moonbi Plutonic Suite of the New England Batholith are well dated as Late Permian to Earliest Triassic (Shaw et al., 1991). Based on biotite/ bulk rock Rb/Sr dating, the age of the Walcha Road Adamellite is 247 Ma (Shaw & Flood, 1991) and the Moonbi Adamellite and Limbri Leucoadamellite are both 248 Ma (S.E. Shaw, pers. comm., 1993). Although the Moonbi and Bendemeer Adamellites have similar cooling ages, the Moonbi pluton intrudes the Bendemeer pluton (Chappell, 1978). All of these plutons probably have indistinguishable cooling ages.

The site mean of palaeomagnetic results of the Moonbi and Walcha Road plutons is Dec=288.0^0, Inc=+86.2^0, α_{95}=4.5^0, N=7 with a South Palaeomagnetic Pole position at Long=142.9E^0, Lat=28.4^{0}S, $\delta p=\delta m$=8.9^0 (Lackie, 1989) and Dec=205.9^0, Inc=+87.5^0, α_{95}=13.5^0, N=4 with a South Palaeomagnetic Pole position at Long=148.5^{0}E, Lat=35.6^{0}S, A_{95}=26.5^{0}respectively. All directions have reversed polarity. The combined data from those two plutons yields a mean direction of Dec=268.5^0, Inc=+87.3^0, α_{95}=4.7^0 with a corresponding South Palaeomagnetic Pole position at Long=144.9^{0}E, Lat=31.0^{0}S, A_{95}=9.1^0.

Oriented samples of the hornfelses around the Moonbi pluton were collected both to the west of the Peel Fault (from the Early to Mid Devonian of the Yarrimie Formation in the Tamworth Group and the overlying Upper Devonian Baldwin Formation) and from the hornfelses in the Devonian rocks of the Woolomin and Sandon Association around both the Moonbi and Walcha Road plutons east of the Peel Fault. All sites are within the biotite isograd, as outside the isograd the palaeomagnetism predates the folding which itself predates the emplacement of the plutons (Sunata, 1993).

The site mean of the palaeomagnetic directions from the hornfelses around the Moonbi pluton is Dec=122.3^0, Inc=+87.3^0, α_{95}=5.7^0, N=19 (South Palaeomagnetic Pole at Long=156.9^{0}E, Lat=33.2^{0}S, A_{95}=10.8^0) with all having a reversed polarity. This mean includes site WS20 which is just east of the Bendemeer pluton. The site mean from the hornfelses in the structurally less complex area west of the Peel Fault fail a fold test and show that the magnetisation of these hornfelses postdates the hornfelses postdates the folding. The mean palaeomagnetic results from the hornfelses around the Walcha Road pluton is Dec=2.9^0, Inc=-83.5^0, α_{95}=9.6^0, N=7 (South Palaeomagnetic Pole position at Long=150.8^{0}E, Lat=43.2^{0}S, A_{95}=18.4^0), all having a normal polarity (Sunata, 1993). The combined site mean of the hornfeses around both plutons is Dec=330.6^0, Inc=-86.8^0, α_{95}=4.7^0, N=26 when reversed polarity is converted to normal. The South Palaeomagnetic Pole position from the combined hornfels data is Long=155.3^{0}S, Lat=35.9^{0}S, A_{95}=9.0^0 (Fig. 1).

About midway between the Moonbi-Limbri and Walcha Road hornfelses at site WS12 (GR:281 685), red metachert contains two subvertical palaeomagnetic components where the normal is softer than the reversed polarity. These components are interpreted as remagnetisation during the Moonbi-Limbri (reversed) and Walcha Road (normal) suggests that the Walcha Road pluton is indeed younger than the Limbri Leucoadamellite and/or the Moonbi pluton.

The Late Permian/Early Triassic palaeomagnetic pole from the Moonbi and Walcha Road Adamellites and the surrounding hornfelses are consistent with other results for the Late Permian/Early Triassic. (e.g. the Dundee Rhyodacitic Ignimbrites in the New England Fold Belt and the Patonga Claystone and the Broughton Formation of the Sydney Basin).

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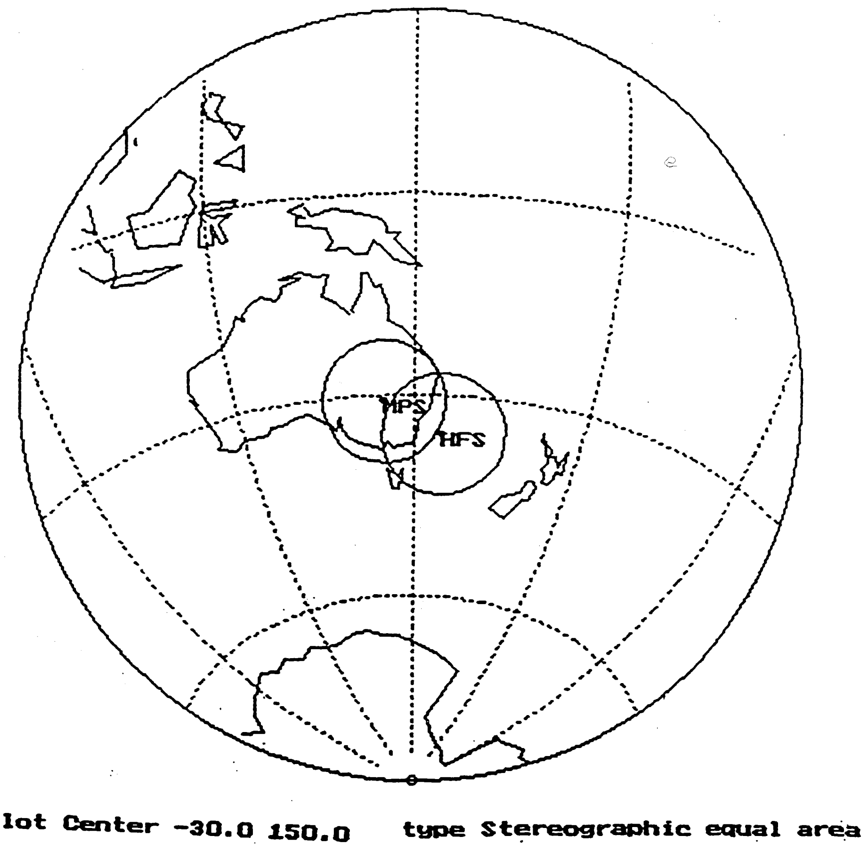

Fig. 1.
South palaeomagnetic pole from the Moonbi and Walcha Road Adamellites (MPS) and its hornfelses (HFS) at about 247 Ma. Circles represent radius of 95% confidence cone of the palaeomagnetic poles.

PROTEROZOIC GEOLOGY OF AUSTRALIA AND PALAEOMAGNETISM

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Palaeomagnetism has two principal applications to Proterozoic geology: correlation and tectonic analysis. Both are interdependent. Both rely on, and are in turn crucial to, the integrity of the reference apparent polar wander path (APWP). This paper discusses the significance of the Australian Proterozoic APWP to the applications above, and suggests areas where the APWP might be best refined.

Uncertainty or inaccuracy in the APWP derives from three main sources:

1. *Precision and/or interpretation of individual poles.*

As the domain of the specialist palaeomagnetist, this is not considered further herein.

2. *Relative and/or absolute age.*

Constructing an APWP requires that the *relative* age of *all* poles is known. Locally this may be provided by field geological relationships. Interregional comparisons require some other correlation parameter (e.g., isotopic age) to ascertain correct chronological order. A reference APWP requires calibration through critical poles of known age.

3. *Tectonic integrity of sampled blocks or terranes*

A single APWP assumes derivation of poles from a single coherent tectonic province or terrane, since the time of magnetisation. Ideally, complete APWP's should be compared between potentially separate terranes; data are rarely sufficient for this. At the very least, several reference poles from each block, and of equivalent ages, must be compared between blocks.

It is theoretically possible to construct an APWP without any direct isotopic age control. The grouping of poles should be clearly apparent. Path directions and loops should be resolved by stratigraphic order in local segments. Lack of tectonic integrity between blocks should appear as clearly separate paths. The present data for the Australian Proterozoic are far too sparse for this ideal situation.

The Australian Precambrian Shield may be divided into several fundamental blocks or cratons, separated by younger mobile belts (Plumb, 1979). The Archaean Yilgarn and Pilbara Blocks, and the Palaeoproterozoic Capricorn Orogen between, constitute the West Australian Shield. The West Australian Shield is separated from the Palaeoproterozoic Gawler and Curnamona Cratons by the Palaeo-Mesoproterozoic Albany-Fraser Province. All these southern Australian provinces are separated from the Palaeoproterozoic North Australian Craton by Meso-Neoproterozoic mobile belts: the Musgrave Block, Arunta Inlier, and Paterson Province (Fig. 1).

Integrity of young platform covers demonstrate that northern and southern Australia have comprised a single block or terrane since at least about 1000 Ma ago. The West Australian Shield has been a single tectonic unit since about 1600 Ma ago. Relative positions of the constituent blocks before these times remain conjectural.

Australia has almost no Proterozoic geological record prior to 2000 Ma. Interpretation of palaeomagnetic measurements from highly deformed, metamorphosed orogens is complicated. The simplest record to interpret begins after major platform covers developed; effectively ~1800 Ma to base of Cambrian (Fig. 1).

Sixty-three poles define the latest APWP for the Proterozoic of Australia (Fig. 2). Thirty come from the ~1800-1400 Ma McArthur Basin of northern Australia (Giddings and Idnurm, this volume; Idnurm, Giddings & Plumb, this volume). Most others were used by Idnurm and Giddings (1988) and are referenced therein.

The McArthur study highlights the need to derive the Proterozoic APWP from detailed studies through continuous stratigraphically-controlled sequences. Ten stratigraphically-ordered primary poles and sixteen overprint poles radically revise the APWP segment for the interval ~1700 - ~1600 Ma, both in terms of position and direction. A complex loop and switchback, with an angular rotation of ~120°, is comparable to the Logan Loop of North America. Further overprints range up to Cambrian and Tertiary. A geomagnetic-reversal record was constructed for ~2000 m of section. Preliminary poles for the <1500 - >1400 Ma Roper Group are displaced more than 90° from the earlier path segment.

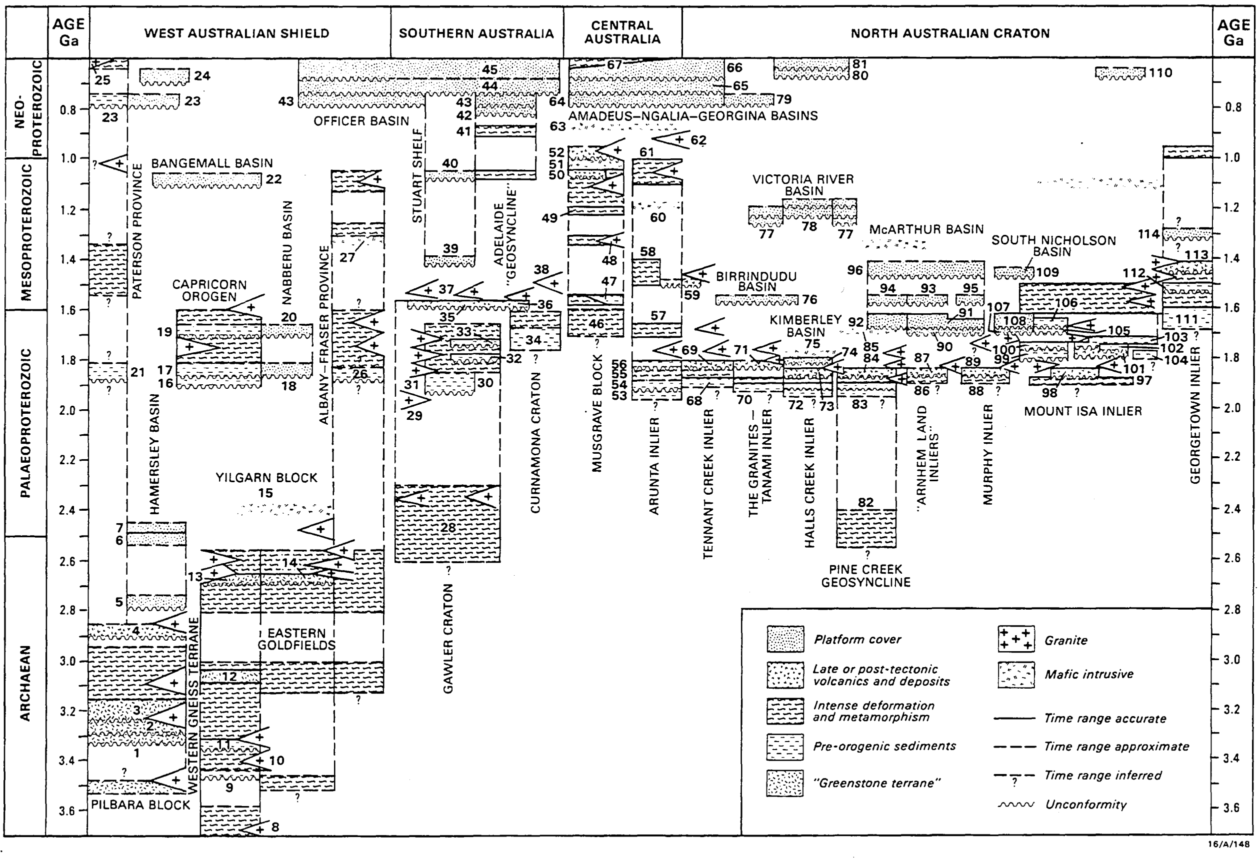

Figure 1. Time relations of principal Precambrian sequences of Australia (After Plumb, 1990)

The McArthur Basin APWP contrasts with the sparse data elsewhere. The 1700-1600 Ma McArthur Basin segment (100 Ma) contains about one-sixth of the total angular length of 1800--550 Ma (1250 Ma) APWP (Fig. 2). The McArthur Group primary poles alone define a 60° rotation for what may be just a few, or even less, tens of Ma. There are no known geological reasons why the McArthur Basin rate of shift should be unique. How many complex loops and switchbacks remain undetected in the remainder of the APWP?

A small stratigraphically-controlled study through the ~1350 Ma Morawa Lavas and related units on the Yilgarn Block (not shown on Fig.1) shows an angular shift (~30°) of comparable magnitude to the McArthur Basin segment and, again, reverses the direction of polar motion of previous APWP interpretations. The Morowa Lavas position, apparently older than the >1400 Ma Roper Group (RGBI, RGBH), means that either the preliminary mean age of the lavas (1360 ± 140 Ma) is too young, or that the Roper Group poles are overprints. The latter are close to a Kombolgie overprint (KFE).

The only other stratigraphically-controlled studies through sequences are several through the Neoproterozoic Amadeus Basin and Adelaide Geosyncline (Fig. 1). The latter, in particular, cluster around the Early-Middle Cambrian APWP segment, suggesting that most of these poles are overprints. Widespread active rifting and basin formation throughout the Neoproterozoic suggest that this interval should have experienced a rate and complexity of polar wander comparable to that during McArthur Basin times.

Instrument limitations of past studies confined most remaining pole determinations on Figure 2 to highly-magnetic rocks - mafic dykes and sills, and iron ores.

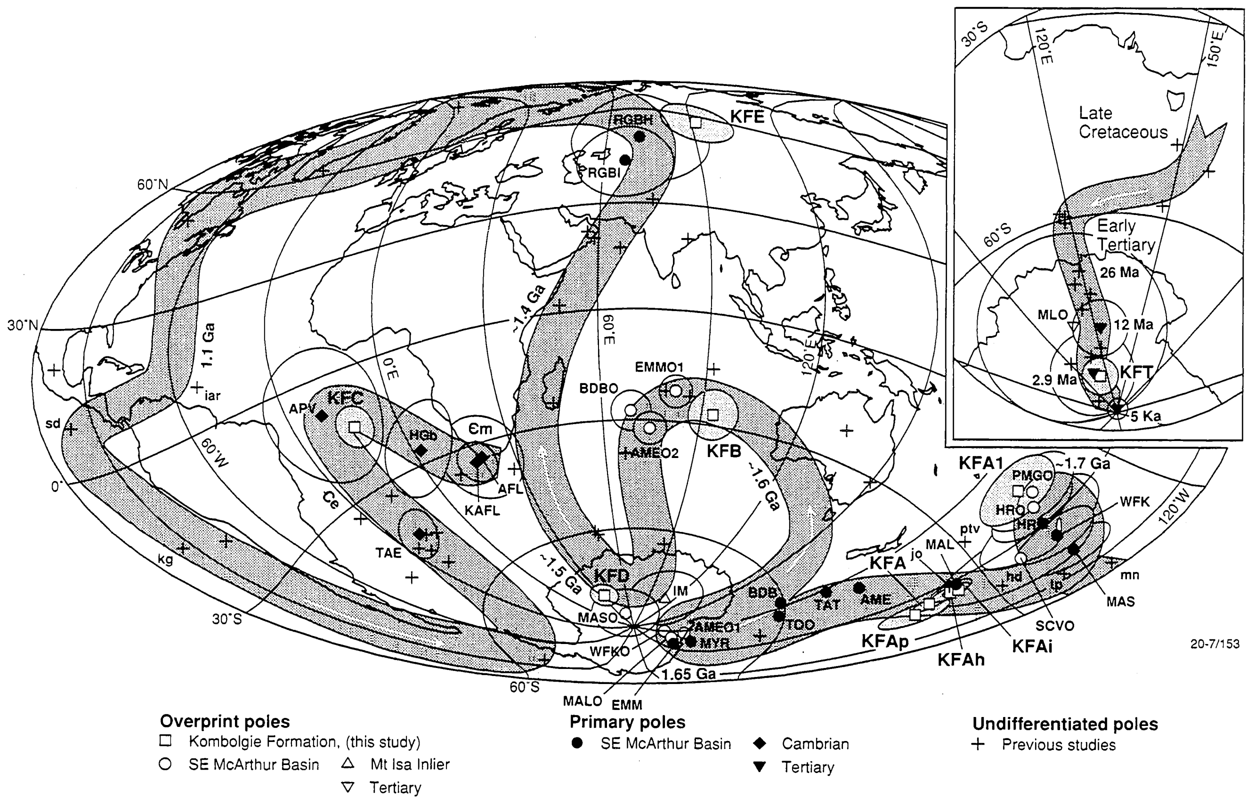

Figure 2. The 1800 Ma to Middle Cambrian and Tertiary (Inset) segments of the reference APWP of Australia (After Giddings and Idnurm, this volume).

Mafic intrusions are notoriously difficult to date isotopically. Some (Hart Dolerite, ~1800 Ma; Gawler Craton, ~1500 Ma & ~1600 Ma; Mount Isa, ~1100 Ma; Arunta Inlier & Musgrave Block, ~1050 Ma) may be constrained to significantly less than 100 Ma, and are essentially consistent with the APWP. Others from the western Yilgarn Block, while constrained relative to each other by cross-cutting relationships and baked contact tests, plot on the APWP at positions far removed from their reconnaissance isotopic ages.

There are no direct constraints on the age of magnetisation of iron ores, other than the ages of their host rocks, which are commonly very much older than the magnetisation itself. Indeed, the positions of poles on the APWP have been used to determine the age of magnetisation/formation of the iron ores, rather than to define the APWP itself.

In terms of application to correlation, a single APWP can be plotted through almost all of these data (Fig. 2). Apparent discrepancies relate to confusion between primary and overprint poles or to poor age constraints. The data are sparse, unevenly distributed, and sometimes poorly-controlled chronologically. Major departures from the presently simple APWP almost certainly remain to be discovered. Correlation from the present APWP is possible only within the broadest of limits. Magnetostratigraphic correlation by geomagnetic reversals is demonstrably possible. However, the sheer volume of data required to define the reversal pattern of what is still only a minor part of the McArthur Basin sequence would seem to make routine application impractical with present resources.

Since the present Australian Proterozoic APWP is interpreted as a single curve, most workers interpret the Australian Precambrian Shield as a single tectonic block throughout the Proterozoic. One cannot directly infer otherwise from the present data. But how reliable is this? It is impossible at present to construct independent, pre-1000 Ma APWP's for individual blocks of the Australian Shield. It is almost impossible to find any poles of reliably equivalent age for comparison. Is the coincidence of certain poles more apparent than real, reflecting intersections or crossovers of poorly-defined, separate APWP's?

The ages of the Yilgarn dykes are so uncertain that any direct comparisons are impossible. Uncertainty between ages of the Morawa lavas and Roper Group are discussed above.

The Gawler Craton is constrained only by results from dykes and overprints about 1500-1600 Ma old. Mortimer, Cooper, & Oliver (1988) have dated dykes which probably correlate with the "GB dykes" at ~1600 Ma, and this is in general agreement with regional stratigraphic constraints. They and Middleback iron deposit overprints plot near the ~1600 Ma segment of the McArthur Basin path (EMMO1, Fig. 2). But the 1600 age assigned to this part of the McArthur segment is derived largely from *correlation* with the dykes. This part of the McArthur segment may only be directly constrained as younger than 1640 Ma (Barney Creek Formation, R.W. Page, unpublished data), and *probably* older than the <1500 Ma old Roper Group. Major unconformities separate BDB (Balbirini Dolomite) from the Barney Creek Formation, below, and from the Roper Group, above. The Gawler ~1500 Ma "GA dykes" may probably be constrained by regional stratigraphy to within about $\pm$ 30 Ma. An immediately adjacent pole from the now precisely dated Gawler Range Volcanics (1592 $\pm$ 2 Ma; Fanning and others, 1988), previously regarded as a "1530 Ma" primary pole by Idnurm and Giddings (1988), now appears to be an overprint of uncertain age (p.W. Schmidt, personal communication). Thus, although coincidence between selected Gawler Craton and North Australian Craton poles *appears* compelling from present data, the coincidences *may be* fortuitous. Correlations are subject to further Gawler palaeomagnetic data and, hopefully in coming months, to successful dating of the Balbirini Dolomite from the McArthur Basin.

Therefore, while one can only infer a single APWP and thus a unified Australian Shield from the present APWP *alone* , uncertainties and inadequacies in the database do not allow one to yet preclude significant and independent departures from this idealised curve, and therefore significant relative movements between individual component blocks of this shield. The APWP has little constraint on longitudinal movement between blocks.

Where then can the Australian Proterozoic reference APWP be best refined? Platform covers suitable for detailed, stratigraphically-controlled sampling and minimal risk of overprint are best preserved on the North Australian Craton and adjacent areas:

~1840 - 1800 Ma : *Kimberley Basin succession* and *Hart Dolerite* provides well-exposed continuous sections. Secondary mineral assemblages in mafic lavas indicate likely overprinting.

~1800 - 1700 Ma : Only the upper *Tawallah Group, McArthur Basin* is so far defined, but overprinting is obviously a problem.

~1500 - ~1300 Ma : *Roper Group, McArthur Basin* and later *dolerite sills* are still poorly defined. Overprints appear likely?

~1200 ± 50 Ma : The undeformed, northern *Victoria River Basin* has excellent potential for fresh, continuous sections with minimal overprint. Minimum age only; possibly as old as Roper Group. Underlying *Limbunya Group* may be compared with the Nathan or McArthur Groups.

(?) 1000 Ma - Cambrian : Only the very latest Neoproterozoic of the *Amadeus Basin* sequence has been measured. Unmetamorphosed sections are available right down to Heavitree Quartzite . The structural history is complex. Overprints up to Alice Springs Orogeny are known, but present data does indicate that some primary poles are preserved.

Late Neoproterozoic : *Kimberley glacial successions* have potential to compare or confirm equivalent successions in the Adelaide Geosyncline/Amadeus Basin, provided obviously overprinted mobile zones are avoided.

Elsewhere, the *Nabberu Basin* of Western Australia provides a direct southern Australian comparison with the McArthur Basin. The overlying *Bangemall Basin* is about 1150 Ma old; care is needed to avoid zones of clear low-grade metamorphic overprint. The *Gawler Craton* may be better defined by remeasurement of the Gawler Range Volcanics and of overlying sequences on the Stuart Shelf. A complex structural history means that overprinting will always remain a problem for the thick *Adelaide Geosyncline* sequence, but it remains a clear candidate for further work.

These studies represent a vast amount of work. While the McArthur study has clearly demonstrated the need for detailed, systematic study through continuous sequences, a realistic sampling strategy needs to be developed by interlaboratory consensus, in order to refine the reference APWP within a useful and viable time frame.

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Palaeomagnetism of the Southeastern McArthur Basin: Poles, Overprints and Reversals

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Approximately 1800 samples from volcanic, clastic and carbonate sequences of the southeastern McArthur Basin in northern Australia were analysed palaeomagnetically to define in detail the Australian apparent polar wander path for a period centred at ~1670 Ma and to develop a Proterozoic reversal stratigraphy for correlation and dating. Twelve palaeomagnetic poles are interpreted as primary, including two that are preliminary. These increase the Australian palaeomagnetic database for the Proterozoic by ~30%. Another ten poles record three, or possibly four, periods of overprinting. The study also yields one of the oldest reversal records reported so far.

The ten better-established primary poles were obtained from the lower three of the four main stratigraphic sub-divisions of the Basin: the Tawallah, McArthur and Nathan Groups. These poles define an angular trajectory of about 120° and a time span of least 75 Ma, possibly exceeding 100 Ma. They confirm earlier preliminary results that suggested a major revision of the Proterozoic pole path for Australia. The two preliminary poles were obtained from the youngest sub-division of the Basin, the Roper Group, and confirm a large age gap between the Nathan and Roper Groups.

The poles for the oldest overprints were from igneous units in the Tawallah Group and appear to record metasomatism at the end of the last major period of volcanism in the basin. The pole for the next overprint falls on the path near the apex of a hairpin bend; it coincides with a likely period of rifting and high heat flow that accompanied the deposition of the upper McArthur Group. The third overprint, which appears to have been acquired during the long time-break separating the Nathan and Roper Groups, was found mostly in red dolomitic rocks.

The geomagnetic reversal record represents an accumulated stratigraphic thickness of 2100m, excluding gaps where the polarity remained undetermined because of overprinting, unstable remanences, intervals not sampled, or other causes. Reversal patterns from duplicate sections at different localities were compared for two formations, and showed encouraging consistency. Several parts of the reversal column appear to be distinctive enough for use in stratigraphic correlation.

Overprint magnetizations in the Palaeoproterozoic Kombolgie Formation: Delineation and significance

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A detailed palaeomagnetic study of the Palaeoproterozoic Kombolgie Formation, designed to improve our knowledge of the ~1.8Ga-~1.7Ga part of the Proterozoic Apparent Polar Wander Path (APWP) for Australia, has failed to yield conclusive evidence for a primary magnetization. What is significant though is the discovery that the Kombolgie has preserved a remarkable record of geological events in magnetic overprints, most of which we ascribe to distinct episodes of fluid migration through the Formation. We discuss this record and a number of analysis techniques that were employed to separate the different overprints.

The unmetamorphosed, plateau-forming sandstones of the Kombolgie Formation are the oldest sediments deposited in the Western McArthur Basin and crop out over much of western Arnhem Land in the Northern Territory. They form the basal unit of the Katherine River Group and lie with marked unconformity on most older rocks of the Pine Creek Inlier. They are constrained in age to between ~1.71Ga and ~1.83Ga by preliminary ion-microprobe U-Pb zircon dates on the underlying Plum Tree Creek Volcanics and the West Branch Volcanics at the top of the Katherine River Group. Samples were collected from 7 sections at 3 widely separated localities - the Edith Falls Basin, Mount Callanan Basin, and Arnhem Land Plateau (Deaf Adder Creek) - along the western margin of the McArthur Basin.

Initial distributions of magnetic directions, derived from extensive and detailed thermal demagnetization studies, were characterized by high scatter for all but one of the sections. A cluster-analysis technique in conjunction with blocking temperature analysis successfully enabled those scattered distributions to be broken down objectively into 8 distinct bipolar groups. One section was extremely coherently magnetized by comparison and directions fell into 2 similarly-directed, mono-polar groups differentiated on the basis of blocking temperature. We regard each of the bipolar groups, including the coherently magnetized group, as a distinct magnetizing episode related to a geological event.

Blocking temperature analysis and studies of the thermal demagnetization of IRM reveal that the remanence of each of the 8 bipolar groups is carried by hematite, and that in each case it has a distributed range of blocking temperatures up to the Curie point of hematite, the maximum blocking temperature available. In complete contrast, the remanence of the 2 mono-polar groups is mainly magnetite-based. Consideration of these characteristics and the heterogeneous nature of the geographical distribution of the different groups, strongly favour the magnetizations being high-stability chemical remanences. We argue that overlap of the blocking temperature spectra of these different remanences, resulting in numerous hybrid directions of magnetization, is the source of the high scatter. The bipolar remanences probably result from a similar physical mechanism operating at 'low' temperatures and at different times: fluid movement through the sediments triggered in response to local or regional activity. The coherent remanence is most likely thermochemical.

The different overprints can be dated using the reference APWP for Australia and most can be interpreted in terms of known regional geological events. Figure 1 shows the ~1.8Ga to Middle Cambrian and Tertiary segments of the reference APWP, along with the poles (prefixed by KF) corresponding to the overprints. From youngest to oldest the overprints (tagged by their corresponding pole acronym) record:

- A period of weathering at ~3 Ma (KFT);
- Extrusion of the extensive Antrim Plateau Volcanics in the Early Cambrian (KFC). The effects of this activity have propagated a considerable distance from known outcrop areas;
- A period of dyke intrusion at ~1.4/~1.3Ga (KFE);
- An event at ~1.5Ga (KFD), also found as an overprint in the basal part of the McArthur Group, southeast McArthur Basin, and as a complete remagnetization of dykes from the Mt Isa Inlier in response to regional metamorphism;
- An event at ~1.6Ga which correlates with the age of well-known metasomatic alteration found around the ore zones of the Alligator Rivers uranium deposits and the age of uranium mineralization (KFB). This overprint is also well-developed in the McArthur and Nathan Groups in the southeast McArthur Basin;

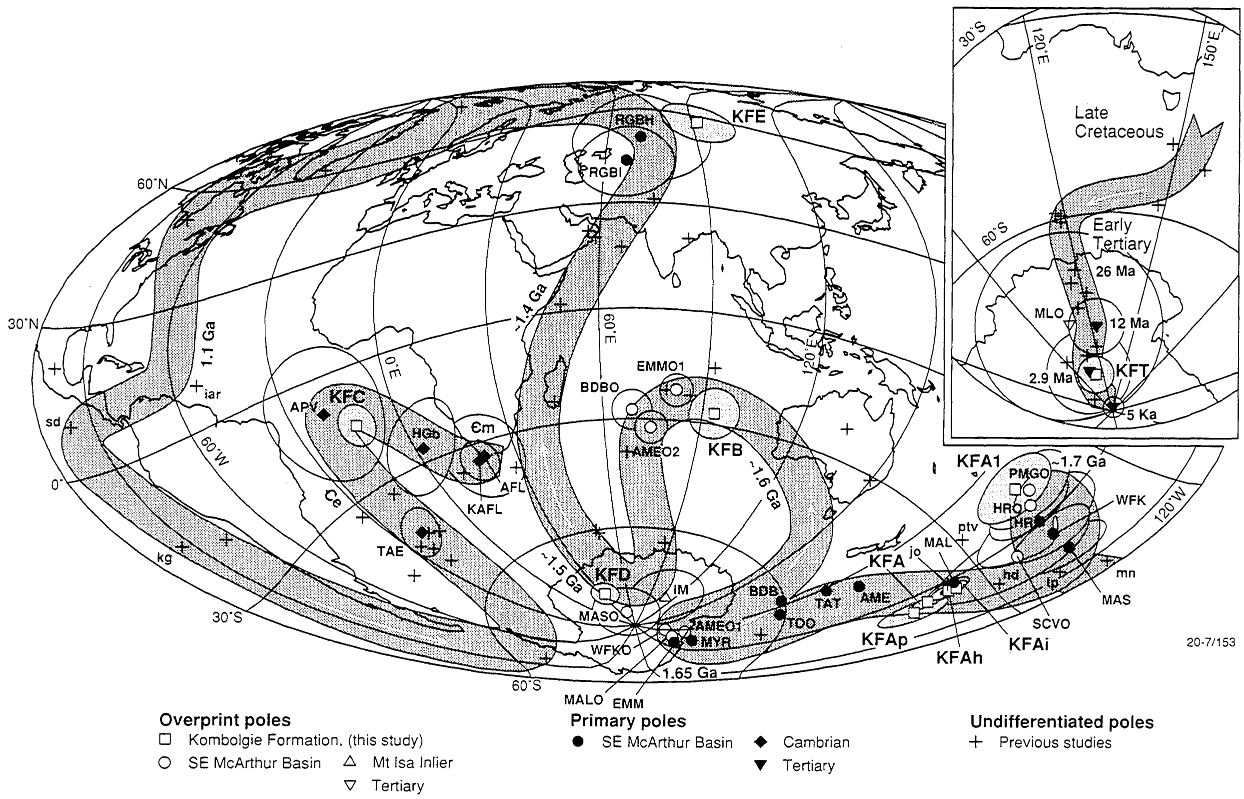

Figure 1. The ~1.8Ga to Middle Cambrian and Tertiary (Inset) segments of the reference APWP showing the location of the Kombolgie overprint poles.

- A period of dyke intrusion immediately post-dating tectonism (descibed in the next item). Two mono-polar magnetizations record this event (KFAh, KFAi) and are identical in direction to the prefolding and postfolding magnetizations defining the tectonism. They are ascribed to a now-eroded ENE-trending dyke intruding the southeast corner of the Edith Falls Basin, one of perhaps many such dykes in the area. Dykes of this age have not previously been recorded from this region. It is interesting to speculate whether the tectonism and dyke activity suggested by the results, and intrusion of the similar-aged Oenpelli Dolerite (~1.68Ga) into the basement and Kombolgie, are not in some way related, perhaps forming part of the same cycle of instability;

- Tectonism estimated at ~1.68Ga (KFA_p, KFA). This event is precisely constrained magnetically, because the component that defines it -the most common direction found in the study - occurs as both a prefolding and postfolding magnetization. Folding in the Edith Falls Basin and presumably the Mount Callanan Basin date from this time. The poles are in excellent agreement with the pole for the Mallapunyah Formation of the lower McArthur Group, southeast McArthur Basin;

- An event at ~1.71Ga which correlates with emerging evidence for regional magmatism about this time (KFA1). This prefolding magnetization is the oldest recognized in the Kombolgie (37 directions out of an original 2493). The similarity of its pole, however, to the Hobblechain Rhyolite and Packsaddle Microgranite (Upper Tawallah Group, southeast McArthur Basin) primary and overprint poles strongly favours an overprint origin: the Hobblechain Rhyolite and its equivalents, based on ion-microprobe dating, correlate with the younger West Branch Volcanics.

Magnetic overprinting in the Kombolgie Formation thus yields new information about the geological history of the region. It shows that the timing of folding in the Edith Falls Basin and at least part of the Mount Callanan Basins, previously elusive and no better constrained than Proterozoic, can now be quite tightly constrained in stratigraphic age. It suggests that an older period (~1.68Ga) of dyke activity is present than has hitherto been recognized. It also neatly illustrates that magnetic overprints can be used as a significant tool in fluid transport studies, not only for detecting such activity, but also for dating it, and establishing its provenance - whether local or regional, focussed or pervasive. In this manner, under favourable circumstances, geochemical overprints may perhaps be dated using magnetic overprints as a proxy.

Potential Applications of Palaeomagnetism in Mineral Exploration in Northern Australia.

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The Problem

In the region from Katherine to Mount Isa, many igneous rocks aged between 1870 and 1500 Ma are extensively, but variably, altered. For example, in volcanics of about 1720 to 1600 Ma alteration is pervasive throughout the whole region (Wyborn et al, 1987), whilst in volcanics of other ages, particularly those from 1870 to 1740 Ma, alteration is usually restricted to the vicinity of fault zones.

On a district scale, most Proterozoic ore deposits are surrounded by alteration halos which are readily detected in igneous rocks by whole rock geochemistry and fluid inclusion studies. Although these halos can extend for up to 5 kms from the known areas of mineralisation, they tend to be concentrated along major fault systems, and span zones up to 1 km wide around those known to control the mineral deposits, e.g. Coronation Hill (Wyborn et al., 1989), Mount Isa copper, (Bain et al., 1992)). The large size of these alteration zones associated with known areas of mineralisation is expected because the volume of rock, with which a mineralising fluid must have interacted has to be of the scale tens of cubic kilometers, if not hundreds of cubic kilometers. For example, Heinrich (1993) has calculated that system which formed the Mount Isa copper deposit must have had dimensions that were of the order of 500 km3.

In the region from Katherine to Mount Isa, the chemical composition of altered rocks close to known areas of mineralisation is in many ways similar to those from regional scale alteration zones, which are not near known areas of mineralisation. Deciding whether these regional scale alteration events are associated with the plumbing systems of undiscovered mineral deposits remains a challenge. Bulk chemistry alone cannot prove a metallogenic connection between source and deposition processes. What is required is some way of determining the age, or some other correlatable characteristic of some of these major regional-scale alteration events away from known areas of mineralisation, so that we then may be able to relate a package of altered rocks to known deposits of an equivalent age and perhaps detect the plumbing system of a hidden ore body. Even near known areas of mineralisation, it may be possible to define further extensions to the associated plumbing system. None of the isotopic techniques is sufficiently established to unambiguously and accurately date these alteration events and therefore any alternative methods to constrain absolute or relative ages of alteration would be useful.

A Potential Solution

The work of Idnurm et al. (in press) and Giddings and Idnurm (in prep.) in the McArthur Basin shows the potential of palaeomagnetism to contribute to efforts to define and date plumbing systems associated with mineral deposits. In their work we see the 'tip of the iceberg' of a new technique in mineral exploration. Their combined efforts in defining the polar wander path for these regions have given to the minerals industry a relative time scale for at least the period 1720 Ma to 1500 Ma by which metallogenic events can be correlated. This period is most important: it spans the time of formation of many major Proterozoic ore deposits.

Regardless of the style or type of alteration surrounding Proterozoic mineral deposits, one of the most common mineralogical changes is in the proportions of hematite and magnetite, which change consistently in response to chemical processes such as carbonation and oxidation. The palaeomagnetic method has the capacity to specifically distinguish overprinting or alteration events on primary sedimentary or igneous units by dating these diagnostic minerals which cannot be dated by radiometric techniques.

In the 1720 to 1500 Ma time period, igneous rocks are extremely rare, and the depositional ages of many sequences have yet to be determined. The attempt at establishing a segment of apparent polar wander and a magnetostratigraphy is promising and offers a definite hope for dating some of these unknown sequences, several of which have been tentatively correlated with the sequences hosting major sedimentary base metal deposits.

Some Examples

The pervasive hematite alteration of nearly all the 1670-1700 Ma volcanics in the Katherine-Mount Isa region has been recognised previously, but attributed to various causes, including modern regolith formation. The new palaeomagnetic results show that hematite overprint (OP1) in the Redbank area occurred soon after deposition, predating the McArthur Group. Further, timing the alteration as occurring not long after the extrusion of these units probably explains why it is so pervasive and invites more detailed work to determine if the alteration is associated with the copper mineralisation in the nearby Redbank breccia pipes.

A second overprint event (OP2) at about 1650 Ma is more geographically restricted and was only found near a prominent north or north-west trending fault system in the Abner Range area, some 70 kms south south-east of the HYC deposit. OP2 affects units in and below the Umbolooga Subgroup of the McArthur Group, which also contains the Barney Creek Formation, host to mineralisation at HYC.

The palaeomagnetic method is thus distinguishing alteration of an equivalent age to known mineralisation elsewhere. It has also defined two distinct alteration events within the southern McArthur Basin: one of known metallogenic significance, the other possibly related to copper mineralisation at Redbank.

A prominent third event (OP3) at ~1550 Ma which is restricted to dolomite sequences in the southeastern McArthur Basin has no known cause, although a significant deformation event has been determined at 1500 to 1550 Ma in the nearby Mount Isa Inlier.

In the Katherine Region, Giddings and Idnurm (in prep.) have defined many more hydrothermal events that were considered to exist from more conventional age determination studies. Of importance is the recognition that in this region, overprinting events have been established at 590 Ma, 1500-1550 Ma, 1600 Ma, 1680-1690 and 1700 Ma. The 1600 Ma is the same age as postulated for the major uranium mineralisation event, but the overprinting event at 1500-1550 has not been detected previously in the Pine Creek Inlier.

The detection of this ~1550 event in both the McArthur Basin and the Pine Creek Inlier is significant and shows that this major deformation event, recorded so far only in the Mount Isa Inlier, is more widespread than previously thought.

Conclusions

The major studies of Idnurm et al. (in press) and Giddings and Idnurm (in prep.) show that palaeomagnetism offers a new tool in tracking the regional plumbing systems for alteration events, and highlights just how widespread some of these regional events are. Significantly, the palaeomagnetic work is picking up lower temperature events than can currently be detected by conventional radiometric methods. Being able to detect lower temperature events makes the technique even more relevant in the Proterozoic of Northern Australia as the likely temperature field of sediment-hosted base metal deposits is $<250^0$C. Most of the low temperature, chemical alteration overprints in Northern Australia contain hematite, which for palaeomagnetic work has a high natural thermal stability, often requiring exposure to temperatures above 600^0C for hundreds of Ma to be reset thermally (see discussion in Idnurm and Heinrich, 1993).

Unfortunately one of the criticisms of palaeomagnetic work is that it requires absolute age determinations to define the exact timing of the polar wander path. Because in many regions this is not possible, many dismiss palaeomagnetism as an irrelevant, imprecise science. In reality, the Proterozoic palaeomagnetic path defined by the work of Idnurm and Giddings is analogous to the palynology zonation widely used to correlate important stratigraphic horizons by the oil industry. These palynological zones are not yet fully calibrated on an absolute time scale; neither is absolute time inherent in any other biostratigraphic zonation. In comparison, precise age calibration of the polar wander path may not be a necessary prerequisite. All that needs to be done is to determine the pole position of an alteration zone known to be associated with a mineral deposit, and then track the plumbing system by identifying those rocks which have a similar pole position. Magnetostratigraphy offers similar potential for correlating sedimentary sequences which as yet, have not been successfully dated by isotopic techniques.

The advantage of palaeomagnetism is that all these potential results and applications come from one set of field measurements.

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Palaeomagnetism and Magnetic Anisotropy of Proterozoic Banded-Iron Formations and Iron Ores of the Hamersley Basin, Western Australia

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Rock magnetic properties and palaeomagnetism of weakly metamorphosed banded-iron formations (BIFs) of the Lower Proterozoic Hamersley Group, Western Australia, and Proterozoic BIF-derived iron ores have been investigated. The BIF units sampled here are slightly younger than 2500 Ma. At Parabudoo, Mount Tom Price and Mount Newman iron ore formation was completed before 1850 Ma. The stratigraphy and geological history of the Hamersley Basin are summarised in figure 1.

Sampling was mainly from the Mount Tom Price and Paraburdoo mining areas and for the first time a palaeomagnetic fold test on fresh (unweathered and unaltered) BIF samples has allowed the nature of the remanence of the BIFs to be defined. The remanence of the BIFs is carried by late diagenetic/low grade metamorphic magnetite after primary haematite. This remanence is pre-folding and is unlikely to be greatly affected by the high anisotropy because the palaeofield inclination was demonstrably low.

Determination of palaeofield directions from measured remanence directions is complicated by self-demagnetization effects in strongly magnetic, highly anisotropic BIF specimens. We present a method for correcting measured directions for the effects of self-demagnetization and anisotropy. For typical BIFs, the effect of magnetic anisotropy on measured remanence inclinations and inferred palaeolatitudes is minor for low palaeolatitudes, but can lead to large errors in calculated palaeopoles for intermediate to moderately steep palaeolatitudes. Anisotropy also causes cones of confidence to be underestimated, due to compression of the range of inclinations. In principle, deflection of post-folding remanence towards the bedding plane by high magnetic anisotropy can produce an apparent synfolding signature, with best agreement between directions from different fold limbs after partial unfolding. Thus high anisotropy can not only bias estimated palaeofield directions and cause underestimation of errors, but can also mislead interpretation of the time of remanence acquisition.

The anisotropy of anhysteretic remanent magnetization (ARM) probably yields an upper limit to the anisotropy of the chemical remanent magnetization (CRM) carried by the BIFs. Figure 2 shows cleaned remanence directions from Paraburdoo BIFs, with respect to the palaeohorizontal. In figure 2(a) these directions are uncorrected for anisotropy and have a flattened distribution, reflecting deflection towards the bedding plane. In figure 2(b) the measured ARM anisotropy has been used to correct the directions, producing a vertically elongated distribution that suggests overcorrection. From the anisotropy of ARM, a maximum inclination deflection of 9^0 is suggested for the sampled BIFs. This corresponds to less than 5^0 change of palaeolatitude.

The palaeomagnetic pole position calculated for BIFs at Paraburdoo is 40.9^0S, 225.0^0E (dp=2.9^0, dm=5.8^0) after tilt correction, but without correction for anisotropy. Other pole positions reported include that from flat lying BIFs from Wittenoom at 36.4^0S, 218.9^0E (dp=4.6^0, dm=9.1^0), from Mount Tom Price iron ore at 37.4^0S, 220.3^0E (dp=5.7^0, dm=11.3^0), and from Paraburdoo ore at 36.4^0S, 209.9^0E (dp=4.7^0, dm=8.8^0). The poles from the BIFs, the Paraburdoo ore and the part of the Tom Price deposit that was sampled in this study are indistinguishable from each other and from the Mount Jope Volcanics overprint pole. The magnetization of the BIFs was probably acquired during burial metamorphism of the Hamersley Group, soon before the main folding and uplift event in the southern part of the Hamersley Province. This tectonic event exposed magnetite-rich BIFs to near-surface oxidizing conditions, producing extensive martite-goethite orebodies and also appears to have produced the syn-folding overprint magnetization recorded by the Mount Jope Volcanics of the underlying Fortescue Group. Figure 3 plots positions of palaeomagnetic poles from this study, together with previously documented poles of similar age.

Ages of magnetization are tentatively interpreted as ~2200 ± 100 Ma for the BIFs, ~2000 ± 100 Ma for the supergene enrichment of BIF to martite-goethite ore, recorded by the Parabudoo and Mount Tom Price orebodies, and ~1950 ± 100 Ma for the metamorphic martite-microplaty haematite ore, recorded as an overprint by the Tom Price orebody and as the only surviving magnetization of the Mount Newman orebody.

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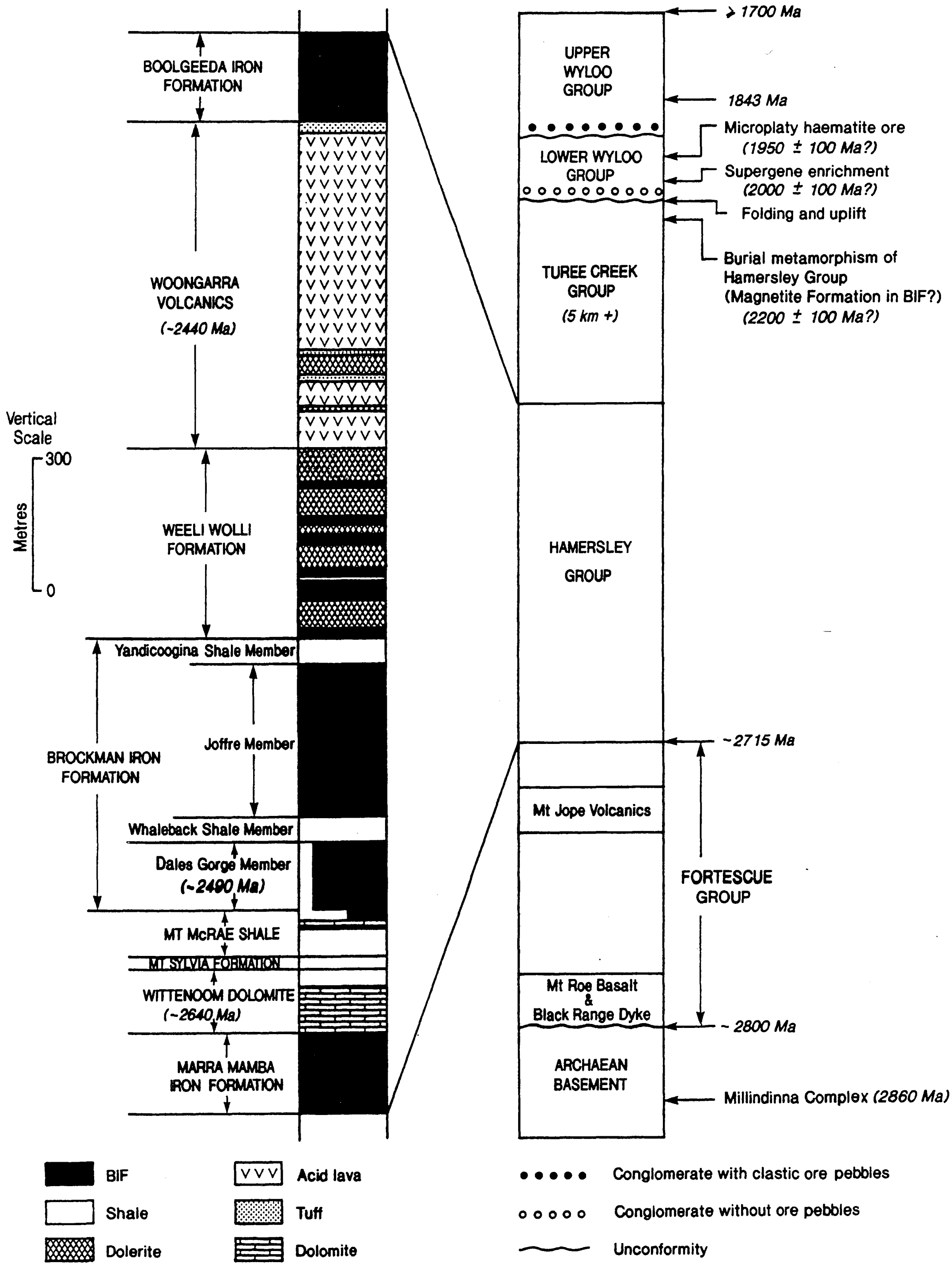

Figure 1. Stratigraphy and key geological events of the Hamersley Basin, including detailed stratigraphy of the Hamersley Group.

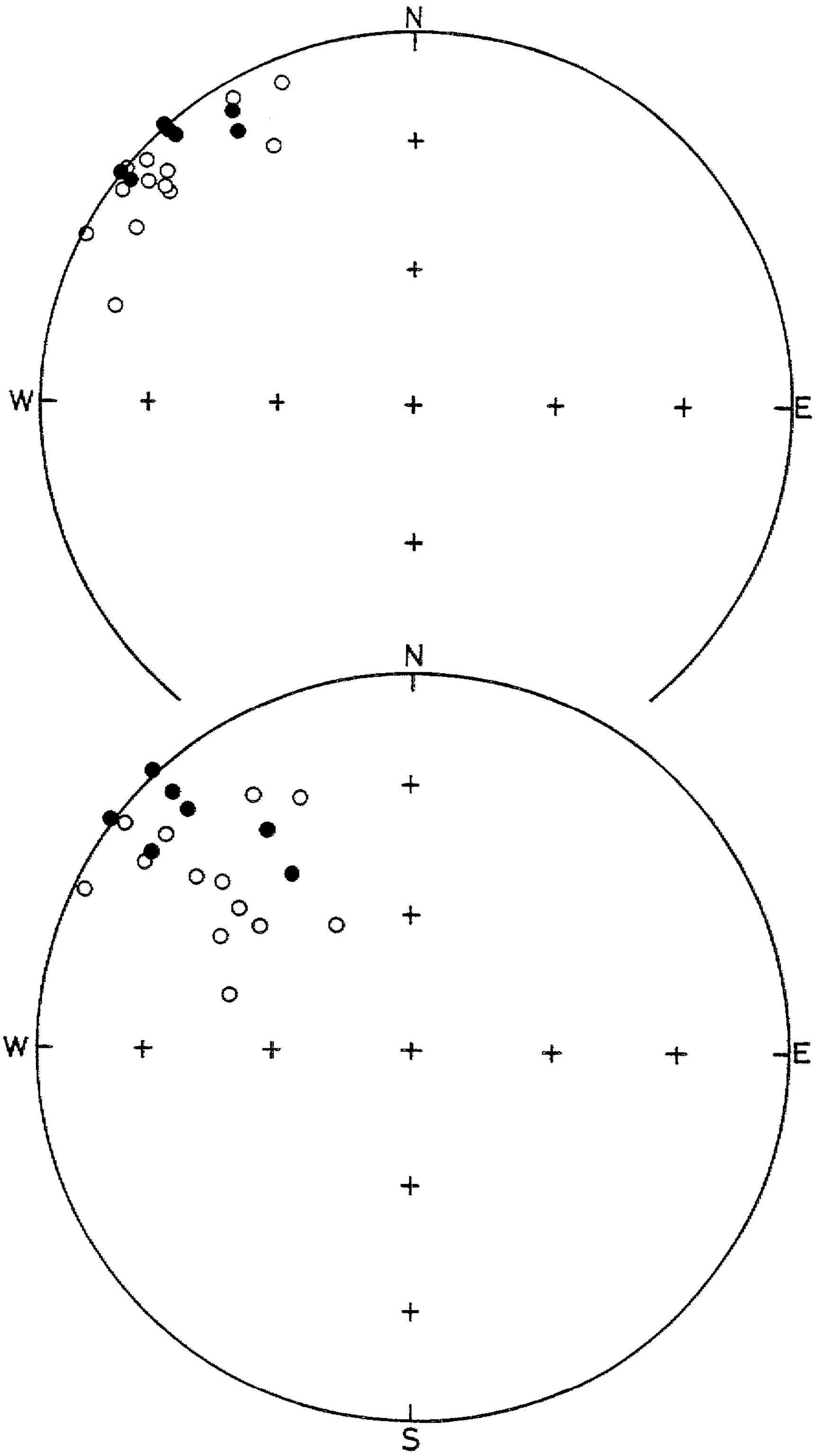

Figure 2. Equal-area stereonet showing, a) cleaned bedding-corrected magnetization directions from BIF at Paraburdoo as measured (note some inclinations are positive and the distribution is flattened), and b) same directions as a) but corrected for anisotropy using anisotropy of ARM as an analogue for anisotropy of CRM (note this over-corrects and smears the distribution vertically).

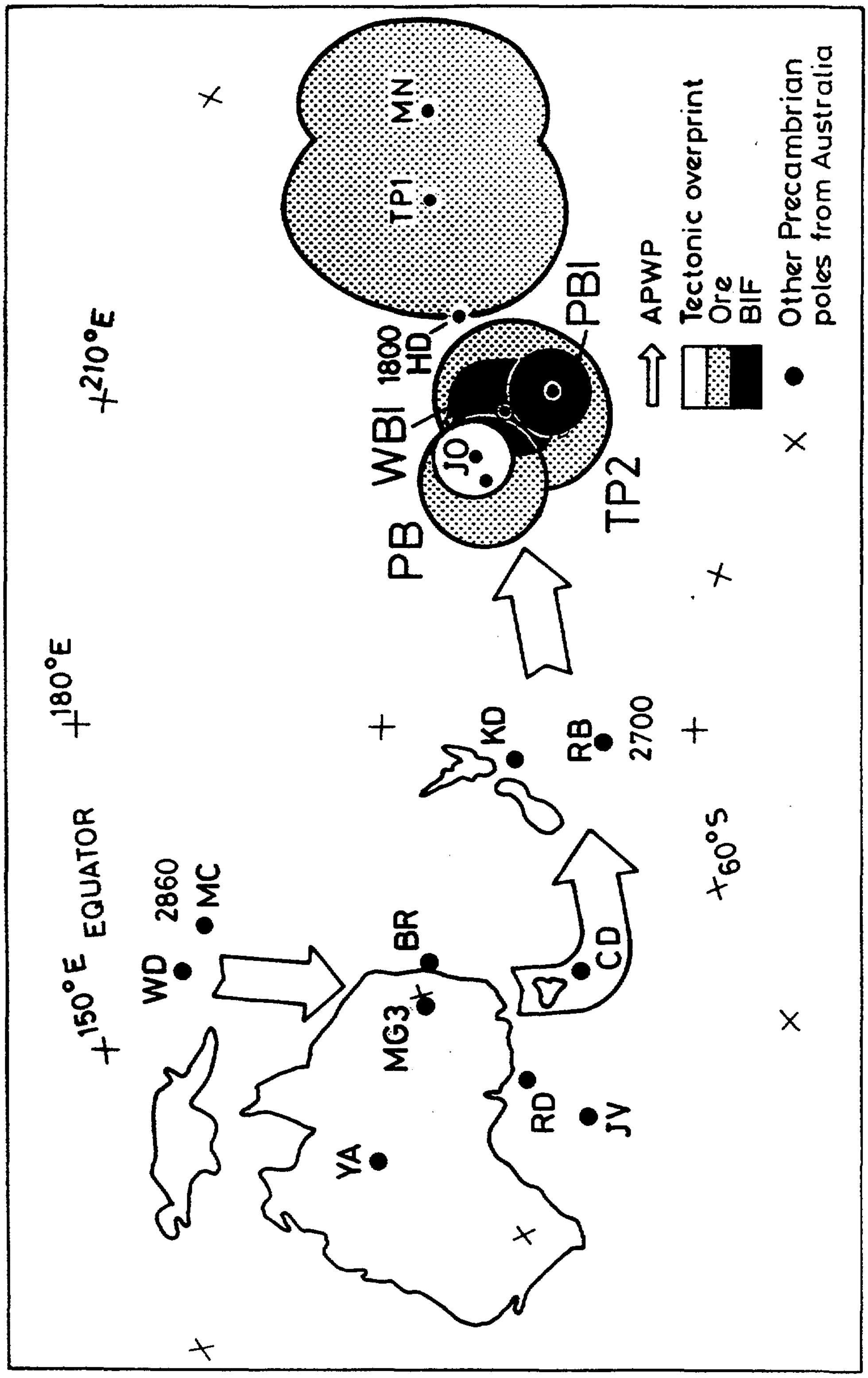

Figure 3. APWP showing poles from this study and related poles. Pole mnemonics are PBI and WBI, Paraburdoo and Wittenoom banded iron-formations (BIFs) respectively, PB and TP2, Paraburdoo and Mount Tom Price iron ore/oxidized BIF respectively. Other mnemonics are those used by Idnurm and Giddings (1988), WD - Widgiemooltha dyke (Evans, 1968), MIL - Millindinna Complex, JV - Mount Jope Volcanics, RB - Mount Roe Basalt and JO - Mount Jope Volcanics syn-folding overprint (Schmidt and Embleton, 1985), YA - Yilgarn A dykes and RD - Ravensthorpe dyke (Giddings, 1976), MG3 - Mount Goldsworthy 3, KD - Koolyanobbing Dowd's Hill, TPl - Mount Tom Price iron ore and MN - Mount Newman iron ore (Porath and Chamalaun, 1968), BR - Black Range dyke and CD - Cajuput dyke (Embleton, 1978), HD - Hart Dolerite (McElhinny and Evans, 1976).

Late Precambrian and Palaeozoic World Palaeogeography
-- A Few Outstanding Problems

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While Palaeozoic global palaeogeography are constantly being refined and debated, rapid advances have recently been made on the understanding of Late Proterozoic palaeogeography, e.g. the development of the SWEAT hypothesis and the concept of Rodinia. We present here a few outstanding problems yet to be resolved about the Late Proterozoic and Palaeozoic world palaeogeography.

1. When was Rodinia formed? How long did it last?

There seems to be ample geological evidence for the connection of Laurentia with Australia and east Antarctica in the Late Proterozoic. A preliminary palaeomagnetic examination (Powell et al., 1993) indicates that such a connection existed during at least the 1000 Ma - 720 Ma interval. There are conflicting hypothesis based on geological evidence about how far back in time such a configuration existed. More palaeomagnetic data from different Australian cratonic nuclei, as well as from Laurentia, are needed to anwser these questions.

2. Where do the West Gondwanan blocks fit in the Rodinia configuration?

There is well-documented geological and palaeomagnetic evidence that the West Gondwanan continental blocks did not join together until latest Precambrian-earliest Palaeozoic. In most of the current configurations (e.g. Hoffman, 1991), these continental blocks are placed along the Atlantic margin of Laurentia at moderate palaeolatitudes. The currently available palaeomagnetic data do not offer much constraints to this configuration. There is also debate about whether the Kalahari block was part of East Gondwana (adjacent to East Antarctica), or West Gondwana adjacent to the Congo Block, during the Late Proterozoic. Whereas geological evidence seem to favour the former configuration, palaeomagnetic data favour the latter (Li and Powell, 1993).

3. When and how was Gondwanaland formed?

Palaeomagnetic data suggest that there was an ocean between East Gondwana and Africa during the latest Precambrian and the Early Cambrian, which was closed by mid- to Late Cambrian. There is yet no convincing geological evidence reported for the closure of such an ocean between India and the Congo Block. Is the palaeomagnetic data from Africa in error?

4. Where do the Chinese blocks fit in the Rodinia configuration?

The Chinese blocks had close relationships with the Indian-Australian margin of Gondwanaland during the Early to mid-Palaeozoic. They were most likely part of the supercontinent in the Late Proterozoic (a comparative study is currently being carried out at UWA in conjunction with Chinese geologists). We tentatively suggest that the North China Block was somewhere between northeastern Australia and northwestern North America during the Late Proterozoic, whereas the rest of the Chinese and Southeast Asian blocks were located along the northern and northwestern margin of Australia (Li et al., 1993). The North China Block was the first one to rift away from Australia during the Cambrian, and was followed by the others during different stages in the Palaeozoic.

5. The polarity problem for the Early Palaeozoic apparent polar wander path (APWP) of Gondwanaland

This problem remains while there is a lack of reliable Silurian palaeomagnetic data from Gondwanaland. The conventional polarity seems to be favoured by the Rodinia configuration, as well as by the migration of glaciation centres during the Silurian. This problem should be solved in the next few years by more palaeomagnetic work on the Late Ordovician-Early Devonian rocks, the examination of the Rodinia configuration, the refining of the Laurentian late Precambrian APWP, and correlation of Early Palaeozoic magnetostratigraphy (work in progress). An alternative polarity (e.g. Schmidt and Morris, 1977) would imply a totally different global palaeogeography for the Late Proterozoic and Early Palaeozoic.

6. Was there a collision between Gondwanaland and Laurentia during the Ordovician?

An Ordovician collision between South American margin of Gondwanaland and the Atlantic margin of Laurentia was recently proposed based on geological observations (Salda et al., 1992). Such a collision is plausible from the presently available palaeomagnetic data.

7. Late Devonian APWP and palaeogeography

There has been controversy for a long time about whether there was a wide ocean between Gondwanaland and Laurentia in the Late Devonian. Both palaeomagnetists and palaeontologists have contradicting views amongst themselves. Our newly acquired high-quality palaeomagnetic results (see Chen et al., this volume) indicate that central Africa was at polar positions during the latest Devonian-earliest Carboniferous. Therefore, there must have been a wide ocean between the two supercontinents at that time. However, palaeomagnetic data do allow a close continental connection between them for the Late Silurian to mid-Devonian interval.

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EARLY TIMING OF REMANENCE IN THE LATE PROTEROZOIC ELATINA FORMATION, SOUTH AUSTRALIA: A KEY POLE ON THE AUSTRALIAN APPARENT POLE-PATH AND CONFIRMATION OF THE LOW PALAEOLATITUDE OF LATE PROTEROZOIC GLACIATION

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(See poster, THE ENIGMATIC LATE PROTEROZOIC GLACIAL CLIMATE: THE LOW PALAEOLATITUDE OF LATE PROTEROZOIC GLACIATIONS)

Late Proterozoic glaciation, which affected all continents (with the possible exception of Antarctica) between about 800 and 600 Ma, presents a major climatic enigma. As reviewed by Embleton and Williams [1], early palaeomagnetic studies of late Proterozoic glaciogenic rocks in Norway, Greenland, Scotland and Canada in general suggested low palaeolatitudes of glaciation, although some of the data were equivocal or contentious. Since 1980, however, palaeomagnetic studies of late Proterozoic glaciogenic rocks and contiguous strata in Australia, South Africa, West Africa, and China have consistently indicated low to equatorial palaeolatitudes of glaciation [1–9]. Virtually all these recent studies, which include rocks from the two major glaciations of the late Proterozoic, indicate glaciation between 0° and 12° palaeolatitude. Indeed, the palaeomagnetic study of late Proterozoic glaciogenic rocks has failed to provide unequivocal evidence for high-palaeolatitude glaciation on any continent, and attempts to relate late Proterozoic glaciation to movement of continents through polar regions [10] have been unsuccessful. Late Proterozoic glaciation in Australia occurred between 0–30° palaeolatitude [2], *not* the 45–60° palaeolatitude incorrectly shown by Chumakov and Elston [7]. Furthermore, the North China block occupied high palaeolatitudes (57–62°) during the late Proterozoic (800–700 Ma) yet affords no evidence of glaciation, whereas the Yangzi block experienced glaciation in low palaeolatitudes (0–20°) during the same time interval [4].

The paradox of low-palaeolatitude glaciation has prompted cautious acceptance of the palaeomagnetic data. However, confirmation of late Proterozoic glaciation and *in situ* cold climate in low palaeolatitudes comes from South Australia: palaeomagnetic study of unmetamorphosed, fine-grained clastic tidal rhythmites of the Elatina Formation, which is part of the late Proterozoic Marinoan glacial succession (~600–650 Ma) in the Adelaide Geosyncline, indicates a mean inclination < 10° and a remanence that is indeed primary [1,9]. The magnetisation of the rhythmite member is extremely stable, typically showing appreciable decay only after heating to above 660°C; there is no evidence of secondary overprinting. The magnetic carriers are mainly grains of haematite and martite of high temperature (igneous or metamorphic) origin. Since the haematite and martite grains are detrital and the Elatina Formation has undergone only burial diagenesis, it was concluded [1] that the remanence must be primary and date closely to the time of deposition.

Positive fold tests on soft-sediment slump folds in the Elatina rhythmites [5,9] confirms that the remanence is primary and was acquired very soon after deposition; apparently the remanence was acquired prior to soft-sediment slumping and then slightly sheared by the disturbance [9]. The Elatina pole must be considered a virtual geomagnetic pole because the tidal rhythmite member studied represents only 60–70 years of deposition [11–13]. The mean pole position, however, is similar to other late Proterozoic poles for South Australia, which implies that the low inclination (< 10°) obtained for the Elatina Formation does not record a geomagnetic excursion or reversal but does indeed indicate deposition in low palaeolatitudes [9]. The similarity of the Elatina pole to other late Proterozoic pole positions for South Australia also indicates that inclination error is not significant.

The Elatina palaeomagnetic data satisfy six of the seven reliability criteria of Van der Voo [14], the only criterion not fulfilled being of course the presence of reversals because of the very short time interval sampled (60–70 years). Palaeomagnetic data for the Elatina Formation, together with data for other late Proterozoic rocks in the Adelaide Geosyncline, thus provide a pole of high reliability on the Australian late Proterozoic-Phanerozoic apparent pole path. The findings also provide the clearest evidence available for the low palaeolatitude of late Proterozoic glaciation.

Fossil permafrost horizons displaying periglacial seasonal (winter-summer) contraction-expansion structures in several late Proterozoic glaciomarine basins indicate frigid, strongly seasonal palaeoclimates near sea level [15]. Such structures are particularly well preserved on the Stuart Shelf near the western margin of the Adelaide Geosyncline [16], and are perhaps the most reliable of palaeoclimate indicators because they formed through processes of *physical* weathering and their interpretation thus avoids such uncertainties as the former nature of the atmosphere and biosphere and subsequent diagenetic alteration. Primary sand-wedge structures imply mean annual air temperatures as low as –12° to –20°C or lower, and a seasonal temperature *range* of ~40°C or more (mean monthly air temperatures ranging from < –35°C in midwinter to < +4°C in midsummer) [17]. Palaeomagnetic and palaeoclimatic data for the late Proterozoic thus present the enigma of *frigid, strongly seasonal climates near sea level in preferred low palaeolatitudes*. Indeed, the late Proterozoic glacial climate is one of the major paradoxes in contemporary earth science. Possible explanations of this paradox are reviewed elsewhere [18,19].

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Palaeomagnetic research in Southeast Asia: progress, problems and prospects

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Southeast Asia is a complex assembly of allochthonous continental terranes now far removed from their original sites of origin together with island arcs, accretionary complexes and small ocean basins (figure 1). The boundaries between these terranes are marked by major fault zones or by sutures recognised by the presence of ophiolites, mélanges and accretionary complexes. Stratigraphical, sedimentological, palaeobiogeographical and palaeomagnetic data suggest that most, and probably all, of the Southeast Asian continental terranes were derived directly or indirectly from Gondwanaland. These terranes were assembled between the Late Palaeozoic and Cenozoic, but the precise times of rifting from Gondwanaland and timings of amalgamation and accretion are still contentious. Cenozoic modification of the region involves major strike-slip faulting, rotations and spatial displacements of crustal blocks and the development of marginal basins. Palaeomagnetic data is vital for constraining the movements of crustal blocks in this region and ongoing systematic regional palaeomagnetic research is critical for an improved understanding of the geological evolution of Southeast Asia.

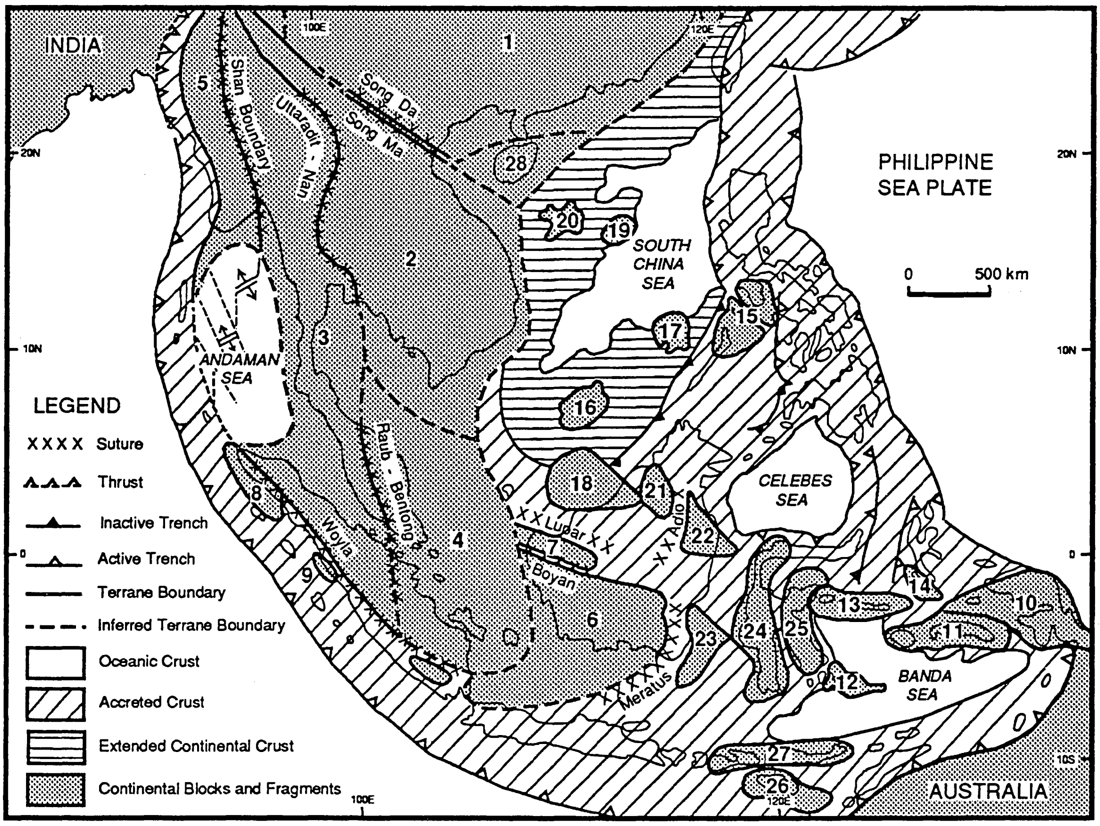

Figure 1. Distribution of continental blocks and fragments (terranes) and principle sutures of Southeast Asia (modified after Metcalfe, 1990). 1. South China 2. Indochina 3. Sibumasu 4. East Malaya 5. West Burma 6. S.W. Borneo 7. Semitau 8. Sikuleh 9. Natal 10. West Irian Jaya 11. Buru-Seram 12. Buton 13. Bangai-Sula 14. Obi-Bacan 15. North Palawan 16. Spratley Islands-Dangerous Ground 17. Reed Bank 18. Luconia 19. Macclesfield Bank 20. Paracel Islands 21. Kelabit-Longbowan 22. Mangkalihat 23. Paternoster 24. West Sulawesi 25. East Sulawesi 26. Sumba 27. Banda Allochthon 28. Qiongzhong and Yaxian terranes of Hainan.

The palaeomagnetic database for the region has grown dramatically over the last decade but must still be regarded as at the reconnaissance stage in most areas. Palaeozoic and Mesozoic results remain problematic due to the widespread presence of Late Mesozoic and Cenozoic overprints and the rotations of disrupted parts of terranes by Late Mesozoic and Cenozoic strike-slip faulting. In particular, the Palaeozoic and Early Mesozoic rocks often carry a Late Cretaceous overprint. Some Early Palaeozoic results have also yielded spuriously high inclinations (implying high palaeolatitudes) which may represent a Late Palaeozoic remagnetisation. An Apparent Polar Wander Path (APWP) has now been proposed for the South China Block and work on constructing an APWP for the Sibumasu Block is underway but still at a very early stage of development. APWPs for other Southeast Asian Blocks have not yet been constructed. Comparisons of Southeast Asian APWPs and single poles with the APWPs of probable parent cratons (Australia, India etc.), other East Asian continental blocks, and "stable" Eurasia, depends upon current controversies regarding the APWPs of these blocks being resolved. Of particular importance is the Palaeozoic portion of the Australian APWP since a number of Asian blocks are believed to have rifted from the Australian region of NE Gondwanaland in the Palaeozoic. Palaeolatitude vs. time plots for some of the principal allochthonous continental blocks of the region indicate large latitudinal displacements for some of these and translation from the southern to the northern hemisphere. There is now a sufficient body of palaeomagnetic data to be useful, along with other constraining data such as palaeobiogeographic and palaeoclimatic information, in generating palaeogeographic reconstructions. It must be stressed however that palaeomagnetic results should not be used "in vacuo" when making these reconstructions.

Some of the current problems plaguing those who work on the geological evolution of Southeast Asia, which may be partially or totally solved by palaeomagnetic investigations are:

1. The original contiguity of now disrupted terranes (e.g. were the Lhasa and Changtang Blocks of Tibet originally contiguous with Sibumasu or Sibumasu and Indochina?).
2. The amount and timing of movements of micro-continents in the region during Palaeozoic - Cenozoic times.
3. The ages of suturing (amalgamation/accretion) of the various terranes.
4. The amounts and sense of Cenozoic rotations of crustal blocks and plates in Southeast Asia and their bearing on tectonic models for Cenozoic evolution of the region.

Prospects for solving these problems are good providing a systematic approach is made to palaeomagnetic studies in the region. For any real progress to be made for Early Mesozoic and Palaeozoic palaeomagnetism, we must fully understand the Cenozoic and Late Mesozoic magnetic signatures and be able to strip off younger components. Future palaeomagnetic studies need also to be carried out in conjunction with rock magnetic studies and palaeomagnetists must work together with geologists familiar with the geology of the region, from the sampling stage right through to interpretation of results.

Palaeogeographic Mapping Projects and palinspastic reconstructions of the Australian plate.

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Australian Geological Survey Organisation

Two palaeogeographic mapping projects have been carried out at AGSO over the past several years. They have been jointly funded by government and the petroleum exploration industry with the aim of producing new syntheses of Australian geology relevant to the search for fossil fuels. The contribution of industry was co-ordinated through APIRA, the petroleum division of the Australian Mineral Industry Research Association.

The Palaeogeographic Maps Project conducted from 1984 to 1987, was the initial AGSO-APIRA project. It produced the first complete set of timeslice palaeogeographic maps for the Australian Phanerozoic. The palaeogeographic maps were supplemented by correlation charts, data and structure maps, and source rock data overlays. The results of this first project are being published as the AGSO Palaeogeographic Atlas series.

To maintain the data base established, and to maximise the benefits from this effort a second phase of the project was considered. In consultation with industry the Phanerozoic History of Australia Project was developed. It built on the first project, improving on some aspects. In particular, it has extended the maps to the edge of the plate and made them palinspastic; and systematically included seismic information by producing regional cross-sections. The crucial emphasis on biostratigraphically controlled time slices was retained in the second project.

In the second palaeogeographic mapping project information was compiled for eastern Indonesia, Papua New Guinea, the south west Pacific, New Zealand, Antarctica and the Indian Ocean. It was synthesised into summary stratigraphic columns showing lithology, thickness, depositional environment, age control and hydrocarbon occurrences. Lithology and thickness were plotted on time slice data maps. Various reports summarise the basic data compiled for the individual areas (see Bradshaw, 1992; Struckmeyer, 1990, 1991a; Walley, 1989, 1991a & 1991b; Yeung, 1992). In all, three hundred new data points and 195 summary stratigraphic columns were added to the original palaeogeographic maps data base. The mapping scale was 1:10 m using the circum-Pacific south-west quadrant map as the base for the data maps.

The time slice palaeogeographic maps were plotted onto reconstructed bases that reflected the plate tectonic history of the region. The TERRA MOBILIS program was used to produce computer reconstructions of the plate model for the required time slices. Over 80 individual tectonic elements in the region were identified and added to the generalised global model used in this program. Reports by Struckmeyer & others (1991), Struckmeyer (1991b) and Walley & Ross (1991) describe the development of the reconstructions and discuss the plate tectonic evolution of the various regions.

The Australian palaeogeographic maps from the first AGSO-APIRA project (BMR Palaeogeographic Group, 1990) were updated and integrated with the new regional interpretations to produce palaeo-environmental maps of the plate for sixteen time slices from the Triassic to the Recent. The New Zealand/Antarctic compilation was restricted to the Cretaceous and Cainozoic and India was not included in scope of the project. The report by Langford (1991) provides palaeogeographic maps of Gondwana for the Permian.

The palaeogeographic maps show the facies and tectonic relationships through time between Australia and the region. Some of the relationships revealed are of relevance to petroleum exploration as they point to the extension of successful plays into new areas and suggest new play concepts. However, it should be remembered that the maps are interpretive and based on reconstructions that represent only one of several plate models that may apply.

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New Guinea Tectonics and Why We Need Palaeomagnetic Studies

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The modern New Guinea region is a tectonically complex area of microplates, island arcs and mountain building that is considered an excellent analogue for the mountain building processes that have ocurred in the past elsewhere in the world. Most research aimed at unravelling the complexity of the region have, as their ultimate objective, a desire to be able to reconstruct the processes that have led to this complexity and to a further understanding of the processes that control mountain building and their influences on the accumulations of resources.

The New Guinea Orogen contains numerous terranes and the adjacent east Indonesian region contains a number of microcontinents that are purported to have been derived from that part of the Australian craton that is now found in New Guinea. Determining the origin and movement history of these terranes is essential to reconstruction of the region so that palaeoenvironments can be analysed, and structural settings determined. Post emplacement translation and rotation of terranes are also a feature of other orogenic belts and preliminary work in New Guinea suggests that similar processes have, perhaps are operating in New Guinea.

Palaeomagnetic studies are vital part of the analysis of the development of the New Guinea region and provide an essential methodology for unravelling the tectonic history. Perhaps most importantly, some of the work that is to be presented at this meeting, which reports the results of a few widely scattered palaeomagnetic studies that shows that methodology is applicable and holds great promise for assisting in unravelling the tectonic evolution of this region.

The New Guinea Orogen also contains a well exposed Australian craton Mesozoic passive margin section which should be exploited to refine the Apparent Polar wander Path of Australia which of course provides the reference curve for all analysis of tectonic events. In the paper a few of the tectonic models will be briefly examined to highlight the need for palaeomagnetic work in New Guinea.

Palaeomagnetic results from the Bird's Head, Irian Jaya: a new look at old data

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The northern margin of Australia is a complex zone of interaction between three major crustal plates: the Australian, Pacific, and Southeast Asian. The Australian plate is currently moving northwards and impinging on, and overriding, the margin of the westward-moving Pacific plate, while the Southeast Asian plate is essentially stationary, undergoing small counter-clockwise rotation. The interaction of these plates during the major part of the Tertiary has been collisional. The complex array of terranes of island arc, oceanic, and more rarely, continental affinity now found in the Indonesian Archipelago, the New Guinea Orogen, and the South West Pacific, the numerous small ocean basins, and the rapid development and evolution of microplate boundaries, are the inevitable consequence of this convergent tectonic regime. Large rotations and translations are not uncommon. Some of the terranes now found in the Indonesian sector of the collision zone, for example, have been interpreted as being derived from the northeastern region of the Australian sector, hundreds to thousands of kilometres to the east. For earlier times, in the Mesozoic and Late Palaeozoic, passive margin extensional regimes appear to have operated along the northern edge of the Australian craton and it has been argued that the juxtaposed continental terranes forming Southeast Asia were originally some of the fragments rifted from this part of northeast Gondwana during one of the extensional cycles.

Most of the analyses concerning the former position of terranes within the zone between the three major plates have largely been based on detailed examination and interpretation of the geological record with some constraints derived from the incomplete and ephemeral oceanic record. Clearly there is a great need for palaeomagnetic input to provide constraints on, and discriminate between, models of the evolution of the zone, particularly for periods older than the middle Tertiary, by verifying the reality and timing of postulated rotations and translations. Palaeomagnetic input into such models has so far been sparse. Indeed, some results must now be regarded as of dubious significance in view of the advances made in palaeomagnetic analytical techniques and our deeper appreciation of magnetic overprinting as a common phenomenon. Likewise, conclusions based on palaeomagnetic analysis must also be reviewed occasionally as knowledge of the regional reference Apparent Polar Wander Path (APWP) improves.

A palaeomagnetic study conducted on late Palaeozoic to Tertiary rocks of the Bird's Head, Irian Jaya, illustrates the use of palaeomagnetism in identifying constraints for models for the evolution of one of the terranes within the collision zone and shows how recently improved knowledge of the late Palaeozoic Australian reference APWP impacts upon previous interpretation of the data. The Bird's Head of far western New Guinea lies close to the junction of the three major crustal plates of the region and protrudes into the Pacific Plate; the Sorong Fault zone, aligned east-west through the top part of the Head, marks the boundary between the Pacific and Australian Plates. The tectonic history and origin of the Bird's Head have been the source of much controversy over the years. A number of hypotheses have been advanced concerning its position with respect to Australia: rotation in the Neogene of either clockwise or counter-clockwise sense; fixed position since either the Mesozoic or Palaeozoic; and a separate drift history for at least part of the period since the early Mesozoic. It has been regarded as an integral continental block in some cases and in others as a composite microcontinent comprising a number of terranes. In the latter case, the two main terranes, of continental affinity - the Kemum and Misool - underlie most of the area south of the Sorong Fault zone. Aspects of the geology of the Kemum terrane, when compared to that of the adjacent Australian craton, have been interpreted to strongly favour a derivation of the Kemum terrane from the eastern zone of the New Guinea Orogen.

Briefly, nine formations were studied ranging in age from Late Carboniferous (Cl) to Middle Miocene (Tmm). The rocks form part of the carbonate and clastic cover sequence that drapes over the Kemum terrane and crops out along the southwestern margin of its exposed area. From oldest to youngest they are: the three members of the Aifam Group - Aimau Fm (Cl), Aifat Fm (lPe), and the Ainim Fm (Pl); Tipuma Fm (Tr-Je); Jass Fm (K); Faumai Lst (Tem-Tel); Sirga Fm (Tme); Kais Lst (Tme-Tmm); and Klasafet Fm (Tme-Tmm). No useful palaeomagnetic information was extracted from the Sirga Fm and Kais Lst: remanence directions were very scattered. For the remaining units, however, generally two or three components of remanence were recognized. One component was similar for most: it was interpreted as an overprint magnetization acquired in post-Klasafet times. The mean pole lies *on* the Australian reference APWP and is estimated as Late Miocene to Early Pliocene in age. The second component is systematically directed for each unit, but generally varies between them. Apart from the Jass Fm, this component is regarded as primary: the direction for the Jass Fm is identical to that of the Klasafet Fm and is regarded as an overprint acquired in Klasafet times. The third component, when present, is generally scattered between the first two components, and is interpreted as a hybrid magnetization resulting from overlapping of the primary and secondary remanece spectra: no geological significance can be attached to it.

Knowledge of the reference APWP at the time of the initial interpretation of this data was such that the reference Permo-Carboniferous pole was regarded as lying to the southwest of Tasmania, while a pole for the latest Permian lay out in the southwest Pacific. The position of this latter pole was regarded as anomalous compared with the pole for the Permo-Triassic, located in southeast Australia, but it nevertheless remained a possibility that it defined additional complexity in the path. As a result and given their precision, the Kemum poles were regarded as in gross agreement with this reference path apart from some small clockwise and counterclockwise rotations and some relative north-northeastward directed translation. Movement independant of Australia was thus established, large clockwise rotation in the Neogene was ruled out, but no clear palaeomagnetic evidence emerged for or against a derivation of the Kemum terrane from the eastern zone of the New Guinea Orogen.

Recent improvements in our knowledge of the late Palaeozoic APWP for Australia and refinement of a couple of Kemum poles, however, render this original interpretation no longer tenable. The Late Carboniferous part of the reference APWP is now located off the coast of southwestern Western Australia and the late Early Permian part to the south of Tasmania. The pole regarded as latest Permian in the southwest Pacific, by comparison with new results from similar aged units, is now probably best regarded as a middle Mesozoic overprint. The poles for the late Palaeozoic and early Mesozoic of the Kemum terrane are consequently substantially removed from their expected reference positions, although we note that their angular separation is similar to that observed for positions on the Australian path of similar age.

With due attention to the geological evidence, comparison of the Kemum poles with the new reference APWP now provides us with evidence which is consistent with a derivation of the Kemum terrane from the east. It shows that the Early-Middle Miocene pole (Klasafet times) is ~10° counterclockwise rotated from its reference position; that the pole for the Middle-Late Eocene (Faumai times), corrected for the Miocene rotation, is displaced west-northwest of its reference position but can be restored by a translation of the Bird's Head eastward by ~20°; and that the poles for the late Palaeozoic (Aifam group) and early Mesozoic (Tipuma Fm), after correction for younger rotations, are ~55° counterclockwise removed from their expected positions.

These results suggest the following preferred simple model for the sequence of events recorded in the remanence of the Kemum terrane cover sequence. In the late Palaeozoic to early Mesozoic, the Kemum terrane was located on the eastern side of the New Guinea Orogen, in the viciniy of ~150°E and to the north of the Papua Peninsula. It formed part of the Australian cratonic margin. Some time between deposition of the Tipuma Fm and the Faumai Lst, the Kemum terrane underwent a ~55° counterclockwise rotation. We may be witnessing in this displacement the initiation of rifting of this terrane from the northern margin. The most likely time slot is the latest Mesozoic to early Tertiary, a period for which there is ample evidence that this sector of the northern margin was breaking up: the opening of the Coral Sea, Solomon Sea, and an inferred basin to the north of the Papua Peninsula. Unfortunately, the Jass Fm is magnetically overprinted and provides us with no palaeomagnetic constraints. After deposition of the Faumai Lst, the Kemum terrane is rafted westwards. This motion may represent a mature stage of the initial rifting process. By Klasafet times, the Kemum terrane is located on the western side of the New Guinea Orogen near its current position. Its journey from the eastern sector must have occurred prior to the middle Oligocene which marks the initiation of collision in the Orogen. Further westward motion may have been impeded by the proximity of the Southeast Asian plate. Collision of the Kemum and Misool terranes in the latest Oligocene occurred in this period. Finally, the capture of the Bird's Head and its continued driving into the margin of the Pacific plate by the northward-moving Australian plate caused the Bird's Head to rotate counterclockwise by ~10° in post-Klasafet times. The position of the overprint poles, which lie *on* the reference APWP, suggests that the majority of this rotation was taken up between Klasafet deposition and the ~Late Miocene to Early Pliocene. We note that the Bintuni Basin in the southern Bird's Head and western Bird's Neck deepened assymetrically eastward very rapidly in post-Klasafet times with the accumulation of over 4 Km of clastics shed from the Lengurru terrane, adjacent to the Bintuni Basin and forming the eastern half of the Bird's Neck, and the concurrently uplifting Kemum terrane. We also note that the fold structures developed in the cover sequence of the Lengurru terrane, which may be thrust over the Kemum terrane, also date from the same post-Klasafet times. We therefore suggest that the post-Klasafet counterclockwise rotation of the Bird's Head that we identify palaeomagnetically has driven development of the Bintuni Basin and the fold structures of the adjacent Lengurru terrane, as a result of the compressive nature of the forces involved. The pervasive overprint magnetizations we observe, we attribute to regional thermochemical effects associated with the tectonism.

We thus see that palaeomagnetism has a useful role to play in constraining models of terrane evolution in this complex collision zone. Only by integrating a number of such studies in close conjunction with the geological framework can a robust picture of the evolution of Australia's northern margin be constructed.

Palaeomagnetic Constraints on Terrane Tectonics; Highlands and Sepik Region, Papua New Guinea

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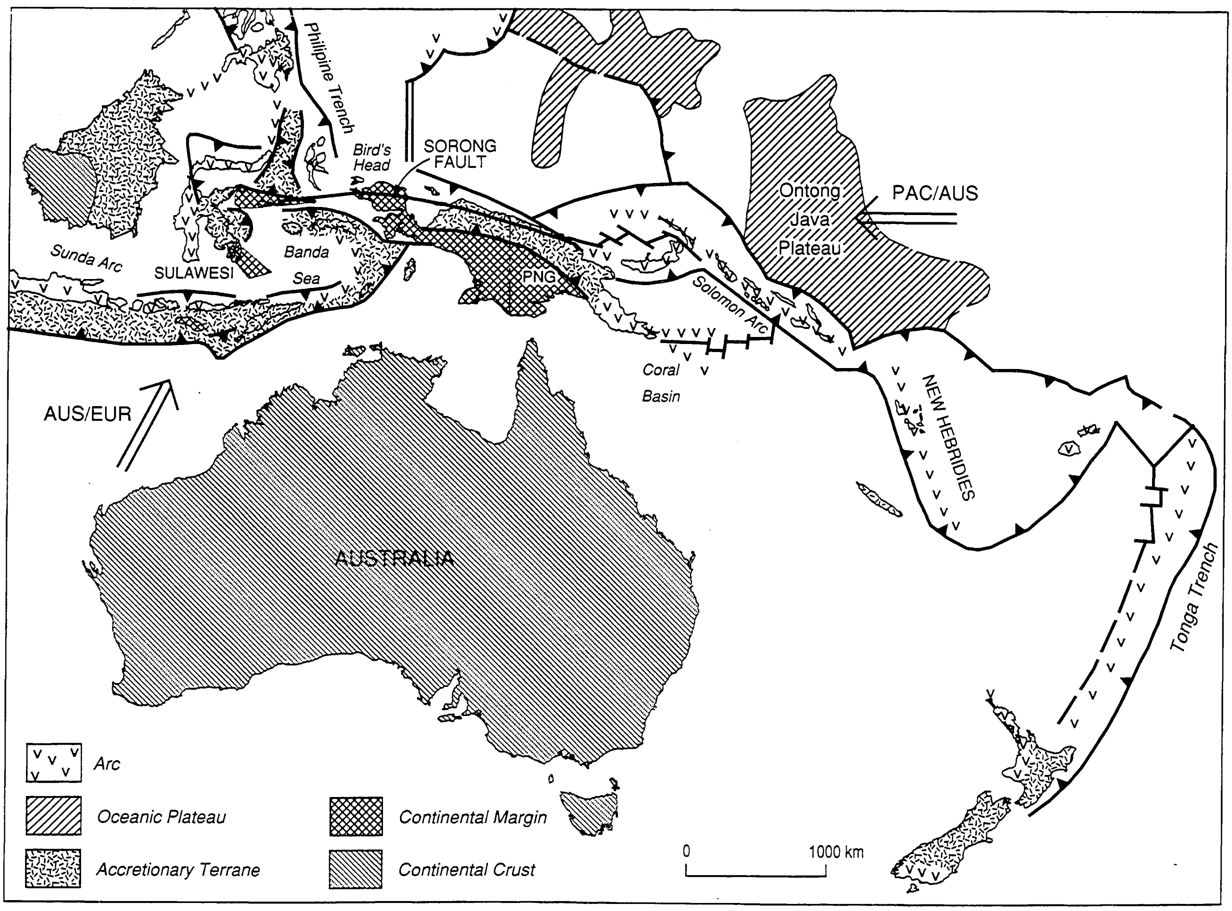
Tectonic development of the northern margin of the Australian plate in the Eastern Indonesia-New Guinea-SW Pacific region has been governed for the last 43 Ma by interaction of three major plates. That is the west-north-westward moving Pacific plate, the northward moving Australian plate, and minor movement of Southeastern Asia toward the southeast. Current movement rates are 10.2, 7.8 and 0.4 cm/yr, with a resultant Australian-Pacific convergence rate of 12.6 cm/yr. This high rate of oblique convergence is taken up largely in a highly active and structurally complex bufferzone with rapid development of microplates. This Tonga-Sulawesi megashear region may represent a present-day analog of the Mesozoic development of terrane accretion along the North American Cordillera (Silver and Smith,1983). For the New Guinea segment of this megashear Pigram and Davies (1987) identified more than 32 terranes of oceanic, continental or composite affinity. Palaeomagnetic control on terrane movement is restricted to the Bird's Head region of Irian Jaya (Giddings et al.,1993), and the North Sepik and Highland regions of Papua New Guinea. Results from the latter two regions will be discussed.



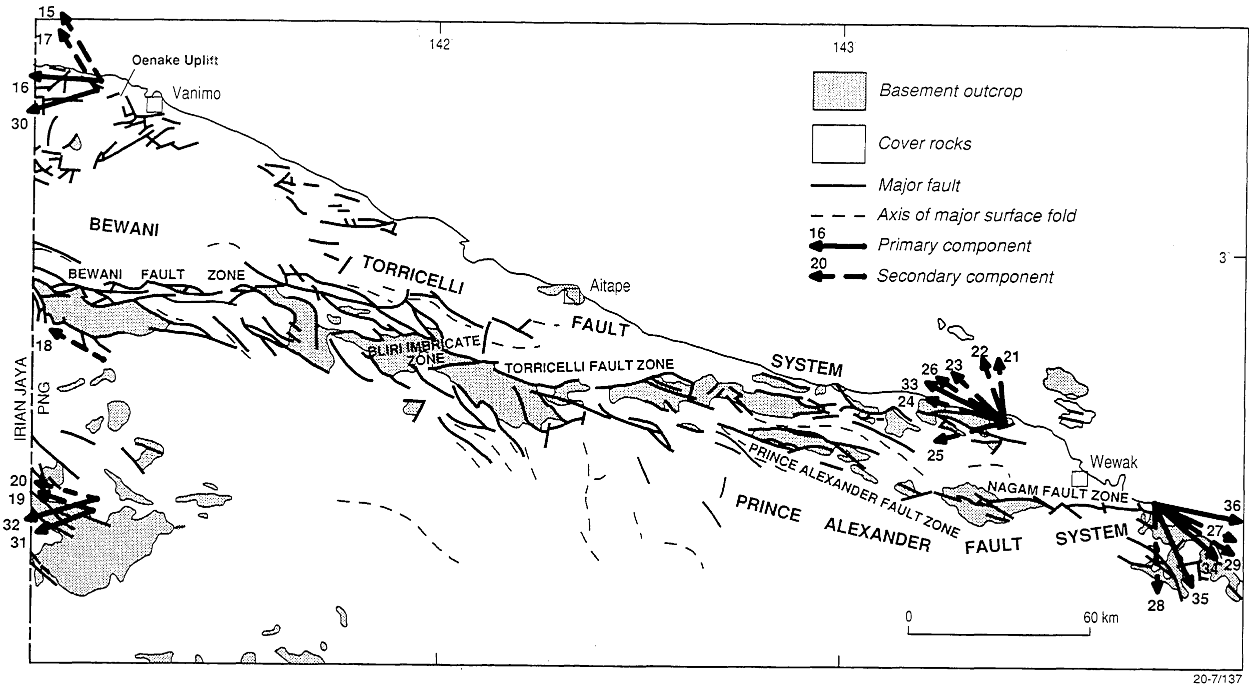


Fig.2 Structural overview of the Bewani-Torricelli Arc complex (after Hutchison and Norvick, 1980). Arrows indicate rotations with respect to the Australian craton, according to primary (full) and secondary magnetizations (dashed).

Results from the Bewani-Torricelli Arc complex in the North Sepik region are from the Bliri Volcanics of Palaeocene to Early Miocene age and from Late Oligocene to Middle Miocene cover sediments. The Bliri Volcanics show a predominant overprint acquired at a latitude of about 15^0S. This is attributed to latest-Oligocene-Early Miocene accretion of the Bewani-Torricelli arc (Torricelli terrane) onto the northern margin of the Australian plate and its earlier accreted arc terranes. Sediments of the cover sequence provide further latitudinal control on the evolution of the accretionary margin through a Late Oligocene primary magnetization, and a post-accretion post-Middle Miocene overprint. Declinations from the Bliri Volcanics and the cover sediments show a general meridional trend and indicate large-scale counterclockwise rotations of the Bewani-Torricelli Arc between 30^0+ and 110^0+ relative to the Australian craton, and contrasting clockwise rotations between 100^0+ and 170^0+ for the structurally detached Tring Block. These rotations are attributed to ongoing impingement of the northward advancing cratonic rim upon the westward moving Pacific plate, resulting in tectonic shaving of the accreted northern margin of the Australian craton along the Tonga-Sulawesi megashear with continuing large-scale westward transport presumably since the Early to Middle Miocene. The landward continuation of the Bismarck Fracture Zone, i.e. the Prince Alexander and Bewani-Torricelli Fault Systems, and possibly the Sorong Fault System in Irian Jaya are the more prominent sinistral shear zones of the Tonga-Sulawesi megashear.

Fig.1 Present-day interaction between the Australian plate, the Pacific plate, and an intervening belt of microplates along the Tonga-Sulawesi megashear, after Silver and Smith (1983).

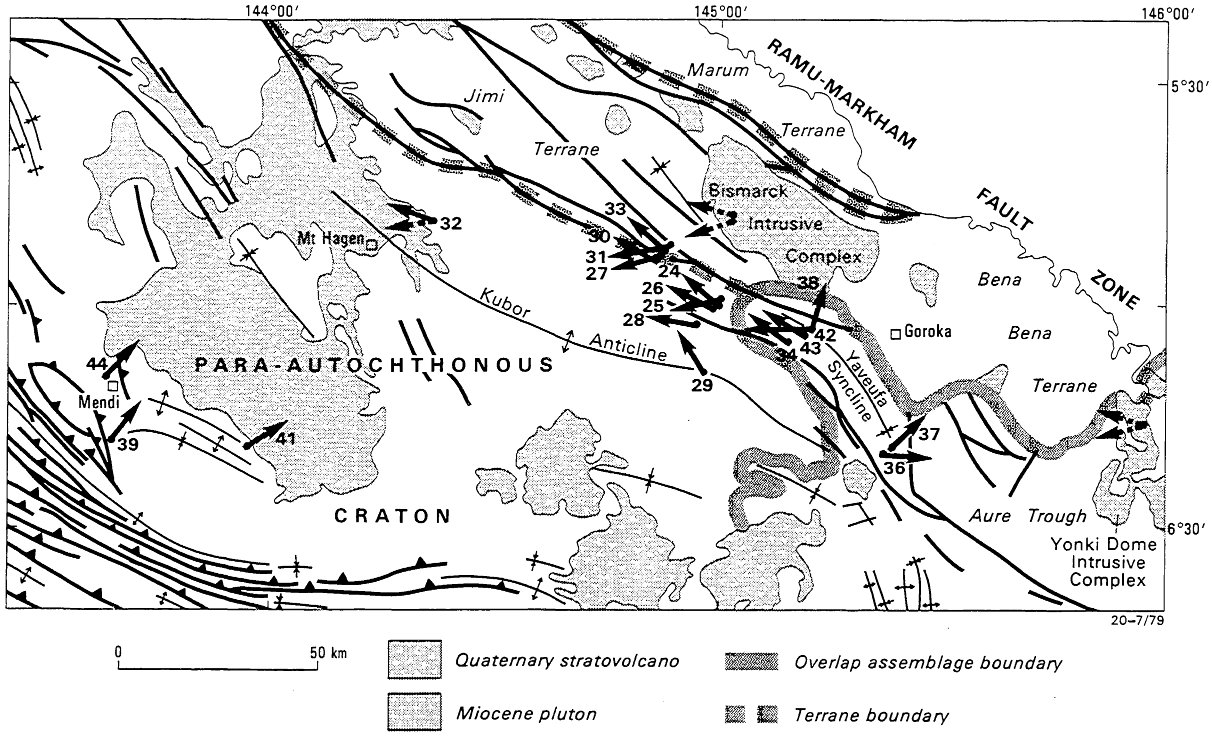


Fig.3 Overview of rotations with respect to the Australian craton as observed for the Kubor Anticline-Jimi Terrane-Yaveufa Syncline and the southern Highlands of the Papuan Fold Belt (full arrows). Magnitude and sense of rotations are indicated by the arrows' angles with respect to north. The dashed arrows indicate rotations determined from an earlier palaeomagnetic study by Manwaring (1974). Geology after d'Addario et al. (1976), and Pigram and Davies (1987).

In the Highlands region samples were studied from an exterior and an interior zone of the Central Cordillera. They are respectively from : (i) a Triassic to Miocene sequence of sediments and subordinate volcanics from the Kubor Anticline, Jimi Terrane, and Yaveufa Syncline in the central and eastern Highlands; and (ii) Middle Eocene to Middle Miocene carbonates and clastics from the southern Highlands of the Papuan Fold Belt. The two zones form the southern part of the New Guinea Orogen and represent the para-autochthonous northeastern margin of the Australian craton. The exterior Papuan Fold Belt forms a basement-involved Pliocene foreland fold-and-thrust belt. The interior zone is made up of a cratonic spur of uncertain, probably displaced, origin.

Two main magnetic components have been identified which constrain the tectonic evolution of, in particular, the interior zone: (i) a pervasive overprint of mainly normal polarity which is attributed to extensive Middle to Late Miocene intrusive activity in the Central Cordillera, and (ii) a primary component identified in only 7 of the 21 localities studied. The secondary and primary components show patterns of rotation which are consistent per sampled area but differ between the two tectonic zones. Large-scale counterclockwise rotations between 30^0+ and 100^0+ have been established throughout the Kubor Anticline and Jimi terrane of the central and eastern Highlands, with some clockwise rotations in the southern part of the Yaveufa Syncline. In the Mendi area of the southern Highlands, in contrast, clockwise rotations between 30^0+ and 50^0+ have been observed. These contrasting rotation patterns indicate effective decoupling of the two tectonic zones, probably along basement-involved faults. The clockwise rotations in the southern Highlands of the Papuan Fold Belt reflect its structural grain, and are probably governed by regional basement faults and transverse lineaments. In contrast, the pattern of counterclockwise rotations in the Kubor Anticline-Jimi terrane cratonic spur was not expected. The pattern probably reflects a system of non-rigid rotations of continental terranes, transported across the northeastern margin of the Australian craton. This margin became reorganized after the Middle Miocene, when the northward-advancing Australian craton started to impinge into the westward-moving Pacific plate/Solomon microplate system and underwent tectonic shaving under influence of the sinistral Tonga-Sulawesi shear.

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Late Mesozoic-Cainozoic Polar Wander Path and Regolith Dating

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Among the main applications of the Late Mesozoic-Cainozoic pole path for Australia is the dating of lateritic profiles. If, as is often stated, weathering is a long-term process, starting possibly at the first exposure of the rock to the surficial geochemical environment, what is actually being dated? The clustering of remanence directions that is usually reported for individual profiles suggests that the dates record discrete events in the history of profile building. These events clearly involve iron, but not necessarily other elements. The existence of ancient remanence also implies that the iron mineralogical record has been at least partly preserved in an otherwise dynamic system.

Palaeomagnetic dating is based on the apparent polar wander path, and the pole path therefore largely governs its precision. Other factors affecting the precision include the magnetic characteristics of the material and the number of samples, giving a realistic limit of a few Ma. This, although low compared to the precision of isotopic methods (e.g., about ± 0.5 Ma for many Tertiary basalts), may still be quite adequate considering that the weathering event itself may have been of similar or even longer duration.

Besides precision, the accuracy of palaeomagnetic dating is governed largely by the time-calibration of the apparent polar wander path. The calibration is at present by relatively few poles, the main difficulty in improvement being the lack of material that is well-dated, avoids large errors due to secular variations in the geomagnetic field, and does not at the same time introduce other errors such as those sometimes caused by depositional processes. Work is in progress to determine new calibration poles and to refine some of the existing poles.

Hardpan as a dating medium for regolith: Yilgarn examples.

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A ferruginised siliceous hardpan from the northeastern Goldfields of the Western Australian Yilgarn region has been assessed as a palaeomagnetic dating medium. Five samples collected from the region yielded widely scattered remanence directions. The scattering appears to result from randomly oriented maghemite grains effectively concealed within a cemented sandy-clayey matrix. IRM contributions from lightning effects is unlikely because the samples were collected from unexposed pit faces of current mines. Therefore, further progress with palaeomagnetic dating depends on the location of maghemite-free phases of the hardpan.

Paleomagnetism of ferricrete associated with glacial sediments, Western Tasmania: implications for Tasmanian Cenozoic glacial history

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Recent paleomagnetic results from ferruginised glacigenic sediments from the Lake Lea Valley, western Tasmania, give a paleomagnetic pole position consistent with a pre-Pliocene, probably mid Miocene age for the ferruginisation. Uranium-thorium dating of the ferricrete gives an infinite age, indicating that it has been a closed system since at least the mid-Pleistocene, which is consistent with the paleomagnetic results. They are both minimum dates for the host glacigenic sediments and suggest that the Lake Lea valley was glaciated before the mid Cenozoic.

Evidence for early Oligocene glaciation has previously been found in a core drilled at Lemonthyme Creek, Forth Valley (Macphail et al., in press). The early Oligocene event identified from the Lemonthyme core may correlate with major cooling of waters around Antarctica interpreted from Ocean Drilling Project cores from the Southern Ocean (Wei, 1991) and the Kerguelen Plateau (Zachos et al., 1992) ~35.5 Ma. It is not possible to correlate the Lake Lea glacial sediments with those from the Lemonthyme core, but the probable minimum age of mid-Cenozoic for the ferricrete magnetization suggests that glaciation of the Forth Valley during the mid Cenozoic was not an isolated event.

Palaeomagnetism of New Zealand glacigenic deposits

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The late Cenozoic record of glaciation of the Southern Alps is one of the most detailed in the Southern Hemisphere. Despite attempts to improve the resolution of the terrestrial record recent research has confirmed the presence of a gap in the terrestrial record of glaciation between 2.1 Ma and 0.35 Ma which has been attributed to the combined effects of rapid uplift and erosion. In contrast, evidence from South America and Tasmania suggest that glaciers were most extensive in the Southern Hemisphere middle latitudes at about 1 Ma. In these two locations palaeomagnetic studies have proven to be a useful means of identifying Early Pleistocene deposits on the basis of polarity of glaciolacustrine sediments. The Tasmanian research stimulated a pilot project that was designed as a simple test of the existing New Zealand stratigraphic model and to examine which lithologies preserved a stable magnetic remanence. Initial results suggest that some New Zealand deposits that were thought to be of Late Pleistocene age have a reversed polarity and therefore may be considerably older. In addition, the preliminary work suggests that some estuarine deposits and organic lacustrine sediments may not preserve a stable remanence. These initial results suggest that the gap in the terrestrial record of glaciation of the Southern Alps may be the result of accurate dating rather than to destruction of the record by the combined effects of uplift and erosion as has previously been suggested.

Phanerozoic Timescales

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A time framework is essential to any investigation of geological history. Traditionally, biostratigraphic zones based on palaeontological research provided relative age control for sedimentary sequences, a method subsequently augmented by isotopic dating of igneous rocks. In recent years, detailed investigations of magnetic reversals, sea-level oscillations, and other cyclical phenomena have provided new methods of age control.

Today the emphasis is on integration of these different data sets to provide a reliable timescale applicable to all aspects of earth history, including research into the development and structure of sedimentary basins which host Australia's major petroleum, coal, and sedimentary mineral deposits. This is a major aim of the Chronology of Sedimentary Sequences Project of the OSPG program in AGSO. The recently produced *Phanerozoic Timescales Series* provides a preliminary biochronological framework for the whole of the Phanerozoic, presented as charts for each of the 10 geological periods. This framework is based on local biochronological research within and between Australasian sedimentary basins, made necessary by the endemic (Gondwanan) floras and faunas resulting from Australia's palaeogeographic position on the eastern margin of Gondwana throughout much of Phanerozoic time. The *Timescales Series* subdivides the Phanerozoic into over 200 fossil zones directly applicable to Australian sequences, some representing durations of less than 0.5 Ma.

Current research has focused on improving the numerical calibration of these subdivisions by dating zircons using the SHRIMP ion microprobe facility developed at the ANU. The microbeam technique can date small samples from thin ash beds within sedimentary sequences, and is capable of accurately resolving magmatic zones in individual crystals from inherited and altered areas. Numerical calibration of biochronological zones with the precision (±1%) provided by SHRIMP zircon dating has given significant new results, and integration of other dating methods, particularly magnetostratigraphy, is seen as a high priority. Although data compilation is a significant component, the Chronology of Sedimentary Sequences Project is primarily research-driven, and emphasises testing between different data sets to resolve inconsistencies. Recent results which combine data from eastern Australia and the northern hemisphere include research to constrain the age of the Devonian-Carboniferous boundary, and of the Permo-Carboniferous Reversed magnetic superchron.

Application of multidisciplinary correlation techniques to the Cambrian-Ordovician boundary problem

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It is suggested that unambiguous correlation of potential Cambrian-Ordovician boundary stratotype sections in North America, Kazakhstan, China and Australia is only attainable when several correlation strategies are applied simultaneously to common sample sets. Few of the techniques commonly utilised, such as correlation based on conodont and graptolite biostratigraphy, stable isotope fluxes, history of magnetic polarity reversals and sea level changes, provide a satisfactory result individually. This is demonstrated by the continuing failure to secure the resolution of a global boundary stratotye section for the Cambrian-Ordovician boundary, despite intensive study. Used in combination, however, such techniques provide a powerful tool for the documentation and prediction of sedimentary and biological events, thereby becoming a sophisticated technique for detailed correlation between biostratigraphy and sequence stratigraphy. At Black Mountain, in the Burke River Structural Belt, Georgina Basin, western Queensland, a total of 190 samples were taken from a complete and continuous 1000 m thick measured section in carbonate rocks. These were examined for conodonts to provide a biostratigraphic framework and biochronologic dating, cored for magnetostratigraphic analysis, and the core ends used for stable isotope analyses. Strontium extracted from the conodonts is also currently under study. Results to date indicate a clear correlation between change in sea level, values of marine inorganic carbon, and conodont zonal boundaries reiterated over five conodont biozones. There appears to be a mechanistic link between sea level fall, minimum values of $\delta^{13}C$, and evolutionary change in cordylodid conodont lineages. It is unlikely that such links are confined to Black Mountain. If their extent is global in scale, this raises exciting possibilities for the definition of the Cambrian-Ordovician boundary.

Late Triassic magnetostratigraphy and implications on the origin and the evolution of Turkish blocks during the Triassic

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During the last few years, magnetostratigraphic results have been obtained for the Lower Mesozoic magnetic polarity time scale which follows the long Carboniferous-Permian reversed polarity period (Kiaman). We will present a synthesis of the Late Triassic magnetostratigraphic data we have obtained from Carnian to Norian sections from southwestern Turkey. The two studied sections (Bolücektasi Tepe and Kavur Tepe sections) provide a sequence of about 40 magnetic polarity intervals during the Lower Carnian and the Norian. We also have reviewed the available magnetostratigraphic results obtained for the Early Triassic and Permian. All together, these results probably yield a good picture of the Paleozoic and Lower Mesozoic magnetic polarity time scale. The magnetic reversal frequencies which can be derived from these results show a pattern in rough agreement with the suggested 150-200 Ma time constant in the reversal process since the Kiaman superchron.
The Taurus (southwestern Turkey) consists of several nappes of uncertain and debated origin. To provide new temporal and spatial constraints, about paleogeographic belonging, we carried out a new sampling of paleomagnetic sites in the Upper Antalya Nappes (UAN) unit. Magnetostratigraphic correlations are quite positive and the following paleogeographic results are obtained: (i) The Kemer Gorge unit appears to be the northernmost unit of the UAN with a paleolatitude of 20.9^0N $\pm$ 2.3^0 during the Late Triassic; (ii) The Bakirli Dag unit had a paleolatitude of 7.4^0N $\pm$ 2.3^0 during the Carnian and of 13.7^0N $\pm$ 3.3^0 during the uppermost Carnian-Middle Norian. This paleolatitudinal evolution is accompanied by a large clockwise rotation (29.5^0 $\pm 6.7^0$) which may correspond to the breakup of the north African margin during the Middle-Late Carnian; (iii) The paleomagnetic results obtained from the Kavur Tepe section, previously considered as belonging to the UAN, lead to a paleolatitude of 17.4^0S $\pm$ 1.1^0 during the Norian. This result surprisingly locates this unit in the vicinity of the Northern Indian margin.

Magnetostratigraphy of Glacial Lake Sediments and the Ages of Tasmanian Glaciations

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Morphological and stratigraphical studies of Tasmanian glacial landforms and deposits, coupled with the application of radiocarbon and relative dating techniques had indicated three major periods of glaciation during the Late, Middle and probably Early Pleistocene. These glaciations were initially termed the *Margaret, Henty* and *Linda*, though later work suggested greater complexity of glacial events particularly during the Henty and Linda.

Application of palaeomagnetic techniques to glacial lake sediments associated with the pre Last Glaciation drift sheets allowed separation of the older drifts into those with dominant normal polarity and those with dominant reversed polarity. The former, of Brunhes Chron age, dates the drifts as Middle Pleistocene while the latter indicate drifts of Matuyama Chron age. Analysis of mean directions of magnetization and α_{95} cones of confidence indicate that several glaciations probably produced the old weathered drifts of Tasmania that were formerly related to the *Linda Glaciation*, and several glaciations or phases of glaciation produced the less weathered drifts formerly mainly related to the *Henty Glaciation.*

What can mound-building termites tell us about palaeomagnetism?

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The accurately-aligned, tombstone-shaped termite mounds in northern Australia can be explained by supposing that the termites have a genetically-fixed mound-orientating behaviour that uses directional cues from the geomagnetic field. Such a behaviour appears to impose constraints on the secular variation of the geomagnetic field over the evolutionary history of the termites.

Applying Environmental Magnetism To Sediment Tracing

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Magnetic minerals can be used to trace suspended and bed-load sediment in fluvial environments. The method is based on the assumption that sediment transport mechanisms have an averaging effect as sediment is delivered to stream channels and then transported for some distance over some period of time. The amount of time and length of channel in which an average sediment mix may occur will depend on the size and other characteristics of the upstream catchment. Low concentrations of magnetic minerals in sediments also tend to be uniformly mixed, resulting in linear relationships between environmental magnetism parameters. It has been empirically demonstrated that these relationships, and therefore the assemblages of magnetic minerals from which the relationships originate, are spatially and temporally constant in the fluvial environments studied. Given that the tracing parameters are stable, they must also be able to distinguish between different sources.

Adjacent catchments that have different rock types usually produce distinctive magnetic parameter relationships. At confluences these relationships can be used to determine the proportionate sediment contributions of each catchment. Using this method, the principal source catchments can be ascertained by a progressive sequence of confluence measurements along a drainage network.

Examples of the application of the tracing method for suspended and bed-load sediments are presented. The technique can be used to establish spatial and temporal links between upland erosion and downstream sedimentation. Monitoring relative sediment contributions at confluences provides information about the temporal variability of sediment delivery. Alluvial deposits are also a source of temporal data about changes in sediment sources. Bed-load sediment movement in channels can be studied where magnetically distinguishable sediment pulses are detected. The close relationship between sediment and associated pollutants and nutrients means that a rapid, relatively inexpensive way of tracing water quality problems is available using environmental magnetism.

Beyond Susceptibility: Identification of Magnetic Components in Marine Sediments

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The application of 'environmental magnetism' has mostly been directed towards studies of detrital components in which magnetic minerals are used as sediment tracers. In the marine environment detrital components occur with authigenic and biogenic magnetic fractions to give a very complex assemblage of magnetic minerals. In these conditions conventional application of environmental techniques was found to lead to misleading interpretations, mostly because the techniques are not designed for interpretation of multi-mineral assemblages. Several new techniques were developed to distinguish component mineralogies in marine sediment samples from the Tasman Sea.

High calcium carbonate content in some cores makes reliable calculation of the frequency dependence of susceptibility impossible. A new method was developed to express superparamagnetic content using the differences between rescaled values of susceptibility and SIRM: σ values.

Mixing between ferrimagnetic and antiferromagnetic components can be distinguished by plotting normalized backfield remanences. End-members and mixing lines are readily apparent. In addition to the conventional mineralogies, magnetite and haematite, ?maghemite appears to be distinguishable. The contribution of this component (termed 'D') can also be isolated and plotted as a function of core depth.

The determination of magnetite grain-size is a primary aim of many mineral magnetic studies. It was found that parameters such as χ_{ARM}/SIRM and IRM_{20}/ARM do not give unambiguous interpretations of magnetite grain-size in mixed assemblages. Haematite has similar values of both parameters and, when mixed with a uniform fine magnetite population can give a range of values of either 'size' parameter which could be interpreted as resulting from a continuum of magnetite size fractions. Real size variations can be distinguished in plots of either 'size' parameter against normalized backfield remanence.

The 'hard', antiferromagnetic, component was found to be most reliably interpreted from IRM_{-300}/SIRM. Some ferrimagnetic components contribute to the S-ratio (IRM_{-100}/SIRM), but are reversed by the higher field.

In all, magnetic minerals in these marine sediments were found to be responsive to their chemical environment and therefore provide a record of palaeoceanographic conditions rather than detrital inputs. There is therefore a need for some caution when interpreting mineral magnetic results from marine records.

Paleomagnetic measurements on Quaternary corals, Huon Peninsula, New Guinea

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The spectacular uplifted coral reefs of Huon Peninsula represent one of the most complete records of sea-level change over the last 300,000 years. The reefs contain unrecrystallised corals in original growth positions, which I surmised might preserve a magnetic remanence from the time they grew. Oriented paleomagnetic samples were drilled from 15 well preserved coral specimens, and one giant clam (Tridacna gigas), in various reefs up to 200,000 years old. Most of the corals were the genus Porites, which has a massive, dense skeleton, and which can readily be assessed as being in growth position or otherwise. One specimen of the genus Goniastrea, was sampled in growth position from a recently uplifted (May 1992) area of the modern reef. At one Holocene site two adjacent Porites corals were sampled, one in growth position, and the other upside down but clearly cemented within the reef structure.

Between 4 and 12 cylindrical specimens from each coral and clam were measured on a two-axis cryogenic magnetometer at Victoria University of Wellington. NRM intensities in the corals range between xxx and yyy mA/m, and in the giant clam between xxx and yyy mA/m. In most cases a close clustering of NRM directions was obtained. Stepwise alternating field (a.f.) and thermal demagnetisations were carried out on a number of specimens. A strong secondary component of magnetisation in some specimens was not removed by a.f. cleaning, but successfully removed in others by thermal cleaning. Results so far indicate that the corals do indeed carry a stable remanent. Further paleomagnetic and rock magnetic measurements are in progress to identify the remanence carrier(s).

Pleistocene stable oxygen-isotope signal from the upper-slope east of the Great Barrier Reef

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A coherent, high-resolution, oxygen-isotope signal has been established from planktonic foraminifers for the upper 220 m of Site 820 in 280 m of water off the northeastern Australian margin.

Isotope stages 1 to 32 have been interpreted on the basis of pattern-matching with other deep-sea cores and guided by the paleontological datums from Hole 820A established during the drilling operations. On these bases, we think that isotope stages 4,7 and 23 are missing and are represented by three hiatuses at depths of 8.02 to 12.1, 34.55 to 35.8 and 146.28 to 150.98 mbsf.

Using isotope data from Hole 677A as a reference curve, a regional isotopic change for the northeastern margin has been calculated that, if interpreted in terms of local temperature variations, indicates an increase in sea-surface temperatures of approximately 4^0C during isotopic stages 11 to 8.

Visual examination of the isotope curve indicates a marked change in amplitude and frequency of the isotope signal at about 80 mbsf. Frequency analyses confirm a major change in frequency of $\delta^{18}O$ values for intervals younger and older than 400 k.y., that corresponds to both a marked temperature change and changes in depositional styles at Site 820. We suggest that these phenomena are related, and may have catalyzed the growth of the Great Barrier Reef.

Magnetic record of Quaternary change near the Great Barrier Reef (ODP Leg 133)

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Palaeomagnetic and rock magnetic properties have been determined for sediment cores collected during ODP Leg 133 from the continental slope adjacent to the Great Barrier Reef (GBR). Magnetic susceptibility appears to reflect cyclic glacio-eustatic sea level variations, and shows a strong inverse correlation with both $\delta^{18}O$ and carbonate content. However, during the last several glacial maxima there are marked changes in magnetic properties, largely grain size-related, with sharp peaks in susceptibility. These are accompanied by a reversal of the $\delta^{18}O$ - susceptibility phase relationship. A possible explanation can be found in terms of fluvio-deltaic processes and inter-reefal lagoonal reservoirs that develop during times of low sea level and become reworked during transgressions. The relative importance in this process of climate-controlled run-off conditions on the mainland, has yet to be established. Overall, there is a modulation of the magnetic susceptibility records from different sites that appears to be related to the initial growth of the GBR and its subsequent evolution. Prior to about 0.8-0.75 Ma the susceptibility record is characterized by relatively smooth cyclic oscillations. From thence to about 0.45-0.35 Ma susceptibility values remained low. Thereafter the susceptibility records show a characteristic pattern of sharp peaks associated with glacial maxima/early transgression. The two age boundaries thus defined by the magnetic data are related, respectively, to the prograding-plus-transitional seismic geometries associated with the initial formation of the GBR, and to a change in shelf/slope sediment dynamics that coincides with a change in the frequency spectrum of the $\delta^{18}O$ record. Similarity between the marine susceptibility record and its counterpart from lakes in SW Victoria can be used to infer a link between sea level and lake level fluctuations during the Holocene.

Geodynamics of the Balleny Seamount Chain and implications for Australian APWP

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Seamount chains are a primary source of data on lithospheric plate motions relative to the mantle and hotspot reference frame[A-C]. They also provide an independent test of geomagnetically derived plate motion paths. The Balleny Seamount chain is a 4000km long seamount chain, which on recent work[F,J] has been traced from the Balleny Islands at 67^{0}S in the Ross Sea sector of the Southern Ocean to 36^{0}S in the central Tasman Sea (Fig.1). To identify the seamounts, we used a combination of techniques including bathymetry[D-G], seismic profiles[E,I], high-resolution satellite gravity data[K-M]. The chain is marked by two changes of direction and at least one insertion of younger crust - events which represent past changes of absolute motion and/or transfer of the volcanic centre from one plate to another across a spreading ridge. Thus, it is divided into four approximately linear segments:

A, passing west-south-west from Seamount 'LH15' on the west flank of the Lord Howe Rise at 35^{0}40'S 161^{0}15'E, past the Heemskirk-Zeehan Seamounts, to near 38.2^{0}S 157.2^{0}E in the central Tasman Sea;
B, from near seamount CT3 at 38^{0}17'S 154^{0}17'E, southwest to near seamount 'Kl' at 42.2^{0}S 149.2^{0}E and southeast of Tasmania; includes Janszoon and Soela Seamounts;
C, thence south beyond seamount 'Q' at 55^{0}50' S 152^{0}22'E; and
D, embracing the Balleny Islands from Slava Bank at 65^{0}27'S 161^{0}00'E to south of Sturge Island.

At least 2 close and parallel tracks exist within the chain, as evidenced by: (i) the scatter of seamounts within the 100km cross-chain width; and (ii) most particularly by the ANARE Seamounts[M,N], which straddle the Balleny Islands. It is clear from bathymetric and gravity data[M,N] that no link exists between the Balleny Islands or the ANARE Seamounts and fracture zones of the Southern Ocean Spreading Ridge.

Radiometric (K-Ar) and palaeontological dating was carried out[F] on several of the seamounts with these results: (i) the twin seamounts Heemskirk and Zeehan[Y], yielding K-Ar radiometric ages of 59-71Ma; (ii) chalk with volcanic debris and from the summit of Janszoon Seamount[Z] contained a Late Eocene-Early Oligocene (29-39Ma) foraminiferal assemblage; (iii) volcaniclastic sandstone from Soela Seamount yielded foraminifera of Eocene age (35-39Ma); (iv) hawaiite basalts from Sturge Island[N] were isotopically (K-Ar) dated as 1.8Ma.

In addition to these direct dating methods we could confidently assign approximate ages to parts of the chain based on geodynamic arguments.
(i) The abrupt northern end of the Balleny group at Slava Bank[M,N] signifies the transfer of the volcanic activity to the Antarctic Plate across the Southern Ocean Spreading Ridge. Accordingly, the northernmost Balleny group seamount is dated at approximately 10Ma - the age of the underlying crust[P,Q].
(ii) The strong change of direction SE of Tasmania and between segments B and C

without having crossed an active spreading ridge. The seamount radiometric and biostratigraphic dates show that the bend is approximately at 40Ma, identifying it with the 43Ma Emperor-Hawaiian bend[C] and plate motion reorganization.
At this stage we cannot determine if the Tasman Sea Spreading Ridge was active when the line of seamounts transferred from the Lord Howe Plate to the Australian Plate, i.e., from segment A to B.

Based on bathymetrically determined positions for the largest seamounts and allowing up to 3 parallel traces of volcanism calculations were made of the plate motion poles, directions and rates[V]. Table 1 list the results. The 47 mm/yr northwards motion of the Australia Plate indicated for segment C is much less than the 63 (to 71) mm/yr measured for the 6-24Ma old Tasmantid Seamounts because a period of slow Australia-Antarctic separation prior to 35.5Ma (21.8mm/yr; A13m to A20y) is included in Segment C. An exceptionally good correspondence exists between the Australia Plate Motion calculated from the derived poles of rotation and the recent smoothed Australian Apparent Polar Wander Path by Musgrave[G] that incorporates igneous and laterite palaeomagnetic data. A good match is obtained in terms of APWP location and ages.

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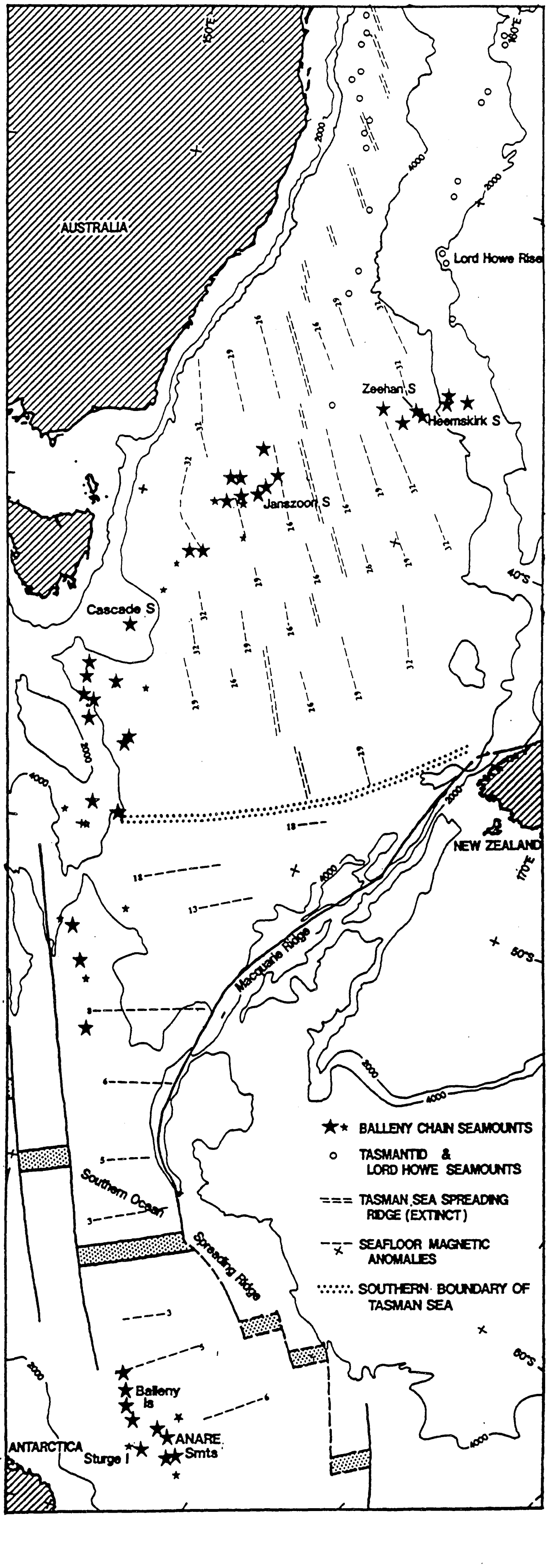

AUSTRALIA
150°E
160°E
Lord Howe Rise
Zeehan S
Heemskirk S
Janszoon S
Cascade S
40°S
NEW ZEALAND
170°E
Macquarie Ridge
50°S
Southern Ocean
Spreading Ridge
60°S
Balleny Is
ANARE Smts
Sturge I
ANTARCTICA
BALLENY CHAIN SEAMOUNTS
TASMANTID & LORD HOWE SEAMOUNTS
TASMAN SEA SPREADING RIDGE (EXTINCT)
SEAFLOOR MAGNETIC ANOMALIES
SOUTHERN BOUNDARY OF TASMAN SEA