Earth and Planetary Science Letters 40 (1978) 91–100

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THE PRECAMBRIAN-CAMBRIAN BOUNDARY PROBLEM: PALEOMAGNETIC DIRECTIONS FROM THE AMADEUS BASIN, CENTRAL AUSTRALIA

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Received January 31, 1978
Revised version received February 21, 1978

Late Precambrian to early Cambrian sediments of the Amadeus Basin, Central Australia, contain two stable directions of magnetization. Lithologies are diverse and include red beds, green beds, and carbonates, all of which respond to thermal cleaning. Positive fold and unconformity tests, and a well-defined polarity zonation reveal the primary component and direction of magnetization. This direction lies between those reported for the Proterozoic lower Pound Quartzite and the lower Cambrian Antrim Plateau Volcanics of Australia. Poles calculated from the primary direction of magnetization for three stratigraphic units in the sequence overlap at the 95% confidence level, indicating that little apparent polar wander occurred in the Australian part of Gondwana at this time.

1. Introduction

A magnetic polarity zonation from Late Precambrian and Early Cambrian sediments of the Amadeus Basin, Central Australia, is described elsewhere [1]. Paleomagnetic samples in that study were collected at about 1-m intervals from an 800 m thick sedimentary sequence that crosses the Precambrian-Cambrian boundary. A large difference in magnetic reversal frequency across the sequence is revealed by thermal demagnetization. The lower 500 m contains two magnetozones whose contact is marked by a polarity transition that lies in the lower member of the Arumbera Sandstone. The upper 300 m of section are characterized by mixed polarities with, as yet, an incompletely determined number of magnetozones. Paleomagnetic tests presented in this paper suggest that one component of the stable magnetization was acquired in a geologically short time after deposition, and that this magnetization therefore is equivalent in age to the fossils in the sequence. Apparent pole positions computed from this primary direction should be characteristic of latest Precambrian and early Cambrian strata on the Australian part of Gondwanaland, and therefore of use in establishing correlations at or near the Precambrian-Cambrian boundary.

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2. Structure, stratigraphy, and age

The geologic structure at four sampling localities in the Amadeus Basin (Fig. 1) is simple. A geologic map of the area having the best exposure, Ross River, is shown in Fig. 2. This area is on the north limb of an east-west-trending syncline, and samples were obtained from strata exposed by the Ross River. The strata dip uniformly between 36° and 37° to the south, with no other structural complications. Similar sections are exposed at the other three localities, Valley Dam, Aeryonga Gorge, and Central Mt. Stewart, although structural attitudes are different. Structural deformation in the basin was mainly produced by the Lower Paleozoic Alice Springs orogeny [6]. The orogeny was centered north of the major sampling localities, and did not metamorphically

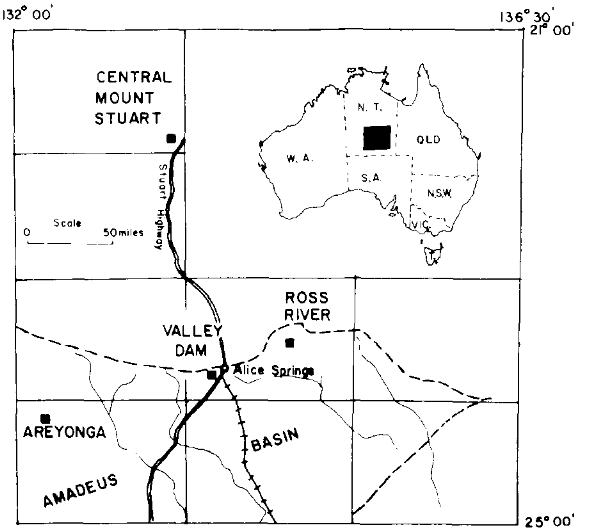

Fig. 1. Location of magnetostratigraphic sections in Central Australia. The dashed line is the approximate erosional edge of the Amadeus Basin.

alter the sediments within the basin.

The stratigraphic section for the northern part of the Amadeus Basin is summarized in the explanation for Fig. 2. The oldest sediments sampled are from interbedded green and red siltstone directly below pale carbonate and shale of the Julie member of the Pertatataka Formation. The basal part of the Arumbera Sandstone, which conformably overlies the Julie member, is an extremely fissile red claystone that grades upward into fine- and medium-grained reddish sandstone. Within much of the Arumbera Sandstone, there are occasional pale greenish-gray ledges that may be traced laterally for several hundred meters. A disconformity marking the Precambrian-Cambrian boundary separates the Arumbera Sandstone from overlying greenish shale and sandstone of the Box Hole Formation [2]. The Box Hole in turn is comformably overlain by red sandstone of the Allua Formation. The youngest rocks sampled are from interbedded reddish and pale gray carbonate of the Todd River Dolomite, which gradationally overlies the Allua Formation.

The presence of soft-bodied metazoan fossils of the Ediacaran and Mt. Skinner fossil assemblages have led paleontologists [2,3] to infer a Precambrian age to formations stratigraphically equivalent to or below the Arumbera Sandstone, whereas trace fossils and archeocyathids in overlying formations belong to the lower Cambrian. The unconformity between the Arumbera and Box Hole Formations has apparently deleted all rocks of Tommotian age, as the overlying units have strong fossil affinities to the Atdabanian and Lenian stages of the Siberian Shield (F. Debrenne and A.Yu. Rozanov, personal communication, 1978). The time represented by the sedimentary sequence studied may be estimated only in a rather crude manner. A single radiometric age reported for the late Precambrian part of the sequence [6] is a Rb/Sr date of 760 m.y. from shale of the lower Pertatataka Formation from the Ooramina No. 1 bore hole. The thickness of the Pertatataka in the northern part of the Amadeus Basin is 1092 m, and the thickness of the overlying Arumbera is 400 m [6]. Daily [2] has placed the Precambrian-Cambrian boundary at the disconformity between the Arumbera Sandstone and the Box Hole Formation. If the age of this boundary is assumed to be 580 m.y., 1492 m of sediment were deposited in 180 m.y., for an average sedimentation rate of 8.3 m/m.y. If this estimate is accepted as a minimum sedimentation rate for the 800 m of strata sampled in this study, it implies that deposition for the sequence spans a maximum interval of about 96 m.y.

3. Field and laboratory procedures

Each of the four localities described in this paper have been sampled across continuously exposed sections; spacing between samples commonly is about 1 m. Consequently, no attempt has been made to subdivide the sections into discrete paleomagnetic sites as has been the common practice in the past. Samples were taken either as oriented blocks or as 2.5 cm diameter cores in a manner similar to that used by Doell and Cox [13]. Between one and five 2.5 × 2.0 cm cylindrical specimens were cut from each sample for paleomagnetic analysis, and every specimen considered in this study was subjected to an average of 9 progressive thermal demagnetization steps.

All magnetic measurements were made at the Australian National University on a two-axis shielded, superconducting rock magnetometer interfaced to a mini-computer for on-line data reduction. Stepwise thermal demagnetization in air was carried out in two

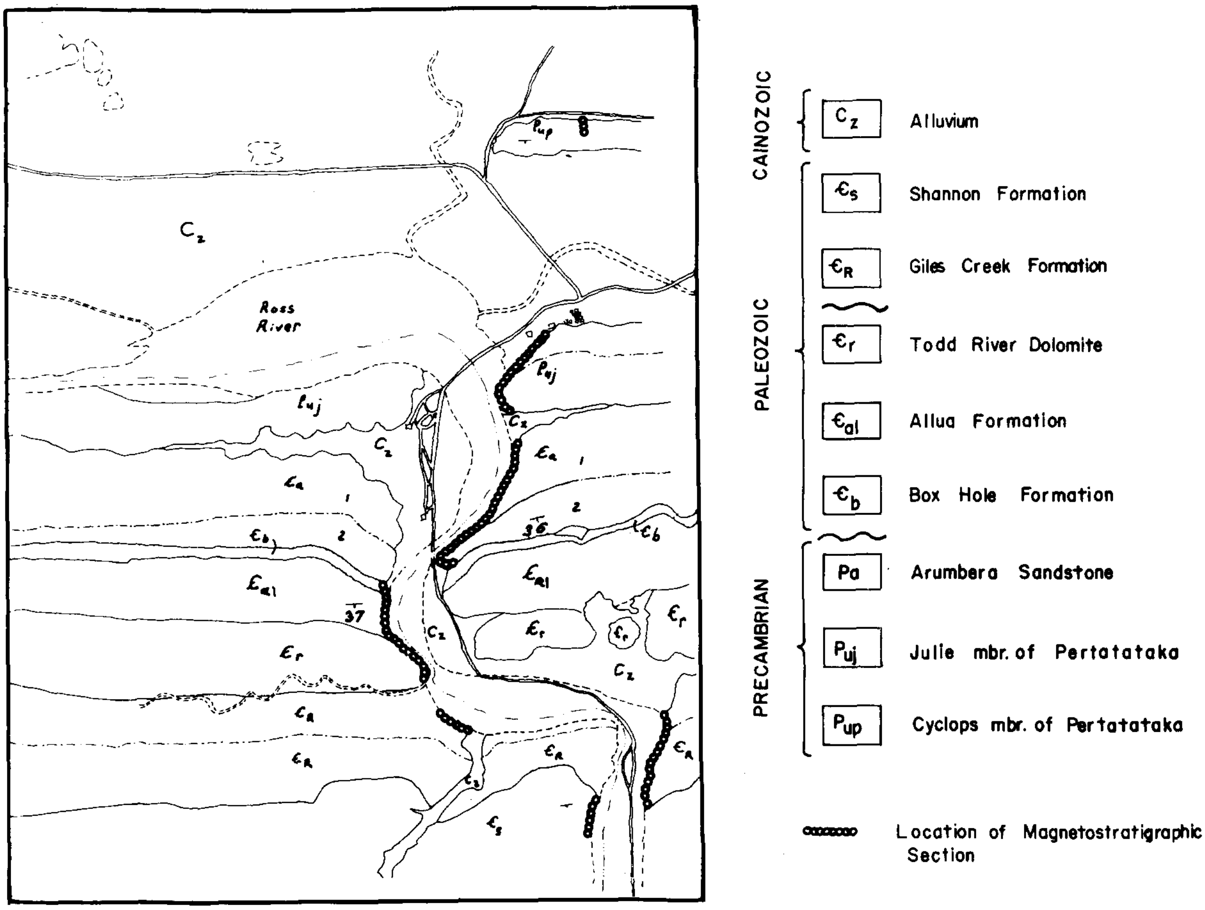

Fig. 2. Geologic map of the Ross River locality, Northern Territory, Australia (lat. 23.6°S; long. 134.5°E). The geology is after Wells et al. [6], with the new formation names of Daily [2]. Ross River has the most continuous exposure of all four localities.

TABLE 1

Summary of paleomagnetic measurements from the Amadeus Basin of Central Australia

Locality	Site latitude and longitude	Average bedding at site	Number of samples	Number of specimens	Number of magnetic measurements	Samples used for primary direction
Ross River	23.6°S, 134.5°E	N95°E/37°S	391	516	4,219	50
Valley Dam	23.8°S, 133.6°E	N72°E/68°SE	220	306	3,513	28
Areyonga Gorge	24.1°S, 132.3°E	N119°E/57°SW	138	204	2,130	23
Central Mt. Stewart	21.9°S, 133.4°E	N252°E/12°N	41	84	928	2
		Totals	790	1110	10,790	103

fast (40 samples/hour), non-magnetic ovens situated in feedback controlled Helmholtz coils [4]. Throughout the demagnetization and measuring process, the specimens were stored in low magnetic fields provided by Helmholtz systems and portable Mu-metal shields. In particular, exposure to the Earth's magnetic field was avoided during the time between individual demagnetization steps. Each complete measurement consisted of 8 readings of magnetization perpendicular to the axis of the cylindrical specimen and 8 parallel to it, for a total of four measurements with the specimen's orientation mark directed upwards and four with it downwards. This four-fold redundancy provides a direct check on the consistency of measurements and homogeneity of the magnetization. Between 50 and 100 samples can be measured each hour on the computerized system. A summary of the data set generated for this study is shown in Table 1.

4. Paleomagnetic results

4.1. Demagnetization analysis

Demagnetization properties of samples of the different lithologies from the Ross River locality (Figs. 1 and 2) are summarized in Figs. 3 and 4, and discussed below.

Vector demagnetization diagrams of representative samples from reddish lithologies are shown in Fig. 3. Natural remanent magnetization (NRM) intensities, which are between 10^{-5} and 10^{-6} emu/g, decrease steadily upon thermal demagnetization. Sample ARR-1, from extremely fissile, red claystone at the base of the Arumbera Sandstone, consistently maintains reversed polarity throughout thermal cleaning. Similarly, sample ARR-35, from a fine-grained red sandstone a few meters above the polarity transition, yields a consistent normal magnetic direction above 300°C. Behavior of the reddish carbonates during demagnetization (e.g., sample ARR-210) is similar to that of the other red beds. The existence of a magnetically hard remanence in all reddish samples after demagnetization to temperatures near 670° indicates that the stable magnetization is carried by hematite. Stable end points are not arrived at in all of the reddish samples, but the demagnetization paths commonly can be used for interpretation of polarity. A consistent magnetic overprint was not observed in the reddish samples.

The NRM intensities of the green sediments and pale gray carbonates vary greatly, but they are generally weaker than corresponding intensities of the red materials. Demagnetization behaviors of these rocks from the Ross River locality are shown in Fig. 4. Some samples (e.g., TRR-44, ARR-608, and PRR-106) lose between 70 and 95% of their NRM intensity at temperatures of 150°C or less, reflecting the removal of a very large magnetic component with a low blocking temperature. The remaining magnetic components exhibit two distinct directions and polarities. The first direction is identical to that seen in the reddish sediments and has both polarities; the second direction exhibits a single reversed polarity and lies about 50° from the first. Samples PRR-106 and ARR-608 show the latter behavior and the directions are interpreted to have been acquired as a consequence of post-depositional remagnetization. In contrast, samples TRR-44 and TRR-45 clean to antiparallel directions that are in good agreement with the clean directions from the red samples. Thermal demagnetization steadily removes the remanence from these samples to a temperature of 425°C. However, between 425° and 500°C, the samples either lose all of their magnetization or undergo chemical changes and start acquiring viscous moments (e.g., sample ARR-608). It commonly is not possible to accurately determine the magnetic polarity of the remagnetized green sediments, as primary components rarely remain; however, many remagnetized carbonates move toward Cambrian directions upon demagnetization. No consistent lithologic differences were noticed between samples with the two types of behavior, but the carbonates in the Pertatataka Formation more commonly possessed the overprint than other units in the sequence. Limestone and dolomite both possessed each type of magnetization, so the secondary component probably was not a result of dolomitization.

4.2. Interpretation of vectors

Precambrian to Early Cambrian sediments of the Amadeus Basin variably possess combinations of several paleomagnetic components of differing sta-

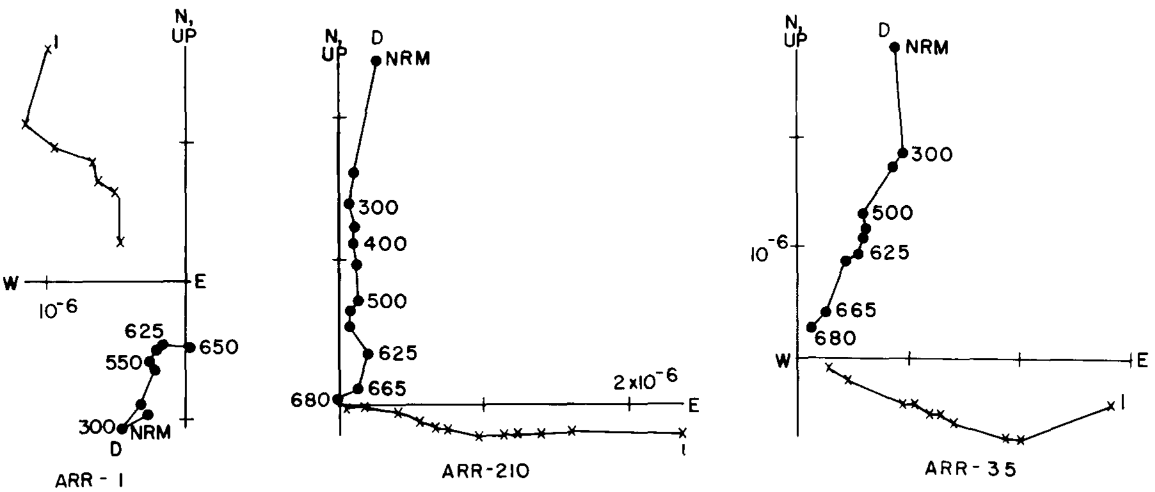

Fig. 3. Vector demagnetization diagrams for red sediments. Samples ARR-1 and ARR-35 are from the Arumbera Sandstone at Ross River. ARR-1 is a fissile claystone at the base, and ARR-35 is a fine-grained sandstone a few meters above the polarity transition. ARR-210 is a red limestone from the base of the Todd River Dolomite at Ross River.

Each plot has two paths, labelled *D* for declination or *I* for inclination of directions after structure correction. The inclination paths show the horizontal component of magnetization, plotted with respect to the vertical component. Numbers alongside the declination plots refer to the maximum demagnetization temperature in °C. The distance of the inclination data point from the origin represents the intensity in electro-magnetic units per gram (emu/g).

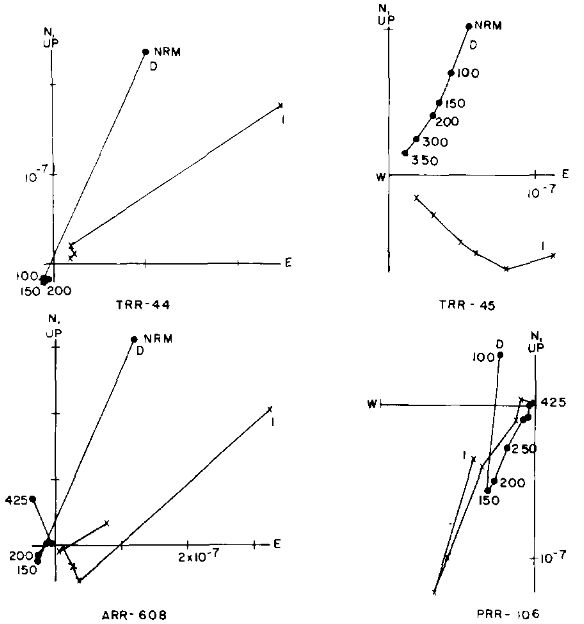

Fig. 4. Vector demagnetization diagrams of green sediments and pale carbonates. Symbols and explanations are given in Fig. 3. TRR-44 and TRR-45 are dolomites from the Todd River Dolomite. PRR-106 is a gray limestone from the Julie member of the Pertatataka Formation. The NRM from this sample has been omitted due to its unusually strong intensity. ARR-608 is a green shale from the Box Hole Formation. TRR-44 and TRR-45 have directions interpreted as primary, while PRR-106 and ARR-608 have the secondary overprint.

bility, which can be recognized by their demagnetization properties (Figs. 3, 4). The magnetic components with blocking temperatures below 150°C are ignored because (1) they vary greatly in direction, (2) are easily removed by thermal treatment, and (3) mostly can be attributed to remagnetization accompanying recent weathering. Above this temperature, some samples show erratic behavior whereas others demagnetize smoothly and produce linear traces on the vector diagrams. Linear behavior reflects the progressive removal of the same magnetic component during demagnetization. Such mono-component directions are valuable for revealing stable components of magnetization. For this study, only samples that display a single component through a temperature range of at least 150°C have been used, and stable directions have been calculated from these intervals by vector subtraction. For determinations of the primary direction, an additional constraint is invoked which requires that the origin of the diagram lies on the trend of the demagnetization path. The trend of the secondary overprint differs enough from the lower Cambrian direction so that the two directions and demagnetization paths are distinct. The number of samples used for the calculation of stable, primary directions is shown in Table 1.

4.3. Determination of primary magnetization

The polarity zonation reported for the Amadeus Basin [1] provides one test for the time of acquisition of the stable primary remanent magnetization. The zonation, examined with respect to an unconformity or disconformity, is termed here an "unconformity test". The logic, diagrammed for a hypothetical basin, is shown in Fig. 5. Sediments, faithfully recording the magnetic field as they were deposited, produced the indicated polarity zonation in the lower part of the section. At some point in time, labelled *A*, sedimentation was disrupted and erosion truncated the section, producing a break within the sequence. Renewed sedimentation resulted in deposition of strata in the upper half of the figure containing a younger polarity zonation. The unconformity truncates both the stratigraphy and its contained magnetic zones. This situation implies that the magnetozones, and hence the magnetizations, are older than the erosional event that truncated them. In many geologic situations a hiatus produced in this fashion is of short duration, and therefore is of nearly the same age as the rock sequence. A positive unconformity test therefore closely limits the age of magnetization. Magnetozones in the Amadeus Basin of Central Australia are truncated at the Arumbera–Box Hole contact [1, fig. 6], and therefore yield a positive test. The magnetization, then, is very nearly the same age as the rock, and, by extension, nearly the same

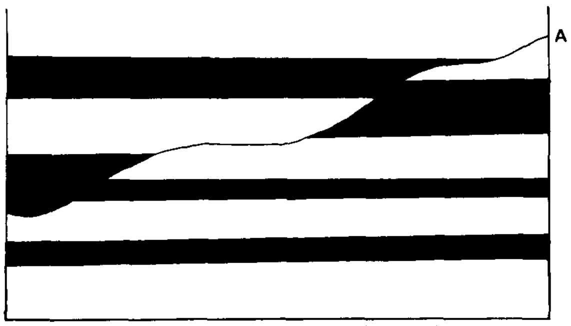

Fig. 5. The unconformity test. Magnetozones truncated by a break in the sequence imply that the magnetization defining the zones is older than the disruptive event.

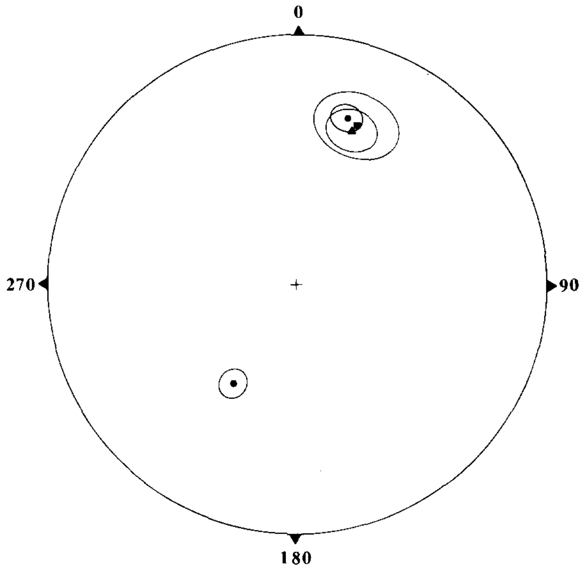

Fig. 6. Equal-area stereographic projection of stable selected mean directions from the Amadeus Basin. Directions have been corrected for structure as given in Table 2. Precambrian primary directions: ■ = lower Arumbera Sandstone and Pertatataka Formation; ● = upper Arumbera Sandstone; Cambrian primary direction: ▲ = Todd River Dolomite, Allua Formation, and Eninta Sandstone; ● = secondary direction (Dev?) from all Ross River units.

age as the fossils within the rock. This is also supported by the existence of statistically antiparallel directions within the interval of mixed polarity.

The fold test of Graham [5] offers a second check on the time of acquisition of the magnetization in the Amadeus Basin. However, before it can be applied to the sequence, it is necessary to determine whether significant amounts of apparent polar wander have occurred in the time interval covered, which, as noted previously, may be as long as 96 m.y. Results for the primary magnetic components have therefore been split into three groups based on the stratigraphy. These groups are (1) the Pertatataka Formation and the basal part of the Arumbera Sandstone, (2) the remainder of the Arumbera Sandstone, and (3) the Box Hole, Allua, Eninta and Todd River Dolomite Formations. The directions for each of these groups shown in Fig. 6 overlap at the 95% level showing that there was insignificant apparent polar wander during this time, and implying that all of the data may legitimately be combined for the fold test. The combined directions for all three groups are shown before and after the structure correction (Fig. 7).

Primary directions that pass the selection criteria come from four separate localities in Central Australia, each with distinct structural attitudes (Table 1). The fold test compares the grouping of the remanent vectors from all localities before and after the structural correction. If the grouping improves after correction, as measured by an increase in Fisher's kappa, the magnetization is more likely to have been present before the deformation occurred. Probability of significance may be assigned to the fold test because the ratio of kappa values follows the F-ratio distribution [7]. In this example, the kappa changed from 10.33 to 17.88 after correction for structure, yielding a ratio of 1.73. The combined 103 samples have $2(n - 1)$ or 204 degrees of freedom, which corresponds to significance at greater than the 99% level. Alternatively, if the four site-means are considered (d.f = 6) the kappa changes from 4.48 to 55.6, for a ratio of 12.1, which has the same high level of significance. This test only shows that the magnetization was acquired before folding, or, in this case, before the Alice Springs orogeny. It is therefore not as powerful as the unconformity test discussed earlier.

A stability test on the secondary direction is not possible because all of the samples that pass the selection requirements come from the Ross River locality and are of the same polarity.

5. Paleomagnetic poles

Average paleomagnetic directions, associated apparent pole positions, and Fisherian statistics have been calculated for the stable magnetic directions from the Amadeus Basin. Results are given in Table 2 and plotted in Fig. 8. The three primary apparent pole positions are derived from the stratigraphic units that were used in the fold test. All samples that have the secondary overprint and pass the data selection criterion were used for calculating the secondary direction, regardless of their stratigraphic positions.

The overlap of the primary directions indicates that there was very little apparent polar wander for Australia, and by implication for the Australian part of Gondwanaland during latest Precambrian and early Cambrian time. This is a "quasi-static" interval (after the terminology of Briden [8]). It is interesting to note that on the apparent polar wander curve for Gondwana of McElhinny and Embleton [9],

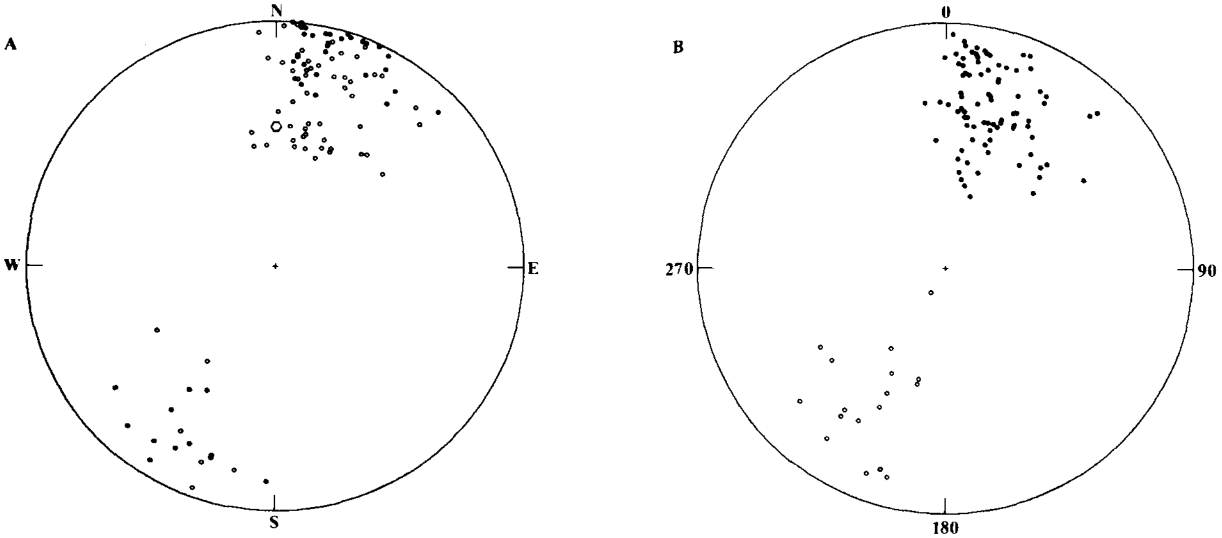

Fig. 7. Equal-area plots of primary directions which pass the selection criteria. A. Primary directions from all localities before correction for bedding. B. Primary directions after correction for bedding. Solid symbols denote lower hemisphere directions, and the open hexigon represents the recent local magnetic field direction.

TABLE 2

Stable paleomagnetic directions from Late Precambrian and Early Cambrian sediments of the Amadeus Basin, Central Australia

Stratigraphic units	Age	N	R	κ	α_{95}	$D(°)$	$I(°)$	Pole		δ_m	δ_p
								lat.	long.		
Primary directions: (corrected for structure)											
Todd River Dolomite, Allua Formation and Eninta Sandstone	Lower €	34	31.8	14.7	6.7	19.3	35.0	43.2	159.9	7.7	4.5
Upper Arumbera Sandstone	Late p€	57	54.5	22.6	4.1	16.2	31.2	46.6	157.3	4.6	2.6
Lower Arumbera Sandstone and Upper Pertatataka Formation	Late p€	12	11.2	14.0	12.0	20.2	32.4	44.3	161.9	13.6	7.7
Fold test statistics, all primary direction:											
before structure correction		103	93.12	10.33	4.56						
after structure correction		103	97.29	17.88	3.42						
Secondary direction: (corrected for structure)											
All units at Ross River, N.T.	Dev(?)	19	18.6	41.7	5.3	212.5	51.3	−60.2	68.1	7.1	4.8

there is a general clustering of directions in the neighborhood of the Precambrian-Cambrian boundary. The cluster might be the result of a sampling bias in the geologic record, but a simpler explanation is that the magnetic pole was there for a correspondingly longer time, and more rocks had the chance to become magnetized in that direction.

The origin of the secondary component of magnetization has not been determined. The random occurrence of this direction through the sequence argues strongly against remagnetization by a thermal event. Zeolites or other metamorphic minerals have not been detected at the localities in the Amadeus Basin, suggesting that burial pressures and temperatures were mild. The direction is found in both limestone and dolomite, which eliminates dolomitization as a cause. The paleomagnetic pole, calculated from the secondary direction before structural correction, is far away from the Australian apparent polar wander curve. After correction, it lies between results from the Australian Mereenie Sandstone (Silurian) and the Paterson Toscanite (Carboniferous) [10,11], suggesting that it is of Devonian age (Fig. 8). The remagnetization must have occurred shortly before or during the Devonian Alice Springs orogeny [6], possibly by a chemical process.

6. Conclusions

Two stable components of magnetization can be recognized from the Precambrian-Cambrian sediments in the Amadeus Basin of Central Australia. The direction that passes both unconformity and fold tests and that has a stratigraphically consistent magnetic polarity zonation is considered to be primary, having been acquired either during or else very shortly after deposition. Fossils within the sequence therefore date this magnetization as late Precambrian and early Cambrian. The lack of apparent polar wander indicates that the Australian part of Gondwanaland was "quasi-static" at this time. A secondary direction seen in some

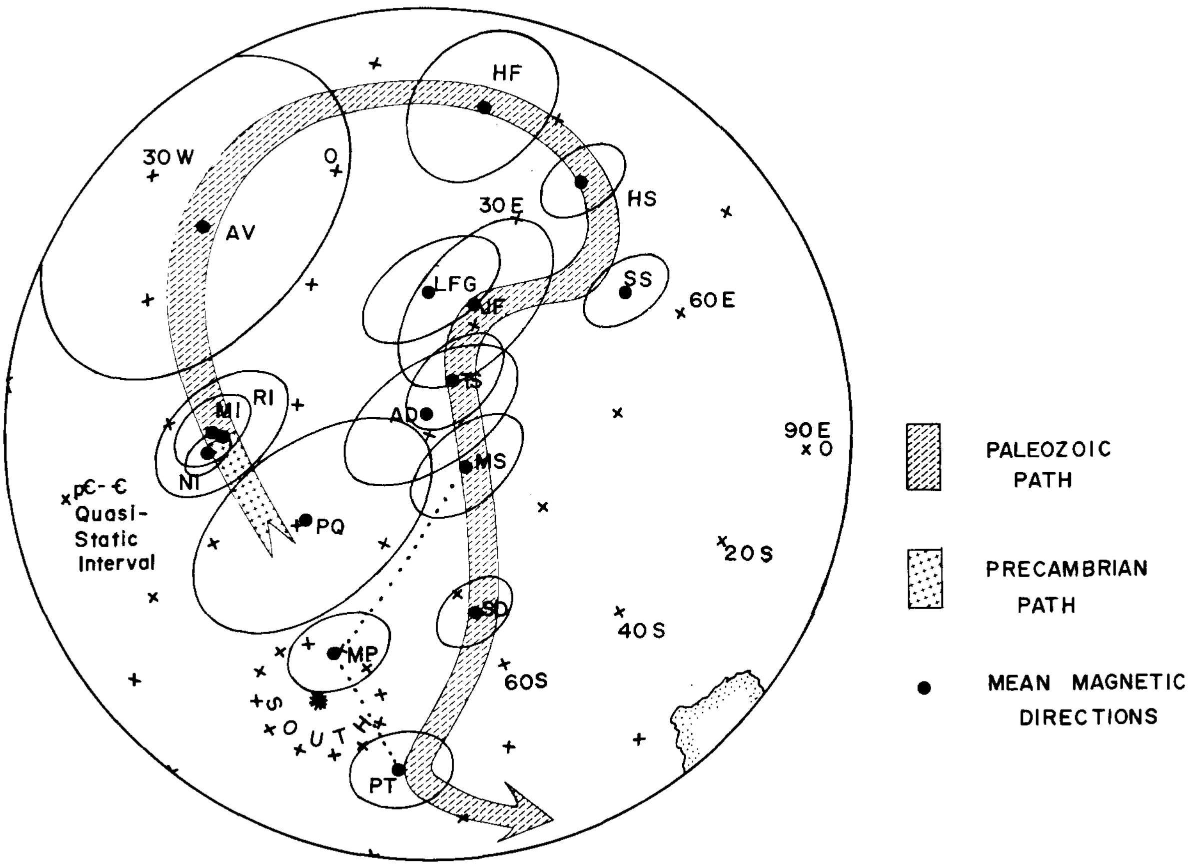

Fig. 8. Paleozoic apparent polar wander path for Australia. Exact ovals of 95% confidence are shown for lower and mid-Paleozoic results. The dotted line shows a portion of the curve previously noted to be ambiguous [11] which is inconsistent with the secondary direction reported in this study. MI = lower Cambrian formations, NI = upper Arumbera Sandstone, RI = Pertatataka Formation and lower Arumbera Sandstone, and SD = the secondary direction from this study. Other abbreviations are as follows: Precambrian: PQ = Pound Quartzite; Cambrian: AV = Antrim Plateau Volcanics, HF = Hudson Formation, HS = Hugh River Shale, LFG = Lake Frome Group, AD = Aroona Dam Sediments; Ordovician: SS = Stairway Sandstone, JF = Jinduckin Formation, TS = Tumblagooda Sandstone; Silurian: MS = Mereenie Sandstone (S?D), MP = Mugga Mugga Porphyry; Carboniferous: PT = Paterson Toscanite. Data tabulations have been given elsewhere [9,11,12].

of the non-red rocks probably was acquired during or shortly before the Devonian Alice Springs orogeny.

Acknowledgements

This work was supported through a fellowship for overseas study from the Thomas J. Watson Foundation. The author is grateful to E.M. Shoemaker of Caltech for the loan and use of a superconducting rock magnetometer. G. Green and D. Green of Ross River Tours, Pty., Ltd., gave valuable encouragement during the sampling. C.T. Klootwijk and M.A. Vincent of the Australian National University helped in various parts of the sampling. Magnetic measurements were made in the laboratory of M.W. McElhinny at the Australian National University, Dr. D.P. Elston of the U.S. Geological Survey edited and substantially improved the manuscript.

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