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Recognition of common Precambrian polar wandering reveals a conflict with plate tectonics

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The controversy concerning the applicability of plate tectonics to Earth processes during Precambrian time has centred on discussions of geological aspects of continental evolution, particularly the significance of mobile belts which seem to separate large tracts of cratonic nuclei[1–4] and on analyses of palaeomagnetic data[5–8] which could provide quantitative evidence defining the spatial relationships of the cratonic nuclei comprising continental mosaics. Briden[9] has described the salient features of the plate tectonic model in relation to geological processes for Earth history in pre-Mesozoic time. The results of the published palaeomagnetic analyses for North America[5,8,10], Africa[6,8] and Australia[7,8] strongly suggest that the cratons which comprise the individual continents retained their relationships for much of Precambrian time and that the younger, intervening mobile belts and major sutures did not result from convergence of previously widely separated microcontinents; their origin is ensialic. The implication is that tectonic styles have changed through geological time[8].

A landmass may be regarded as having existed as a single continent for a particular interval of time if the apparent polar wander paths (APWP) for the individual blocks or cratons coincide[6]. Collectively, they may be regarded as defining a master curve that describes the motion of the pole with respect to the continent. Of course, we rarely have a sufficiently complete data set to realise this ideal and we often need to resort to results from one block or craton to compensate for gaps in the record from other blocks. However, the overall continuity of the path is maintained and the known chronology of points on the APWP is not violated. On this basis APWP which have been constructed for North America, Africa and Australia have led to the conclusion that the three landmasses maintained their integrity for substantial amounts of Precambrian time. We have also included results from Greenland[11,12] for the period from ~1,700 to 1,600 Myr, although these data only come from one craton and its surrounding mobile belts.

For the present analysis we take the comparisons a stage further. Accepting that continental integrity has been maintained, what can be deduced about the relative positions of North America, Greenland, Africa and Australia during the Precambrian? As we are primarily interested in making intercontinental comparisons, we are constrained to comparing APWP for the interval of time where defined sections of the paths from more than one continent are available. In the time interval 2,300–1,600 Myr, which also covers the periods for which the palaeomagnetic data have been considered to indicate the existence of single continents, the APWP for North America has been constructed[8,10,11,13] and can be shown to be continuous without significant time breaks. Similarly, paths have been constructed for Africa[6,8] for the period 2,300–~1,900 Myr and for Australia[7,8] from ~1,800–1,600 Myr, again supporting single continent models.

Figure 1 shows the North American and African data for the period 2,300–1,900 Myr and Fig. 2 compares the data for North America, Greenland and Australia for the period 1,800–~1,600 Myr. The quality of the data has been discussed elsewhere[7,10,11,14] and reliability criteria have been implemented to designate pole status. The following discussion is based on a comparison of those data independently produced by a number of research groups using their own reliability framework.

The poles for the interval 2,300–1,900 Myr from North America and Africa respectively (Fig. 1) may be considered to define the same general track. The track for North America seems to be displaced a few degrees south of the track for Africa. This is a second order observation and may require further assessment.

The pole tracks for North America and Australia respectively coincide for the interval 1,800–1,600 Myr (Fig. 2). The tracks for Australia[7] and Greenland[11] have been drawn with a northward trend from ~1,700 to 1,600 Myr.

The North American track has previously been drawn to extend into the eastern Pacific Ocean at ~1,500 Myr[13,15]. However, this interpretation was based largely on an age of 1,500 Myr for the Western Channel Diabase. Subsequent radiometric evidence[16] no longer justifies extending the North American track westwards. Recent re-evaluations of the North American data[17,18] have lead to similar conclusions.

The observation that the polar tracks coincide is made without applying any continental reconstructions. The geocentric angle subtended from a point fixed within one continent to a point fixed within another continent (North America and Africa for the interval 2,300–1,900 Myr; North America, Greenland and

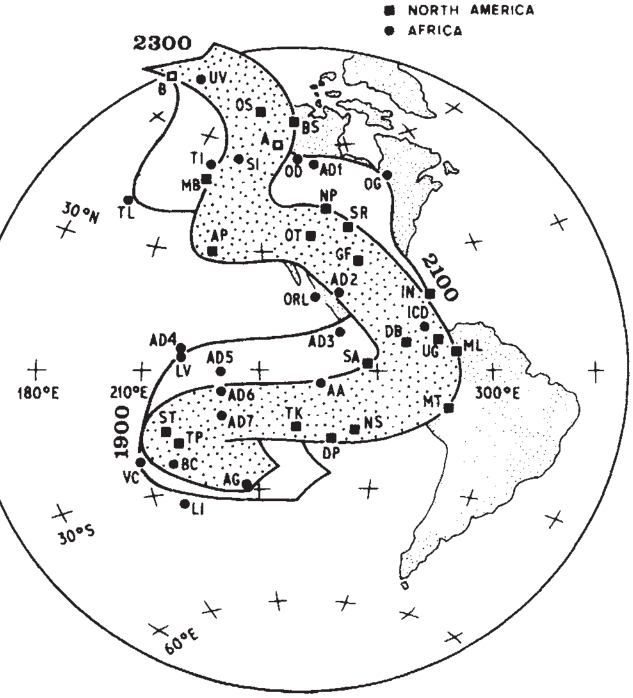

Fig. 1 APWP for Africa (unstippled) and North America (stippled) for the interval 2,300–1,900 Myr. Pole positions are identified for North America[13,15] and Africa (ref. 8 following Piper[24]) using mnemonics to represent rock formations. Note poles A and B (open symbols) plot on the obscured hemisphere.

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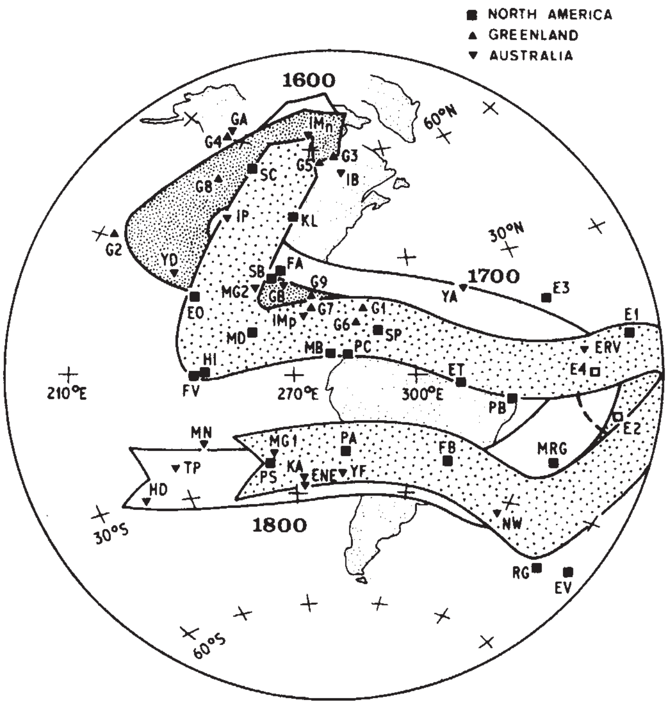

Fig. 2 APWP for North America (light stipple) and Australia (unstippled) for the interval 1,800–1,600 Myr, and for Greenland (heavy stipple) for the interval 1,700–1,600 Myr. Pole positions for North America are identified with mnemonics used previously[13,15] and by Schmidt[18]. Poles for Australia are identified following refs 7 and 8. ENE and NW are unpublished results from dykes from Northwestern Australia. They independently confirm the track already published[7,8]. Pole position mnemonics for Greenland follow Piper and Stearn[11]. Poles E2 and E4 plot on the obscured hemisphere.

Australia for the interval 1,800–1,600 Myr) is similar to the geocentric angle subtended by those same points with the continents in their present geometrical configurations. The four continents have also retained their same relative meridional orientations.

Relatively few palaeomagnetic data for the time interval 1,600–1,000 Myr are available and consequently APWP construction has not been so easily compared, for example, McElhinny and McWilliams[8] have considered the data for Africa for the periods 2,300–1,900 Myr and 1100–650 Myr, and for North America for the period 2,600–1,400 Myr. We have already noted that the North American track has been modified after 1,600 Myr. It is therefore inappropriate to extend the comparison to include the time interval of 1,600–1,000 Myr.

There is evidence[7] in support of Gondwanaland's existence during the time interval 1,000–600 Myr. The data come from most of the continents comprising the supercontinent. The requirement that the continents be reconstructed to satisfy the palaeomagnetic data, implies conversely that with the continents in their present positions, the poles remain scattered and preclude the construction of a common APWP. It has been noted[6,9] that the APWP for North America and Africa for this period are also quite different. A comparison of the Hadrynian track[14] (which from 950 to 670 Myr indicates polar movement from an equatorial region, across high latitudes to an equatorial position removed by 180°) with the African path from ~1,100 to 700 Myr (which exhibits polar movement from high latitudes through the Equator to opposite high latitudes[8]) further emphasises that Africa and North America have ceased to maintain the relative locations on the Earth's surface as occupied before 1,600 Myr. A transitional phase would seem to have begun, as the pole paths do not concur with the continents in their present locations. Relative drift is implied to satisfy the palaeomagnetic data.

Apparent polar wander for the Phanerozoic has been well documented[19]. Before the Mesozoic, the palaeomagnetic data are only satisfied by reconstructing continents to form supercontinents (for example, Gondwanaland); even Pangaea may have existed during the late Palaeozoic/early Mesozoic[9]. APWP do not generally overlap with the continents in their present positions.

That a single pole path can be constructed for continent pairs for the interval 2,300–1,600 Myr implies that little or no relative plate motion occurred between North America and Africa for the period 2,300–1,900 Myr and North America and Australia for the period 1,800–1,600 Myr. By restricting our analysis to reasonably well-defined APWP sections, speculation about relative plate motion in the Lower Proterozoic is thus minimised. Clearly, the most exciting observation from these data is the apparent affinity of continents to occupy certain locations relative to one another. We feel we can confidently reject the idea that the present relative positions of North America, Africa and Australia have resulted by coincidence from a set of random plate movements. The preferred viewpoint is the concept of ordered plate motions which may be expressed in some form of systematic APWP[20].

The distribution of continental crust is apparently in some way dictated by mantle dynamics. This is not a new idea[21] but we suggest that an important constraint on whatever form the coupling may take is that the relative locations occupied by three continents for ~700 Myr in the Lower Proterozoic have been regained following at least 1,000 Myr of relative plate motion. If a unique crust–mantle association can be substantiated then the pole tracks shown in Figs 1 and 2 may result from displacement of the crust, and perhaps mantle, with respect to the axis of rotation, that is they represent true polar wander.

Following a fixed disposition during the Lower Proterozoic, the continents then drifted to form supercontinents which eventually fragmented with continents curiously returning to their proemial locations. That is, a global process analogous to the Wilson cycle[22] has been operative. Palaeomagnetic support for single continent models does not preclude the creation and destruction of small oceans. However, it has been stressed[8] that these would have to be very special oceans that open and close to return adjacent cratons to their same relative positions. The simplest plate tectonic solution therefore appeals to a set of very special circumstances operating as the rule rather than as the exception to it.

The analysis presented here is based on the palaeomagnetic data which led to the confirmation of single continent models. Yet on the one hand these data indicate continental fixation throughout the earlier Precambrian, while on the other, continental drift since ~1,000 Myr ago. Indeed, if the Precambrian data had been available before the Phanerozoic data, proving that drift had indeed occurred would have been considerably more difficult. Now, plate tectonics is the accepted dogma and has provided a framework for the interpretation of our observations. However, an alternative model may prove equally suitable for the interpretation of Precambrian palaeomagnetic data. For instance, the Lower Proterozoic and present locations of the continents are consistent with some elements of Carey's model[23] of radial Earth expansion. The relevance of this model to studies of Precambrian 'geodynamics' will partly depend on support for the existence of a Precambrian supercontinent such as Pangaea.

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Cenozoic sedimentation in the central North Pacific

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The central North Pacific, one of the largest sedimentary provinces in the world ocean, is covered by red clays and abundant manganese nodules[1,2]. Few studies have focused on the sedimentation history in this area, presumably because of the difficulty of dating these sediments; biostratigraphically useful fossils are rare or absent, and palaeomagnetic stratigraphy is limited in this area to the past 2–3 Myr (refs 3–5 and R. A. Prince *et al.*, in preparation). We present here a history of Cenozoic sedimentation for the central North Pacific based on lithologic, stratigraphic and sedimentological data from a single 25-m long giant piston core (B.H.C. and C.D.H. in preparation). A sedimentation model incorporating the present-day sedimentation patterns in the central North Pacific and the north-northwest movement of the Pacific plate during the Cenozoic seems to explain the observed sedimentological variations seen in this unique core.

Geological formations in the mid-plate, mid-gyre (MPG) regions of the ocean have been suggested as possible sites for the disposal of high-level nuclear waste[6]. In 1974 a study was initiated to assess the sub-seabed in the mid-plate, mid-gyre region of the North Pacific (MPG-1) as a potential repository for high-level nuclear waste (ref. 7 and our work in preparation). A more complete presentation of the data will be published elsewhere.

The MPG-1 area is centred at about 31°30′ N, 158° W between the Murray and Mendocino fracture zones 1,100 km north of Hawaii, and lies on pre-Cenozoic crust of the magnetic quiet zone[8] with no teleseismic activity reported[9]. The region is marked by low abyssal hills or swales with most of the region having water depths of 5,800–6,000 m (ref. 10). Red clay with grain sizes of about 1 µm is the dominant sediment type[1], with calcium carbonate being less than 10% of sediment weight in the North Pacific[11]. The circulation of Pacific bottom water ($\theta =$ 1.0–1.1 °C) is sluggish[12,13], with current speeds rarely exceeding 10 cm s^{-1}, and mean speeds of about 1 cm s^{-1} (refs 14 and 15). Tidal flow dominates the current records.

One giant piston core, GPC-3 (30°19.9′ N, 157°49.4′ W; 5705 m) was taken on Long Lines cruise 44 (Fig. 1). The core consists of a brown lutite ('red clay') with several altered ash layers. The colour of the sediment from 0 to 632 cm is a light yellowish brown and from 632 to 2,431 cm, a dark reddish brown. Calcium carbonate percentages range from 0 to 4%, indicating that the core site has been below the calcium carbonate compensation depth throughout the Cenozoic. Seven ash layers are present in the core; the ash layer at 1,077 cm has a 0.1-cm thick manganese crust on both sides, and the ash layer at 1,135 cm has a partial coating (<0.1 cm) of manganese.

The palaeomagnetic inclination data (Prince *et al.*, in preparation) are correlated with the palaeomagnetic stratigraphy of Cox[16] from the top of the core to the Matuyama–Gauss boundary (2.43 Myr ago). Below this level, the correlation breaks down, the DRM decreases in intensity and there is a change in the sediment colour. Based on the palaeomagnetic data, the sedimentation rates are 2.5 mm per 1,000 yr for the last 2 Myr and 1.1 mm per 1,000 yr before that to 2.4 Myr ago (Prince *et al.*, in preparation). This increase in Pleistocene sedimentation rates has been suggested to be due to the increase in glacial erosion, providing more material for transport than in previous times[17,18]. Ichthyolith stratigraphy used to estimate ages of pre-Pliocene sediment indicates sedimentation rates of 0.2–0.3 mm per 1,000 yr from 65 to 5 Myr ago (P. S. Doyle and W. R. Riedel, in preparation). The ichthyolith stratigraphy is based on the distribution of fish skeletal debris in DSDP cores[19–21]. The distribution of the ichthyoliths has been related to established biostratigraphic sequences within these cores to establish a chronostratigraphic framework (Doyle and Riedel, in preparation).

Size analysis of the sediment with a Coulter counter shows that mean grain sizes of the >0.63-µm to <13-µm fraction vary from 1 to 4 µm. A 30-µm aperture tube yielding a range from 0.63 µm to 12.7 µm was used because the >13-µm fraction generally comprised <2% of the samples. Down-core trends in the finest grain sizes are not meaningful because of problems with flocculation during the analysis of the sediments. Sediment was wet sieved at 38 µm and dry sieved at 63 µm. The >38-µm weight percentage ranges from <1 to 2% of the total dry sediment weight, and the >63-µm fraction is <1% of the sediment weight throughout the core.

X-ray analysis of the <20-µm fraction reveals that the sediment between approximately 24 and 10 m (65–22 Myr ago) consists of smectite, phillipsite, feldspars and clinoptilolite with a minor amount of quartz. From 10 m to the top of the core (22 Myr ago to the present), quartz, smectite, chlorite, cristobalite, kaolinite, illite, feldspars, mica and anatase are found.

The >38-µm size fraction was examined with a light microscope to determine the sediment composition. Sediment between 24 and 10 m is composed primarily of fish debris, with minor amounts of detrital quartz, manganese micronodules and phillipsite. Mica is found in trace amounts between 24 and 12 m. Sediment between 10 m and the top of the core consists largely of manganese micronodules with common fish debris. Unidentified opaques are found throughout the core in trace amounts. The transition between the two sediment types at 20–30 Myr ago (9–12 m) is marked by large numbers of fragments of an agglutinated benthonic foraminifer, *Bathysiphon* sp., zeolite crystals and aggregates of zeolite crystals.

The sediment distribution patterns in the central North Pacific[1,2,22,23] have been well documented. Manganese nodules are found north of 10° N, and are generally associated with non-calcareous clays. The dominant clay mineral in the central North Pacific between 20 and 40 °N is illite which comprises >70% of the <2-µm size fraction. Smectite is associated with abundant zeolites, and makes up 20–30% of the <2-µm fraction between 20 and 40° N, increasing southward to values >70%. Chlorite contributes 10–20% of the <2-µm fraction between 20 and 40° N, and decreases to <10% in most areas south of 20° N, although values between 10 and 20% can be found. Kaolinite contributes 5–20% of the <2-µm fraction between 20 and 40° N, and has a more irregular distribution than the other clay minerals. Quartz shows a maximum concentration of 20% of the sediment at 30° N and decreases to the north and south.

The sediments can be divided into two assemblages (Fig. 2). (1) North of approximately 20° N the sediment contains a large detrital component as well as some authigenic components. This assemblage, referred to as the detrital assemblage, includes illite, chlorite, kaolinite, quartz, manganese nodules and smectite. It results largely from eolian transport of continental detritus by the jet stream or surface winds (westerlies) and reflects the amount of exposed arid regions of the Northern Hemisphere[22–24]. (2) Between approximately 20° N and 10° N the sediment is composed primarily of authigenic components such as smectite and manganese nodules, and is referred to as the

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