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Research paper

Continental velocity through Precambrian times: The link to magmatism, crustal accretion and episodes of global cooling

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A B S T R A C T

Quasi-integrity of continental crust between Mid-Archaean and Ediacaran times is demonstrated by conformity of palaeomagnetic poles to near-static positions between ~2.7–2.2 Ga, ~1.5–1.2 Ga and ~0.75–0.6 Ga. Intervening data accord to coherent APW loops turning at "hairpins" focused near a continental-centric location. Although peripheral adjustments occurred during Early Proterozoic (~2.2 Ga) and Grenville (~1.1 Ga) times, the crust retained a low order symmetrical crescent-shaped form constrained to a single global hemisphere until break-up in Ediacaran times. Conformity of palaeomagnetic data to specific Eulerian parameters enables definition of a master Precambrian APW path used to estimate the root mean square velocity (v_{RMS}) of continental crust between 2.8 and 0.6 Ga. A long interval of little polar movement between ~2.7 and 2.2 Ga correlates with global magmatic shutdown between ~2.45 and 2.2 Ga, whilst this interval and later slowdown at ~0.75–0.6 Ga to velocities of <2 cm/year correlate with episodes of widespread glaciation implying that these prolonged climatic anomalies had an internal origin; the reduced input of volcanically-derived atmospheric greenhouse gases is inferred to have permitted freeze-over conditions with active ice sheets extending into equatorial latitudes as established by low magnetic inclinations in glaciogenic deposits. v_{RMS} variations through Precambrian times correspond to the distribution of U-Pb ages in orogenic granitoids and detrital zircons and demonstrate that mobility of continental crust has been closely related to crustal tectonism and incrementation. Both periods of near-stillstand were followed by rapid v_{RMS} recording massive heat release from beneath the continental lid at ~2.2 and 0.6 Ga. The first coincided with the Lomagundi-Jatuli isotopic event and led to prolonged orogenesis accompanied by continental flooding and reconfiguration of the crust on the Earth's surface; the second led to continental break-up and instigated the comprehensive Plate Tectonics that has characterised Phanerozoic times. The Mesoproterozoic interval characterised by anorogenic magmatism correlates with low v_{RMS} between ~1.5 and 1.1 Ga. Insulation of the sub-continental mantle evidently permitted high temperature melting and weakening of the crustal lid to enable buoyant emplacement of large plutons at high crustal levels during this magmatic event unique to Mesoproterozoic and early Neoproterozoic times.

1. Introduction

The Proterozoic supercontinent Palaeopangaea derives primarily from protracted quasi-integrity of the continental crust defined by the ~2.8–0.6 Ga palaeomagnetic record (Piper, 1982, 1990, 2007). It defines a symmetrical crescent-shaped continent of low order symmetry confined to a single hemisphere on the globe and evidently reflecting a constraint by whole mantle processes (Piper, 2010a,b). As well as global geodynamic significance, this solution identifies strong axial alignment of tectonic elements and spatial concentrations of mineral deposits; the temporal focus of multiple geochemical, isotopic and rift-drift parameters within the Ediacaran

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Period (Bond et al., 1984; Halverson et al., 2010) also accords with the palaeomagnetic prediction by identifying the most important continental break-up in geological history shortly before Phanerozoic times. Prolonged quasi-integrity explains the contrasting signature of continentality during the Proterozoic (e.g. Garrels and Mackenzie, 1971; Engel et al., 1974; O'Nions et al., 1979), and lower levels of tidal friction which require that dispersed shallow marine shelves were rare or absent (Brosche and Sundermann, 1981; Williams, 2000).

The robust nature of the Palaeopangaean premise is that it makes the most severe demand on palaeomagnetic data by requiring polar conformity to a single APW path and, for protracted periods, to a single quasi-static position. Prolonged intervals of little or no polar movement are recognised between ~2.7–2.2, 1.5–1.2 and 0.75–0.6 Ga, whilst the bulk of the intervening data conform to APW loops radiating from a continental-centric position. Because this conformity is evident through imperfections of the database (Piper, 1982, 2010a, b), it demonstrates that palaeomagnetic data are of more interpretative value than widely appreciated. It highlights a style of tectonics that is markedly different from the Plate Tectonics that has operated during Phanerozoic times. In conceptual terms this has long been suspected because the negative buoyancy required to motivate Plate Tectonics could only have been reached following prolonged planetary cooling (e.g. Davies, 1992). The palaeomagnetic quasi-integral conclusion comes from the long temporal duration (>2 Ga) of pole positions demonstrable from most large Precambrian shields. Although significant areas of continental crust, notably Antarctica, West Africa and South American shields, feature only sparse data coverage of little diagnostic value, the vast spatial and temporal duration of this property demonstrable elsewhere suggests that the quasi-rigid premise is likely to embrace the remaining crust. By accommodating such a broad range of geological and geophysical evidence, Protopangaea–Palaeopangaea challenges popular concepts of "Rodinia" and "Columbia" supercontinents, and the general thesis of "supercontinent cycles".

Contrary Rodinia models have failed primarily because they have extended Phanerozoic Plate Tectonic paradigms back into the Proterozoic to postulate episodic accretion and dismemberment of transient supercontinents (Dalziel, 1997; Torsvik, 2003; Li et al., 2007). In general terms this uniformitarian approach is flawed because it fails to accommodate the much lower rates of lunar recession in Proterozoic times, and contrasting (Korenaga, 2006) and episodic (Silver and Behn, 2008; Condie et al., 2009a, b) heat release from the Earth's interior, presumably at much lower levels to avoid "thermal catastrophe" in Mid-Proterozoic times (Davies, 1980; Korenaga, 2003). In specific terms it fails to explain why unique shield reconstructions repeatedly configure palaeomagnetic poles into a single APWP over intervals in excess of 2 Ga (Piper, 1982, 2007, 2010a,b) and why there is an anomalous concentration of Proterozoic magnetic inclinations into low values (Kent and Smethurst, 1998); the Palaeopangaean solution identifies this latter anomaly as a sampling bias and not due to unrealistic departures from a Geocentric Axial Dipole (GAD) source which would otherwise frustrate the use of palaeomagnetic data for resolving Precambrian palaeogeography (Piper, 2010b).

An intriguing aspect of the Palaeopangaean analysis is the recognition of long intervals of quasi-static behaviour in APW between Late Archaean and Ediacaran times. The presence of these intervals provides important confirmation of the essential tenets of the reconstruction: it is otherwise difficult to envisage how poles could be brought into coincidence over such long intervals of time using reconstructions which also apply outside of these time frames. The first and longest interval correlates with granite-greenstone tectonism and extends into a period of magmatic shutdown (Condie et al., 2009a). The first and third intervals correlate with episodes of global climatic cooling when ice sheets migrated into equatorial latitudes (Evans, 2003), whilst the second interval was contemporary with a unique magmatic episode when buoyant anorthosite and rapakivi granite magmas rose through a weakened crust to be emplaced as high level plutons. In this paper the unified Precambrian APW path is outlined from the collective global data and used to evaluate temporal variations in pre-Phanerozoic continental velocity; the links between these variations and these exceptional geological events are then explored.

2. Palaeopangaean reconstruction parameters

The Precambrian supercontinent Palaeopangaea is illustrated in Fig. 1 as derived from Eulerian rotations summarised in Table 1 after Piper (2007, 2010a,b) with some refinements amplified elsewhere (Piper, in press) that incorporate data from South American cratons (e.g. D'Agrella-Filho et al., 1984, 2004), Tarim (Chen et al., 2004; Huang et al., 2005) and Antarctica (Jones et al., 2003). The integrity of the core nuclei comprising Australia, India, South-Central Africa, Laurentia and Fennoscandia is demonstrable from Mid-Archaean times onwards (Section 3) but the positions of some shields such Amazonia, Antarctica and the Ukraine remain poorly constrained and will probably require revision as more results become available. The retention of Laurentia (North America-Greenland) in present-day coordinates in this figure is convenient because it has the largest database and it also provides a neat expression of the high degree of symmetry retained by continental crust for a major part of its history. Specifically the supercontinent possessed a symmetric and hemispheric form constrained within a single global hemisphere (Fig. 1) and these essential low order properties were retained during reorganisation of peripheral shields at ~2.2 Ga and much later during Grenville orogenesis (~1.1 Ga, Fig. 1). The reconstructions in Fig. 1 also highlight the arcuate distribution of Meso-Neoproterozoic tectono-thermal belts and peripheral orogenesis after ~1.0 Ga when subduction-related calc-alkaline magmatism became concentrated in the Afro-Arabian sector of East Gondwana and persisted here until continental break-up in Ediacaran times. Palaeopangaea 'B' thus also embraces a tectonic transition as crustal tectonism moved from dominantly ensialic to dominantly subduction-related and peripheral.

The conformity of Proterozoic palaeomagnetic data to a single APW between Mid-Archaean and Ediacaran times is described in detail elsewhere (Piper, 2007, 2010a, b, in press) and is summarised here in Figs. 2–7. The palaeomagnetic poles defining the master path shown in these figures are compiled in Table 2 for the interval 2.9–1.7 Ga and in Table 3 for the interval 1.7–0.6 Ga; they are listed in these tables following rotation into the common reference frame using Eulerian parameters of Table 1 and ordered from the positional and age constraints to define the unified APWP.

Popular models incorporating "supercontinent cycles" and transient supercontinents such as "Columbia" (Rogers and Santosh, 2002, 2009; Zhao et al., 2004; Meert, 2012; Rogers, 2012) and "Rodinia" contrast with the premise of this assessment by envisaging diverse relative movements between the Precambrian cratons. By invoking large relative movements, to have credibility they must use palaeomagnetic poles selected to a very high standard which are well defined in age and positional terms; the resulting datasets are typically very limited (e.g. Buchan et al., 2000; Pesonen et al., 2003; Evans, 2010) and sometimes involve tortuous discussion of individual results. In contrast, the Palaeopangaean model demands quasi-integrity between ~2.8 and 0.6 Ga and permits no such latitude in the data: it is the assumptions of the model which assess the palaeomagnetic data in this