A planetary perspective on Earth evolution: Lid Tectonics before Plate Tectonics

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Abstract

Plate Tectonics requires a specific range of thermal, fluid and compositional conditions before it will operate to mobilise planetary lithospheres. The response to interior heat dispersion ranges from mobile lids in constant motion able to generate zones of subduction and spreading (Plate Tectonics), through styles of Lid Tectonics expressed by stagnant lids punctured by volcanism, to lids alternating between static and mobile. The palaeomagnetic record through Earth history provides a test for tectonic style because a mobile Earth of multiple continents is recorded by diverse apparent polar wander paths, whilst Lid Tectonics is recorded by conformity to a single position. The former is difficult to isolate without extreme selection whereas the latter is a demanding requirement and easily recognised. In the event, the Precambrian palaeomagnetic database closely conforms to this latter property over very long periods of time (~2.7–2.2 Ga, 1.5–1.3 Ga and 0.75–0.6 Ga); intervening intervals are characterised by focused loops compatible with episodes of true polar wander stimulated by disturbances to the planetary figure. Because of this singular property, the Precambrian palaeomagnetic record is highly effective in showing that a dominant Lid Tectonics operated throughout most of Earth history. A continental lid comprising at least 60% of the present continental area and volume had achieved quasi-integrity by 2.7 Ga. Reconfiguration of mantle and continental lid at ~2.2 Ga correlates with isotopic signatures and the Great Oxygenation Event and is the closest analogy in Earth history to the resurfacing of Venus. Change from Lid Tectonics to Plate Tectonics is transitional and the geological record identifies incipient development of Plate Tectonics on an orogenic scale especially after 1.1 Ga, but only following break-up of the continental lid (Palaeopangaea) in Ediacaran times beginning at ~0.6 Ga has it become comprehensive in the style evident during the Phanerozoic Eon (~0.54 Ga).

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1. Introduction

Ever since the recognition and definition of Plate Tectonics in the 1960’s, there has been ongoing debate about the temporal duration of this process through the planetary history (e.g. Condie and Kröner, 2008; Condie and Pease, 2008; Davies, 1992; Engel et al., 1974; Piper, 1982, 1987; Stern, 2008). Has this tectonic style prevailed throughout the ~3.9 Ga recorded evolution of the continental crust or did Earth experience long intervals of lid-style tectonics punctured by volcanic activity as seen on Mars or episodic mantle overturn and resurfacing as seen on Venus (e.g. Frankel, 1996; Nimmo and McKenzie, 1998)? This debate has been stimulated in recent years by the discovery of numerous planetary bodies or super-Earths from times preceding the oldest crust preserved at the surface is an indication that this recycling has been underway since primary recycling of crustal material throughout the preserved continental record (Armstrong, 1981; Condie et al., 2009a; Hawkesworth et al., 2010; Taylor and McLennan, 1985); the recognition of zircons dating from times preceding the oldest crust preserved at the surface is an important constraint to the current debate is the evidence for recycling of crustal material throughout the preserved continental record (Armstrong, 1981; Condie et al., 2009a; Hawkesworth et al., 2010; Taylor and McLennan, 1985); the recognition of zircons dating from times preceding the oldest crust preserved at the surface is an indication that this recycling has been underway since primary...
determination of the planet (e.g. Van Kranendonk, 2011). However Earth has also experienced intervals of intense magmatic–tectonic activity interspersed with intervals of prolonged quiescence and the motivation for recycling remains largely speculative. Many investigations have highlighted possible causes for periodicity in the recycling process including catastrophic slab avalanching into the mantle, mantle plume generation and supercontinent cycles (Connerny et al., 1992; Gurnis, 1988; Stein and Hoffman, 1994; Tackley et al., 1994) whilst other workers have suggested that surface processes may be entirely shut down for prolonged periods (O'Neill et al., 2007; Silver and Behn, 2008). Although these and other authors have usually implied that this means the shutdown of Plate Tectonics, it remains unclear whether this was really the process operating.

For purposes of this discussion Plate and Lid Tectonics need to be clarified. Our understanding of Plate Tectonics is defined by the way Earth surface processes have operated during the Phanerzoic Eon (~0.54 Ga), and most specifically since preservation of the remaining ocean crustal record beginning with break-up of the supercontinent Pangaea in Jurassic times (~0.19 Ga). Plate Tectonics is driven primarily by buoyancy forces operating within the oceanic lithosphere between young elevated constructive margins incremented by the products of decompression melting and old, cold and dense margins descending back into the mantle. The latter incorporate the process of subduction which defines the destructive boundaries of the plates. Tectonic processes occurring within the continental crust are also focussed on the plate boundaries and a consequence of melting within and above the subducting margins, or are due to the closure of oceans when the constructive margins are absent or overridden. The three key features defining comprehensive Plate Tectonics in the earlier history of the Earth should therefore be evidences for (i) differential mobility, (ii) processes resulting from subduction and (iii) continent collision/break-up. We anticipate these to be absent on planets characterised by Lid Tectonics, or to be only intermittently expressed where lids are subject to episodic resurfacing as on Venus.

The definition of Lid Tectonics is inevitably less precise because the observational platforms are more remote but they nevertheless emphasise that the contrast with Plate Tectonics is transitional rather than abrupt. Thus Mars has a ~2500 mile long fault system, the Valles Marineris, that appears to have once been characterised by strike slip faulting and mass movement and may divide the planetary shell into two plates (An Yin, 2012). However, there is no substantial evidence that Plate Tectonics analogous to Earth has ever occurred on Mars (Hood et al., 2007; Nimmo, 2000) and the planetary evolution is widely viewed in the context of stagnant lid convection with an elastic shell forming as the lithosphere progressively thickened by conductive cooling. The only possible significant indication for past operation of Plate Tectonics is the presence of stripe anomalies (Connerny et al., 1999) but these have latitudinal orientations; they are therefore likely configured to past poles of planetary rotation and most plausibly interpreted in terms of whole lithosphere motion over mantle plumes feeding large volumes of basaltic lavas (Kobayashi and Sperneke, 2010). The latter is of course, a facet of Lid Tectonics still present in the hot spot frame on Earth. On Mars the magma chambers are interpreted to be deeper and much larger than those on Earth (Wilson and Head, 1994) and they have an intra-plate distribution analogous to the hot spot frame on Earth (Carr, 2007).

Volcanic features on Venus are also not clustered into the linear bands characteristic of plate boundaries on Earth but are instead broadly distributed as plume sites (Head et al., 1992) although local subduction may be indicated by arcuate trenches (Nimmo and McKenzie, 1998). Other features that lack terrestrial analogues are coronae, or circular features 60–2000 km in diameter consisting of concentric and radial fractures arranged about a central depression, and tesserae or elevated plateau areas characterized by intense deformation of both compressional and extensional character. The defining feature of Venusian tectonics is the episodic operation of rapid (~100 Myr) resurfacing with the last event completed 300–600 Myr ago (Strom et al., 1994) and the planet appears to be currently heating up pending a future such event. It remains possible that Plate Tectonics analogous to Earth operated during resurfacing although Nimmo and McKenzie (1998) conclude that a combination of high mantle viscosity, high fault strength and thick basaltic crust may prevent subduction from being sustained on Venus and hence preclude the key signatures of Plate Tectonics.

The transition from a quasi-static lid-style to subduction-driven plate-style tectonics is difficult to predict theoretically because it is controlled by a complex interplay of rheological, compositional and thermal parameters, in particular the temperature at the core–mantle boundary, and it also depends critically on the amount of water present at the planetary surface. However, models have become progressively more sophisticated in recent years (Moresi and Solomatov, 1995, 1998; Roll and Tackley, 2011; Tackley, 2000; Trompet and Hansen, 1998; van Heck and Tackley, 2011) and have sought to determine the point at which predicted convective stresses exceed the yield stress of a lithospheric lid. In general they predict three convective modes comprising (i) a mobile lid in constant motion able to generate zones of subduction and spreading, (ii) a stagnant lid covering the whole surface and (iii) an episodic lid where the regime keeps interchanging between static and mobile.

The most comprehensive models all show that plate tectonics will become more likely as the planetary size increases if the convection is basally heated (Korenaga, 2010; Valencia and O’Connell, 2009; van Heck and Tackley, 2011). Thus an inference could be that we see Plate Tectonics on Earth and not on Mars and Venus because of the larger size of the former. Nevertheless such a conclusion would be highly simplistic because over time the temperature and water at the planetary surface will have been highly variable, heat production and compositional boundaries within the interior will have changed (Maruyama et al., 2007), and factors such as tidal forces and giant impacts may have had periodic inputs. Lenardic et al. (2008) propose that an increase in surface temperatures in excess of 38 °C for example, exceptional volcanism and a build-up of a heavy CO2 atmosphere, could cause the mantle to become too viscous to continue flowing altogether. Furthermore Archaeon tectonics was probably constrained by a thicker and hotter lithosphere and more convective vigour influenced by a multi-layer mantle (Polat, 2012); thus geodynamic modelling by Moyer and van Hunen (2012) indicates that any Archaeon (~>2.5 Ga) subduction would have comprised repeatedly-initiated and short-lived episodes lasting no more than a few millions of years. The importance of the deep water cycle on the viscosity of the mantle has also been demonstrated by both experimental and numerical studies with current estimates of mantle temperature and water concentration suggesting that over long time scales the interior will warm while the mantle is degassing and cool while it is regassing (Crowley et al., 2011).

Clearly further clarification of this issue can only be made from observational evidence, with the Earth’s continental crust providing the one substantial laboratory available to us. Whilst the operation of Lid Tectonics during Earth history has been raised by a number of workers (e.g. Korenaga, 2011; O’Neill et al., 2007), the approaches have been theoretical and primarily involved in numerical simulations. In this paper we assess the observational evidence which is provided primarily by palaeomagnetism because only the record of remanent magnetisation in rocks is able to quantify whether the crust was static or dynamic and unified or dispersed in past times. Plate Tectonics is identified by a diverse range of temporal polar changes (apparent polar wander paths, APWPs) from different parts of the continental crust whereas Lid Tectonics is recognised by conformity of pole positions from all parts of the continental crust to a single position. Although the latter point implies no APWP, it is anticipated that internal thermal anomalies will be able to distort the planetary figure from time to time and episodically shift the entire
tectosphere to move elevations towards the equatorial bulge; this effect is expressed by true polar wander (TPW) and must be recorded uniformly over the whole continental area to validate the operation of Lid Tectonics.

3. The Palaeomagnetic Test

The Precambrian palaeomagnetic evidence (>0.54 Ga) comprises a large dataset of pole positions of variable quality and age constraint derived from igneous, sedimentary and metamorphic rocks, with the first generally considered the most efficacious. In view of the great age of the poles and the usual absence of field tests, or inability to undertake them, the record is typically considered only with strong reservation. Influenced by the sporadic record of geological evidence consistent with features attributable to Plate Tectonics, most analyses have deferred to interpretation on the assumption that this process has always operated. The predicted palaeogeographic models show diverse cratonic elements drifting differentially across indeterminate oceans (e.g. Meert and Torsvik, 2003; Pesonen et al., 2003). Thus the recent IGCP Project 440 “Rodinia Assembly and Break-up” evaluated the evidence on the a priori assumption that Plate Tectonics has always occurred through Precambrian time (Li et al., 2007). Although this approach has tended to prevail over the past three decades (Kroner, 1982), its weaknesses have been emphasised by the need to minimise or ignore key aspects of the record showing that the tectonic style in Precambrian times (>0.54 Ga) was very different from that applying to the Phanerozoic Eon. In general terms it has failed to acknowledge contrasting signatures of continentality between Proterozoic and Phanerzoic times (e.g. Condie, 1998; Engel et al., 1974; Garrels and Mackenzie, 1971; O’Nions et al., 1979), the much lower rates of lunar recession during Proterozoic times required to preclude a “Gerskenkorn Event” and implying that dispersed shallow marine platforms were rare or absent (Brosche and Sundermann, 1981; Williams, 2000), and the contrasting (Korenaga, 2003) heat release from the Earth’s interior at appreciably lower, and probably episodic levels (Condie et al., 2009a; Silver and Behn, 2008) to avoid a ‘thermal catastrophe’ in the mid-Proterozoic (Davies, 1980). In specific terms the Plate Tectonic approach has failed to explain how palaeomagnetic poles could apparently conform to a single APWP over two billion years of geological time (Piper, 1982, 1987) and yield an anomalous concentration of Proterozoic magnetic inclinations in low values (Kent and Smethurst, 1998; Piper, 2010b).

Reservations surrounding the use of the palaeomagnetic database apply acutely to the identification of Plate Tectonics because convincing recognition of diverse APW between continental plates requires a high quality selection, especially in the older segment of the dataset where error limits to age assignments critically control the ordering of poles defining APW. However, no such reservations will be evident if Lid Tectonics operated because poles spanning a wide range of assigned ages should then conform to a single position. In the event it is the recognition of this latter property which identifies the prolonged operation of Lid Tectonics on Earth and shows that the palaeomagnetic record is actually of more substantial value than widely recognised.

An early indication that Earth’s continental crust remained essentially integral during much of its early history (Piper, 1982) and comprised a symmetrical low order feature constrained to a hemispheric crescent (Fig. 1) has remained strongly debated. However, as documented in detail in a number of recent papers (Piper, 2003, 2007, 2010a,b, 2013) the great improvement in the size and quality of the dataset has now been able to firmly resolve the special requirements of the quasi-rigid model. The exceptional demand of this supposition, namely that pole positions should conform closely to a single position, or otherwise to a single path if the reconstruction is valid, reverses the

![Fig. 1](image-url)
roles of model and data: the palaeogeographic premise then becomes a possible test of palaeomagnetic data. In the event, it is close conformity of poles to a single position during very long intervals of near-static polar behaviour between ~2.7–2.2 Ga, 1.5–1.25 Ga and 0.75–0.6 Ga employing a reconstruction requiring only peripheral adjustment that justifies the premise that the continental crust remained quasi-integral during Precambrian times. Here we evaluate the key evidence as summarised in Figs. 2–7 from mid-Archaean to Ediacaran times between ~2.8 and 0.6 Ga in the context of the Lid versus Plate Tectonics debate. The primary configuration of the continental lid, the supercontinent Palaeopangaea, is reconstructed by rotating crustal divisions and their associated palaeomagnetic data according to Eulerian operations given in Table 1. The palaeomagnetic poles plotted in Figs. 2–7 are summarised in Piper (2010a,b) updated in Piper (2013) where the poles are listed following rotation according to the rotational parameters of Table 1. These data listings are also included in the supplementary data to this paper.

The integrity of the core comprising the cratons of Laurentia (North America and Greenland) and Central-Southern Africa is demonstrable from at least ~2.8 Ga (Piper, 2003, 2010a), whilst cratonic assemblages with more peripheral positions including Australia, North and South China, Fennoscandia, India, Siberia, South America and West Africa remained clustered with this core although subject to one or two episodes of relative movement (Fig. 1). These conclusions apply to motions detectable by palaeomagnetic poles calculated according to the GAD model and make no predictions about lower scale (~10^3 km) internal deformation of the lid which is well able to accommodate the small scales of mobility envisaged during the Archaean (e.g. Van Kranendonk, 2011). Key features of the data analysis summarised in Figs. 2–7 are noted in the following subsections.

### 3.1. Mesoarchaean–Palaeoproterozoic (Rhyacian) Times (Fig. 2)

The interpretation of this interval is reinforced by a dominant database from igneous rocks with many poles linked to high-definition age determinations. The continental reconstruction of five major shields is tightly constrained by the close conformity of poles within the ~500 Myr interval between 2.7 and 2.2 Ga to a single position near the continental periphery (Fig. 2(a)). A succession of mean poles with assigned ages in the range 2.7–2.2 Ga are plotted in Fig. 2(a) to emphasise the long duration of this quasi-static position. Given the great antiquity of the dataset and the likelihood that much residual dispersion between these poles is caused by later internal deformation of the crust, this is a remarkably robust observation. It produces a reconstruction comparable to the much later Phanerozoic supercontinent of Pangaea (~0.4–0.23 Ga) in being a large scale symmetrical feature of crescent shape confined to a single hemisphere on the globe. In addition, the location of the quasi-static pole position shows that this primeval crust was also constrained to the global surface in the same way as Pangaea (Piper, 2010b). The recognition of this first order feature comparable to the dominant and longest wavelength component of the present-day geoid suggests that the primary continental crust aggregated by differentiation promoted by vigorous whole-mantle convection prior to ~2.7 Ga which carried the continental crust escaping recycling towards a region of low gravitational potential (Burke et al., 2008; Gurnis,
The period 2.75–2.65 Ga initiating this prolonged quasi-static interval has been reckoned to include the most prodigious episode of juvenile continental crustal formation preserved in the continental crust (Barley et al., 2005; Condie, 2001). The primary preserved crustal protolith developed as three clusters referred to as ‘Ur’, ‘Arctica’ and ‘Atlantica’ (Rogers and Santosh, 2004) with ‘Ur’ consolidating in the Palaeoarchaean prior to 3.0 Ga, ‘Arctica’ near the Archaean–Proterozoic transition (~2.6–2.5 Ga), and ‘Atlantica’ consolidating last (~2.2–2.0 Ga). The subcontinental lithosphere was evidently already chemically differentiated during this process as shown by the concentrated distributions of mineral provinces including economic pegmatites, tin-wolfram, chromite and nickel (Fig. 2(b)). This interval also embraces the earliest signatures of anisotropy in the continental crust: whilst the oldest greenstone belts such as the Barberton of southern Africa show essentially isotropic distribution, later ones of Early Proterozoic age show strong axial alignment through the continental crust (Piper, 1987, 2010a), a feature also seen in the succeeding broad zones of distributed strike-slip deformation and reworking otherwise known as “straight belts” (Watson, 1973 and Fig. 2(b)).

A specific outcome of the demonstration of quasi-integrity in Fig. 2(a) is that much of the present continental area had already configured by mid-Archaean times. Although no precise determination is possible, assuming the quasi-integral link between ‘Ur’ and ‘Arctica’ and including the cratons of Siberia and eastern South America (Fig. 2(b)), we find that ~60% of the present crustal area had consolidated by ~2.7 Ga. This conclusion appears to apply closely to continental volume since recent assessment shows that 60%, and probably at least 70%, of the present crust had separated from the mantle by 2.5 Ga (Belousova et al., 2010). The long continuity of mineral age provinces through the Gondwana wing of the reconstruction in Fig. 2(b) supports the conclusion that a large proportion of the Archaean subcontinental lithospheric mantle is preserved beneath the present shields (Begg et al., 2009; Griffin et al., 2009) and provides further support for the early integrity of the continental lid.

The latter part of the long 2.7–2.2 Ga interval of quasi-static polar behaviour was characterised by a near-total shutdown of magma production extending from ~2.45 to 2.2 Ga (Condie et al., 2009b); the continental lid was essentially quiescent during these times with low sea levels and prolonged unconformity development (Bekker et al., 2010), and the deep oceans became strongly stratified during the latter 150 Myr (Bekker and Holland, 2012). The prolonged interval of suppressed thermal and tectonic activity was terminated at ~2.2 Ga by a 90° APW shift (Fig. 2(a)) which reconfigured the continental lid and mantle so that subsequent palaeopoles have a preferred continent-centric location preserved throughout the remainder of Precambrian...
times until the lid break-up occurred in Ediacaran times (Figs. 3–7). This rapid reconfiguration event is the closest analogy in the record of Earth history to the resurfacing seen on Venus and it coincided with the Lomagundi–Jatuli event (LJE), a positive $\delta^{13}C$ excursion recording the largest and longest carbon flux in Earth history (Melezhik et al., 2007 and see Fig. 8). The carbon was probably sourced in volcanic $CO_2$ reduced indirectly by volcanic $H_2$ (Bekker and Holland, 2012) and the same source seems to have terminating the ~2.43–2.2 Ga ‘Huronian’ glacial events. Furthermore, the LJE corresponds to the latter part of a prolonged ‘Great Oxidation Event’ (~2.34–2.06 Ga) and the combination of the two signatures was evidently responsible for the appearance of marine sulphate evaporates and the first episode of widespread phosphatogenesis (Bekker and Holland, 2012) in the geological record. The latter phenomenon is repeated again much later by the continental flooding consequent on the break-up of Palaeopangaea in Edicaran times (Figs. 7 and 8, Section 3.5).

3.2. Palaeoproterozoic (Orosirian–Statherian) times (Fig. 3)

Although ~2.0–1.7 Ga palaeomagnetic poles are the most dispersed in the Precambrian record (Figs. 3(a)) and signify an interval of high lid mobility, they broadly conform to the continent-centric position on the reconstruction defined by older and younger data and are assigned to two long APW loops referred to as the Coronation and Nagssugtoqidian (Piper, 2013). Widespread tectonic activity accompanied the execution of these loops (Fig. 3(c)) and is mirrored in the histogram of continental ages (Condie, 1998) recording a significant interval of post-Archaean crustal growth (Sato and Siga, 2002). It is also proposed that natural fission of uranium prior to decline in the percentage of $^{235}U$ after these times was a regional contributor to heat production linked to this orogenic activity (Rogers, 2012). Tectono-thermal belts formed during these times are widely distributed throughout the continental shields (Zhao et al., 2002) where they are recognised to have a predominantly axial distribution and continuity demonstrable through cratons such as Laurentia and Fennoscandia (Fig. 3). Numerous analyses of these belts, with Johnson et al. (2011), Zhai and Santosh (2011) documenting examples from the Australian and North China Shilds respectively, interpret them in terms of Plate Tectonics in apparent conflict with the tight constraint provided by the palaeomagnetic evidence showing that the continental lid remained quasi-integral during these times (Fig. 3(b)). This conflict is likely to prove more apparent than real both because the palaeomagnetic data are insensitive to smaller scale shuffling movements within the lid, and because the early
signatures of orogenic scale Plate Tectonics are present primarily in the form of subduction attributable to peripheral belts such as those bordering Laurentia–Fennoscandia (e.g. Hoffman, 1988; Windley, 1995 and Fig. 3(b)). Accompanying volcanic activity led to elevated sea levels and in turn, to widespread flooding of the continental lid. The Fe-charged waters, in an environment which was by now strongly oxidising, deposited the extensive banded ironstone formations between ~2.1 and 1.85 Ga (Fig. 3(c)) which comprise more than 50% of world iron reserves. This flooding is also recorded in the drowning and disappearance of stromatolite-forming cyanobacteria (Melezhik et al., 2007).

3.3. Palaeo-Mesoproterozoic (Statherian–Calymmian) times (Fig. 4)

Movements carrying the continental lid episodically away from the prevailing continent-centric position (and likely recording disturbances to the planetary figure) had largely ceased by 1.7 Ga and subsequent motions seem to have been confined to two small loops yielding the tight polar concentrations of Figs. 4(a) and (b). The defining geological signature of protracted quasi-static polar movement between this and the ensuing period to ~1.25 Ga was the emplacement of a temporally-unique magma (anorthosite-mangerite-charnockite-A type granite) suite. The spatial (mostly in Palaeoproterozoic crust) and temporal (mostly Mesoproterozoic concentration of this magmatism (Fig. 4(c)) is not explicable in terms of conventional Plate Tectonics and has been attributed to prolonged thermal blanketing of the mantle beneath a long-lived supercontinent (Anderson and Morrison, 2005). Subcrustal temperatures of 1200–1300 °C are required to produce anorthositic magmas and the large volumes and wide spacings of these intrusions are considered to be the signatures of a thinner and hotter lithosphere (Vigneresse, 2005). Magma ascent driven by gravity instability of buoyant feldspar-rich magmas and the high level emplacement as thin and laterally-extensive plutons also requires comprehensive weakening of the crust (Bradgwater et al., 1974). The near-absence of motion of the continental lid during this prolonged interval explains this magmatic province in terms of thermal blanketing by the continental lid without specific input of exceptional Large Igneous Province (LIP) magmatism (Coltrice et al., 2007). It proceeded in parallel with contemporaneous emplacement of new crust by under- or intra-plating at within-continental settings demonstrated by Hf and U–Pb model ages (Hawkesworth and Kemp, 2006).

The ongoing formation of marginal orogenic belts around southern Laurentia is a continuing signature of peripheral Plate Tectonic-style processes during this era (Karlstrom et al., 2001). However, gold
precipitation provides an indication that this was essentially localised in impact: gold is only reckoned to appear in continental crust by derivation from fluid movement through volcano-sedimentary successions formed as arc successions in orogenic environments (Goldfarb et al., 2001). Following precipitation during intervals of juvenile crust addition at ~2.8–2.55 and 2.1–1.8 Ga, there is a long ~1.8–0.6 Ga hiatus until gold precipitation again appears, this time linked to Late Neoproterozoic orogenesis (Fig. 7).

3.4. Mesoproterozoic to Early Neoproterozoic (Ectasian–Tonian) times (Figs. 5 and 6)

The long ~1.7–1.25 Ga interval of near-static APW behaviour was curtailed by renewed mobility of the continental lid commencing at, or shortly following, outbreak of major LIP events including the Mackenzie and Jotnian igneous provinces in Laurentia and Fennoscandia (Fig. 5(c)). The polar motion that followed executed two loops referred to as the Gardar-Keweenawan (~1.2–1.04 Ga, Figs. 5(a) and 6(a)) and Grenville-Sveconorwegian (~1.04–0.85 Ga, Fig. 6(a)). The developing architecture of the continental lid was moulded during these times by ~1.1 Ga Grenville orogenic belts of part intra-cratonic and part peripheral origin which are widely distributed through both limbs of the lid. In common with the Palaeoproterozoic tectonic elements, these preserve a dominant axial configuration (Fig. 6(c)) with estimates of crustal addition to the lid during this era ranging from ~10% (Belousova et al., 2010) to ~30% (Rino et al., 2008).

3.5. Late Neoproterozoic (Cryogenian–Ediacaran) times (Fig. 7)

The integrity of the continental lid during this last interval of Proterozoic times is demonstrated by the conformity of palaeomagnetic poles from diverse shields to a single APW path between 0.8 and 0.6 Ga (Figs. 7(a) and (c)). This robust observation refutes all ‘Rodinia’ models because the latter require diverse relative movements by the global operation of Plate Tectonics during these times (Li et al., 2007). The quasi-integral constraint is recorded by the coherent (‘Franklin-Adelaide’) APW track comprising the younger limb of a loop commencing at the ~0.85 Ga continent-centric terminus of the Grenville–Sveconorwegian Loop of Fig. 6. Lid motion was initially rapid from ~0.82 Ga through to the time of the Franklin LIP Event at ~0.72 Ga (Fig. 7(a)) but then slowed dramatically as APW motion remained minimal through to ~0.6 Ga (Fig. 7(b)). Following cessation of the widespread Grenville activity, orogenesis was to...
6. Neoproterozoic (Tonia - Ediacaran) Times
~ 0.8 - 0.6 Ga

Fig. 7. (a) Palaeomagnetic poles and the Franklin-Adelaide APW Track assigned to the interval ~0.8-0.6 Ga. (b) Contoured distribution of all selected poles from this interval highlighting the continuing operation of Lid Tectonics. (c) The signature of diverse APW after ~0.6 Ga corresponding to continental break-up and dispersal in Ediacaran times following the Marinoan glacial event; some representative pole positions are shown but note that individual APW paths are only poorly defined during this relatively short interval (0.6-0.5 Ga) of rapid and diverse movements. (d) Contoured distribution of all selected poles from this interval highlighting the transition to comprehensive global Plate Tectonics after ~0.6 Ga. Earth brown areas show the extent of the continental lid. Figures compiled from Piper (2007, 2010b, 2013).

Table 1

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<th>Palaeopangaea 'B':</th>
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<td>123.5</td>
<td>59.0</td>
<td>-131.5</td>
</tr>
</tbody>
</table>

The rotational operations retain North America in present day coordinates and rotate other Precambrian cratonic nuclei towards it. ‘Protopangaea’ refers to the primitive reconstruction in Fig. 2. Palaeopangaea ‘A’ refers to the reconstruction in Figs. 3-5 and Palaeopangaea ‘B’ refers to the reconstruction in Figs. 6 and 7; see Piper, 2013 for further details of these reconstructions.
become peripheral and largely confined to the instep of the lid (Figs. 1(b) and 6(c)). Tectonism is now clearly subduction-related and incorporates emplacement of ophiolites, strike slip movement of terranes and volcanic arc formation within a broad peripheral zone extending from Arabia through eastern Africa, the Seychelles to northern India (Stern, 1994), all characteristic signatures of orogenic-scale Plate Tectonics. The contemporaneous Pan African orogenesis was concentrated within the southern (Gondwana) wing of the continental lid and is interpreted to have comprised three episodes (Meert, 2003; Meert and Lieberman, 2008) with the first including compression and consumption of oceanic lithosphere (~0.9–0.6 Ga) within the developing Plate Tectonic regime; the second was an interval of extensional tectonism corresponding to break-up of the lid (cf. Figs. 7(a) and (c)) the last episode was a widespread thermal event responsible for isotopic resetting lasting through to ~0.45 Ga.

APW and corresponding lid motion remains integral and confined to a single path until the global Marinoan glaciations at ~0.6 Ga (Figs. 7(a) and (b)). After this the unified path explicitly divides into multiple separate paths (Fig. 7(c)), the diagnostic palaeomagnetic signature of Plate Tectonics. Hence break-up of the continental lid with comprehensive imposition of Plate Tectonics on a global scale is identified as occurring in Ediacaran times, or soon after 0.6 Ga. It correlates precisely with a diverse range of environmental indicators (Piper, 2010b) including: (i) the world-wide initiation of rift-drift following Cryogenian–Ediacaran dyke emplacement and alkaline magmatism, and ensuing development of marine passive margins (Bond et al., 1984); (ii) multiple isotopic signatures (Halverson et al., 2010) including negative δ13CORG due to release of isotopically-light carbon and destabilised gas hydrates to the oceans and extinction of Ediacaran fauna; (iii) the largest δ34S signature in the geological record identifying the release of brines from enclosed basins into the oceanic system with enhanced nutrients and organic productivity also recorded by phosphatogenesis, (iv) low values of FeHR/FeTOT (~0.38) recording widespread oxygenation of the oceans in mid-Ediacaran times (Halverson et al., 2010); (v) post-0.6 Ga release of accumulated mantle heat expressed as large scale magmatism (Doblas et al., 2002; Santosh and Omori, 2008) with accompanying atmospheric build-up of volcanically-vented CO2 presumably responsible for bringing the Neoproterozoic glaciations (~0.75–0.57 Ga) to an end.

4. Discussion

Three conclusions with fundamental tectonic implications follow from the summary of Precambrian APW in Figs. 2–7. Firstly, the possibility that poles from diverse Precambrian cratons spanning more than two billion years could conform by chance to a near-static position for intervals of hundreds of millions of years, or otherwise to single APW tracks, using a reconstruction requiring only peripheral modification must be very small. The palaeomagnetic solution can therefore be reckoned to be a highly robust one and confidently exclude the operation of orogenic-scale Plate Tectonics on Earth involving diverse relative movements between continental blocks that only intermittently came together (‘supercontinent cycles’). Instead, following accretion of the primary preserved crust prior to ~2.7 Ga through a mechanism probably analogous to formation of the Phanerozoic supercontinent Pangaea (Piper, 2010b), the continental crust comprised a lid which adopted two stable positions relative to the geomagnetic (and presumed rotation) axis. The first retained the configuration retained until break-up with global Neoproterozoic supercontinent Pangaea (Piper, 2010b) continuing until the second option of comprehensive Plate Tectonics at ~0.6 Ga during Ediacaran times (Figs. 3–7). This latter change was evidently the defining event separating the Neoproterozoic and Phanerozoic eras of Earth history. These phases in tectonic history of the continental lithosphere as constrained by the palaeomagnetic evidence provide a definitive test of the theoretical modelling (e.g. O’Neill et al., 2007; Korenaga, 2011) and broadly conform to the temporal divisions inferred by Ernst (2009). The palaeomagnetic solution evidently incorporates the small scale, short lifespan and repeatedly-initiated character of Plate Tectonics widely postulated during the Archaean but it does
constrain this tectonic style within a large quasi-integral lid limited by large scale mantle processes (Fig. 2).

Secondly, whilst this continent-centred configuration was retained throughout the post-2.2 Ga lifetime of the lid, it was periodically upset by the execution of APW loops (Fig. 8). These are unlike the signature of APW during the Phanerozoic eon (e.g. Besse and Courtillot, 2002); the latter comprises successive small circle arcs of variable length and duration linked by sudden changes in direction unique to individual tectonic blocks. The repeated changes in APW rate and direction are recognised as the record of transformations in plate geometry with corresponding changes in the Eulerian poles accompanying continental break-up or ocean closure/continental suturing. In contrast, Precambrian APW from the continent-centric position exclusively comprised long loops with close outward and return paths linked by a single ‘hairpin’ returning the path to the continent-centred position (Figs. 3–7). Because this feature is a record of whole-lid movement, it is reminiscent of the signature of True Polar Wander (TPW) which occurs when thermal distortions in the figure of the Earth cause the whole tectosphere to reconfigure as developing elevations are aligned by Earth rotation into the equatorial bulge (Goldreich and Toomre, 1969).

The APW paths of Figs. 2–7 can be translated into estimates of the root mean square velocity \( \langle V_{\text{rms}} \rangle \) of the continental lid following the method of Gordon et al. (1979) as shown in Fig. 8 after Piper (2013). Intervals of significant \( V_{\text{rms}} \) derived from APW and the execution of loops conform to thermal-tectonic events as expressed by the record of superplumes, LIP events and crustal ages (Abbott and Isley, 2002; Ernst et al., 2005; Condie et al., 2009a). Fig. 8 illustrates the correlation with the combined U/Pb zircon age distribution from granoids and detrital sediments after Condie et al. (2009b). Since the latter signature incorporates both the record of exposed ancient cratonic crust and the transport and distribution of eroded material, it provides a proxy for crustal age provinces including those no longer exposed or preserved. It is however, evidently largely uncoupled from the growth of the continental lithosphere much of which appears to have been complete by the –2.7 Ga commencement of the data analysis considered here (Belousova et al., 2010 and Fig. 2). Rapid lid motions recording loops in Palaeoproterozoic (Section 3.2) and Late Mesoproterozoic–Early Neoproterozoic times (Section 3.4), and subsequently during continental break-up (Fig. 7), were times of major orogenesis and these followed long intervals of near-static lid behaviour that presumably thermal-blanketed the sub-crustal lithosphere; there is probably no need to postulate major new additions to the continental crust during these events.

A third conclusion is that a dominant ‘Lid Tectonics’ describes Precambrian lithosphere behaviour in general terms as illustrated by consistent and repeated conformity of poles to a single position and illustrated by the contoured distributions in Figs. 2(b)–7(b). This is the key signature of Lid Tectonics and it accommodates the intermittent intra-lid deformation along wide tectono-thermal belts. The finding that Plate Tectonics did not dominate tectonic behaviour until the latter part of Earth history is not unexpected because the negative buoyancy required to motivate it by large scale subduction of oceanic lithosphere would only have been reached following prolonged planetary cooling (Davies, 1992). However, the recognition of Lid Tectonics from the Precambrian palaeomagnetic record should not be seen to be in conflict with the sporadic geological record for Plate Tectonics in the contemporaneous geological record: as discussed in Section 2, a broad transition in both time and space between these dominant styles of lithosphere behaviour is anticipated. Although the lid remained integral until 0.6 Ga, there is evidence for relative movements between the peripheral blocks both in Palaeoproterozoic times and during Grenville orogenic episodes at ~1.1 Ga (Piper, 2010b and Table 1) but during these times corresponding evidence for Plate Tectonics is primarily incipient and peripheral (Fig. 3(c)–5(c): it only becomes strongly focussed in the Neoproterozoic (Fig. 1(b)). Further speculations on the character of lithosphere behaviour before the onset of comprehensive orogenic-scale Plate Tectonics of Phanerozoic times are more extensively discussed elsewhere (see for example, Houseman et al., 1981; Park, 1981; Davies, 1992). Due to the thick continental component to the lithosphere on Earth, it is unlikely that there will be very close comparisons between Earth tectonic regimes and the Lid Tectonics observed on Mars or Venus although the extraordinary events recognised at ~2.2 Ga probably merit comparison with the resurfacing of the latter planet.

5. Conclusions

➢ Plate Tectonics requires a sufficient degree of planetary cooling to provide the negative buoyancy required to motivate large scale subduction and is expected to be preceded by a facet of Lid Tectonics. Lithosphere deformation is expressed by three possible modes comprising mobile lids in constant motion able to generate zones of subduction and spreading (Plate Tectonics), stagnant lids covering the whole surface punctured by volcanism, and episodic lids with regimes alternating between static and mobile (Lid Tectonics).

➢ The probability of Plate Tectonics is anticipated to increase with terrestrial size. The Earth and comparisons with the smaller planets Mars and Venus provides a test for this prediction.

➢ Because of the uniquely-demanding requirement, the conformity of palaeomagnetic poles spanning Precambrian times (>0.54 Ga) to three long quasi-static intervals (~2.7–2.2, 1.7–1.25, 0.75–0.6 Ga) provides a highly robust confirmation that Lid Tectonics dominated the earlier history of the continental crust. Only peripheral adjustments to the quasi-rigid lid (Palaeopangaea) are required to achieve this conformity over a period in excess of two billion years. The stable pole position was peripheral to the lid during the early part of its history (~2.8–2.2 Ga) and became continent-centric for the remainder of its lifetime following a rapid reconfiguration of mantle and crust at ~2.2 Ga.

➢ The quasi-static polar intervals were interrupted by the execution of APW loops radiating from this continent-centric position. These are compatible with the predictions of protracted long-arc True Polar Wander motivated by thermal anomalies in the Earth’s interior or disturbing the global figure. This cause is suggested by a temporal correlation between the loops and tectonic–magnetic events observed in the continental lid.

➢ The dominance of Lid Tectonics during the Proterozoic eon explains the lower levels of heat release from the Earth’s interior during these times and the lower rate of lunar recession compared with the Phanerozoic eon. It is also compatible with the enhanced continental signatures during these times.

➢ There are signatures in the geological record for the incipient operation of orogenic-scale Plate Tectonics since late Palaeoproterozoic times probably as a result of cooling of the Earth caused ocean lithosphere to become more negatively-buoyant. A large scale transition to this style occurred after ~1.1 Ga in the Afro-Arabian region. Following break-up of the continental lid in Ediacaran times it became comprehensive and global in its effects.

➢ This progressive transition from Lid Tectonic to Plate Tectonics suggests that Earth is close to the critical size for the instigation of the latter tectonic regime. Mars and Venus are likely to be too small.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.tecto.2012.12.042.

Acknowledgments

I am very grateful to Kay Lancaster for drawing the figures for this paper. I am also grateful to Professor J.J.W. Rogers and Professor M. Santosh for their valued reviews of the manuscript and suggestions for improvement.


