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Paleozoic supercontinental assembly, mantle flushing, and genesis of the Kiaman Superchron

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Abstract

Two intrinsically different processes, break-up of supercontinents after mantle insulation ('hot-spots') and early formation of supercontinents after mantle cooling ('cold-spots'), show causal links with periods of low reversal rates (superchron events). The formation of Pangea in the Permo-Carboniferous, coincident with onset of the Kiaman Reverse Superchron (KRS), is conceptually different from traditional mantle plume models commonly invoked for genesis of the Cretaceous Normal Superchron. We propose that prolonged subduction and flushing of cold lithospheric material into the lower mantle preceding Pangea amalgamation resulted in persistent cold anomalies at the core–mantle boundary (CMB); large thermal contrasts at the CMB caused variation in circulation patterns in the outer core, and resulted in a change in the geomagnetic field manifested by onset of the KRS in late Palaeozoic time. The correlations we draw between core and crustal processes in the Palaeozoic are supported by paleomagnetic and tectonic data but still beg the question of the role played by true polar wander (TPW).

Keywords: polar wandering; Pangaea; subduction; plate tectonics; mantle; reversals

1. Introduction

Processes in the Earth's core, mantle and crust are linked via complex and enigmatic cause-and-effect relationships. At the base of the issue is the earth's magnetic field, essentially generated in the highly conducting fluid outer core: What causes the field to change polarity? On what time scales do these changes operate? Are surface processes or products associated with superchrons and what are the associated time delays? Can surface phenomena, in turn, affect processes in the core? What is the role of the mantle in this cycle? Analysis of polarity patterns, mantle plumes and their surface manifestations, seismic tomography, numerical modelling of mantle dynamics and experiments on mantle mineral phase transitions [1–6] have delineated many potential mechanisms and products of the core–mantle–crust interplay, but a cohesive model to answer these questions remains elusive. The challenge to generate three-dimensional models of mantle and core dynamics is equalled by the task to correlate the models with observable phenomena [7].

Current understanding of mantle processes and geomagnetic reversals is based largely on Late Jurassic and younger data sets; this focus is primarily due to the ability to identify precisely oceanic crustal anomaly patterns and changing subduction zone po-

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sitions since the late Mesozoic, and to the availability of seismic records for imaging subducted slabs and deep earth structure. Mantle convection modelling has also become more accurate, through the application of well-constrained Mesozoic–Cenozoic plate reconstructions and interpretations of the gravity field and of seismic velocity anomalies in the mantle [8–10]. In the case of the Cretaceous Normal Superchron (CNS), for example, mantle studies have led to the suggestion of temporal links between the initiation of this superchron and the phenomena of TPW, continental break-up, mantle plumes, anomalously high surface volcanic production, and mass extinctions [1,2].

For time preceding the Middle Jurassic, however, only information from the continental rock record is available to investigate crust–mantle–core processes and attendant questions about their causes, periodicity, and products. Our study addresses the relatively untouched issue of Palaeozoic geodynamics, through combined analysis of the magnetic reversal record for the Phanerozic Era, Palaeozoic paleogeographic reconstructions, geologic data offered by exhumed Palaeozoic orogens, and information from analogous, ongoing processes in the Tibetan Himalayas and the Pacific region. This information facilitates correlation between late Palaeozoic supercontinent *formation* and timing of a superchron event, the Kiaman Reverse Superchron (KRS). We advocate catastrophic '*mantle flushing*' [4,9] during a prolonged era of Palaeozoic oceanic crustal subduction which preceded Pangaea amalgamation as the main element behind onset of the late Palaeozoic KRS. We propose that stockpiling of cold lithosphere at the base of the mantle during the Palaeozoic affected thermal and morphologic changes in the D'' layer, which resulted in alteration of the 'normal' convection pattern of the outermost, magnetic-field-sustaining liquid core; a prolonged period of no magnetic reversals — a superchron — was the manifestation of these processes.

2. Polarity analysis and superchrons

An important component of our analysis is the accurate documentation of magnetic field reversals and related issues; such as the age of onset, the duration, and frequency of superchrons. Except for

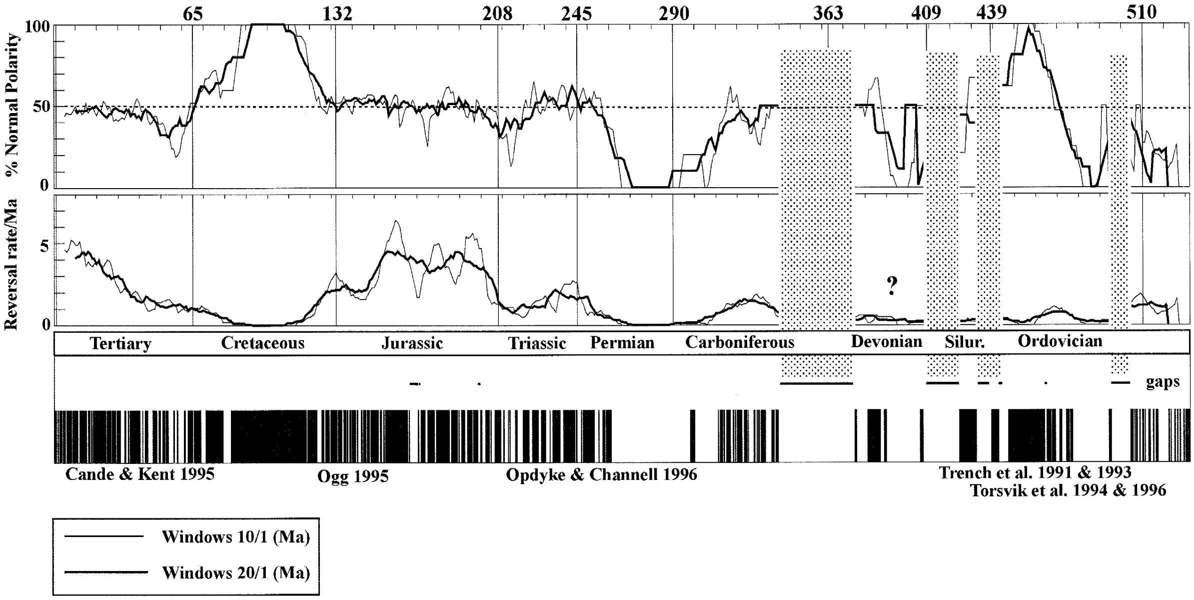


Fig. 1. Estimates of polarity ratio (expressed in percent Normal Polarity) and reversal rates (per Ma) from Lower Cambrian to the present. Data compiled from magnetic anomalies [13] and magnetostratigraphic compilations [14–19]; a detailed data file can be obtained from the authors. Calculations are based on a 1 Ma sliding time-window (window length, 10 and 20 Ma). Gaps or uncertainties in the polarity record are shaded.

the well established KRS (c. 311–262 Ma) and CNS (c. 118–84 Ma) [1,11,12] we find a remarkable 50% distribution in polarity ratios since the mid-Carboniferous (Fig. 1). Minor departures from this distribution have durations of 10–20 Myr and concomitant reverse polarity biases; these are evident at the Triassic–Jurassic boundary and in the early Tertiary.

Since the mid-Carboniferous (c. 330 Ma) we also notice a systematic change in reversal rates in relation to the superchrons. The long-wave, c. 150–175 Myr, build-up and decay in reversal rates associated with the KRS and the post-CNS recovery are very clear. This has been noted earlier [1,5] but with the present data set, it defines a systematic pattern, albeit with some noise, for the last 320 Myr (Fig. 1). Reversal rates peak at around 5/Myr.

Polarity ratio estimates for the early and mid-Palaeozoic are problematic, but Johnson et al. [12] argue for a Lower–Mid Ordovician Reverse Superchron (c. 450 Ma). In conjunction with the timing of the KRS and CNS events, they postulate a 200 Myr. superchron periodicity. Their Ordovician analysis is partly based on magnetostratigraphic data from South Sweden [16,20]. More recent studies, however, have identified additional polarity transitions in the Ordovician record [21]; earlier, inadequate sampling may thus have produced an apparent reverse polarity bias. Instead of a single polarity bias in the Ordovician record, we observe a polarity *shift* from a period of relatively long-reverse to one of relatively long-normal polarity during the mid-Ordovician (Fig. 1). In the Lower Palaeozoic and Precambrian, assignment of magnetic polarity becomes a problem and a rigorous statistical analysis of Precambrian polarity data is enigmatic without a first-hand knowledge of palaeogeography.

3. Palaeozoic plate activity, plate velocities and oceanic destruction

The KRS is time-correlative with the final amalgamation of the Pangean Supercontinent; assembly of Pangea was the result of subduction of large oceanic crustal volumes throughout most of the Palaeozoic Era. As part of the amalgamation process, the rock record reveals a link between plate activity, plate velocities, and destruction of the large Palaeozoic oceans. Exposures of regional high- and ultra-high-pressure (HP–UHP) metamorphic tracts and associated collisional products in eastern North America, East Greenland, the United Kingdom, western Norway, central and western Europe, the Urals, and northwest Africa attest to arc–continent or continent–continent collisions throughout the Palaeozoic as the Euramerican and Gondwanan land masses assembled by the Permo-Carboniferous and the oceans were consumed (Fig. 2). Genesis and preservation of the HP–UHP rocks mandates maintenance of low geothermal gradients in continental crust throughout orogenesis; low geotherms in collision zones are only maintained through some combination of subduction of cold lithosphere and either rapid exhumation, or concomitant exhumation and ‘cold subduction’ (e.g. [24]).

Additional data from Palaeozoic paleoreconstructions for the well-constrained Baltican, Laurentian, and Avalonian plates indicate rapid latitudinal velocity bursts [19] (Fig. 3). These velocities are greater

Fig. 2. Pangea reconstruction for c. 250 Ma with major Palaeozoic orogenic exposures in grey. Orogens were generated during continent–continent and arc–continent collisions as the Pangean supercontinent assembled by the Late Carboniferous. Time-equivalent HP–UHP rocks are found within most of the major orogens (schematically represented as black ovals but not representative of true areal exposure) and are attributed to metamorphism during collision. Regions with coesite are indicative of UHP metamorphism. Reconstruction after Torsvik et al. (in prep.); review resources include [22,23].

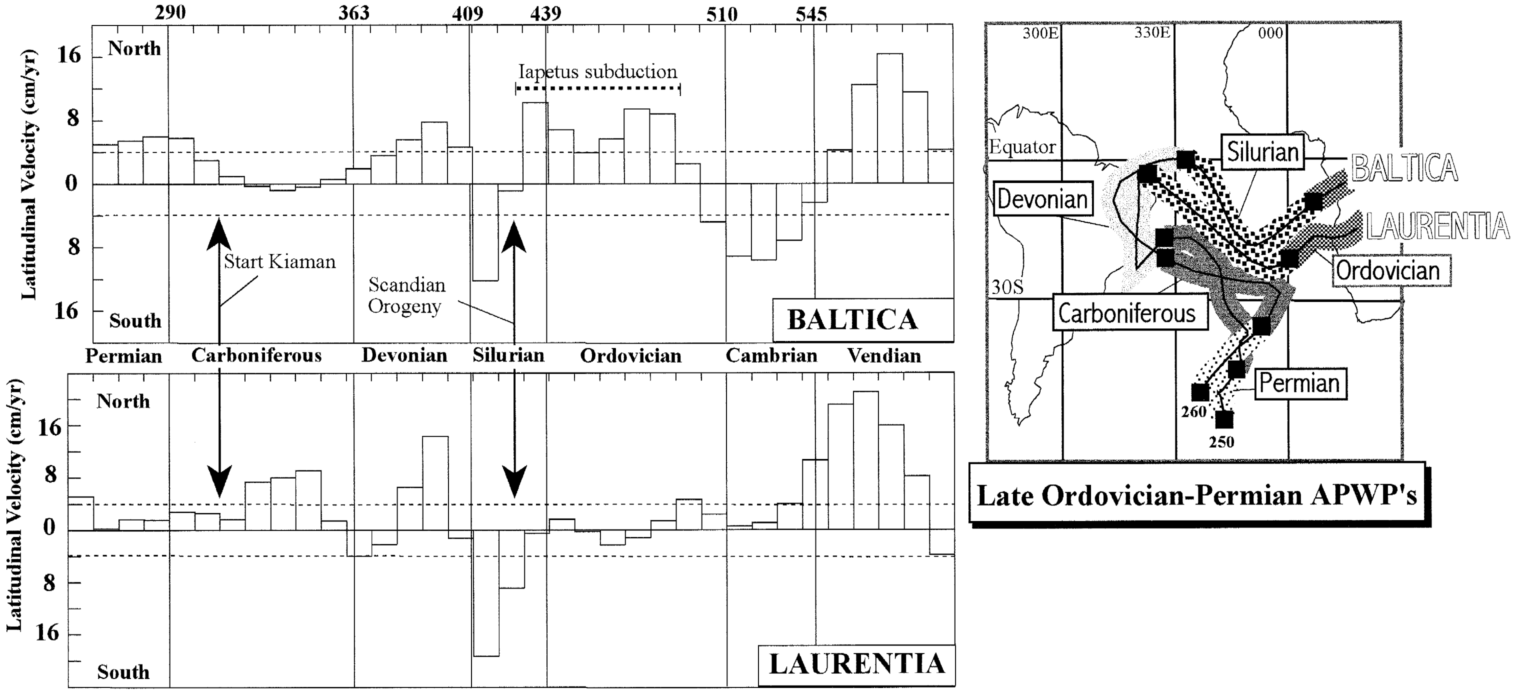


Fig. 3. Latitudinal velocities (Vendian to late Permian) and corresponding apparent polar wander paths (APWPs) (Late Ordovician to Permian) for Baltica and Laurentia (in European coordinates, [25] fit). Reference localities are 60°N–10°E (Baltica) and 60°N–308°E (Laurentia–European coordinates). Baltica and Laurentia both exhibit very high velocities during the late Precambrian after the final break-up of Rodinia. Baltica continued to move at relatively high drift rates throughout the Ordovician, as Iapetus was subducted and destroyed, and until it collided with nearly stationary Laurentia. This collision culminated in the Scandian orogeny and formation of Eurasia and was followed first by rapid southward movement of Eurasia at speeds of 12–16 cm/yr and then by a drastic shift to rapid northward movement in the late Early Devonian (8–12 cm/yr). Relatively low-to-average drift rates for Eurasia are recorded for the remainder of the Palaeozoic prior to Pangea assembly by c. 300 Ma.

than average for the Palaeozoic and generally exceed known plate velocities for modern, large continental masses [26,27]. Orogenic complexes that contain HP–UHP metamorphic rocks are linked to plate collisions that were immediately preceded by Palaeozoic velocity bursts (see, e.g., Fig. 3). The long-term subduction and destruction of large Palaeozoic oceans is, therefore, the 'smoking gun' for pre-collision rapid continental plate velocities: slab pull is the dominant plate-driving mechanism [28] and the components of protracted Palaeozoic subduction included thick, cold, downgoing oceanic lithosphere and cold-mantle downwelling. Attached continents preferentially migrated toward these mantle 'cold spots' [27].

The Palaeozoic rock record thus links high grade orogens to continental collisions and rapid plate velocities, all of which are grounded in prolonged subduction of oceanic lithosphere. The remaining problem is to identify the consequences for earth's surface and interior of subduction of very large volumes of oceanic lithosphere over time scales of hundreds of million years. The Cenozoic collision between India and Eurasia and ongoing subduction of oceanic crust in the Pacific rim region provide analogues for the Palaeozoic situation.

4. Himalayan example

The Himalayan region is the archetypal continent–continent collision zone. In this role, Himalayan tectonics have four basic features in common with interpretations of processes and products present in most Palaeozoic HP–UHP collisional orogens: (1) high pre-collision plate velocities; (2) whole-scale subduction of the continental crust of the colliding plate; (3) rapid exhumation of an orogen that includes HP metamorphic rocks; and (4) partial to complete delamination of the thermal boundary layer (TBL) beneath the over-thickened continental crustal package [29–32].

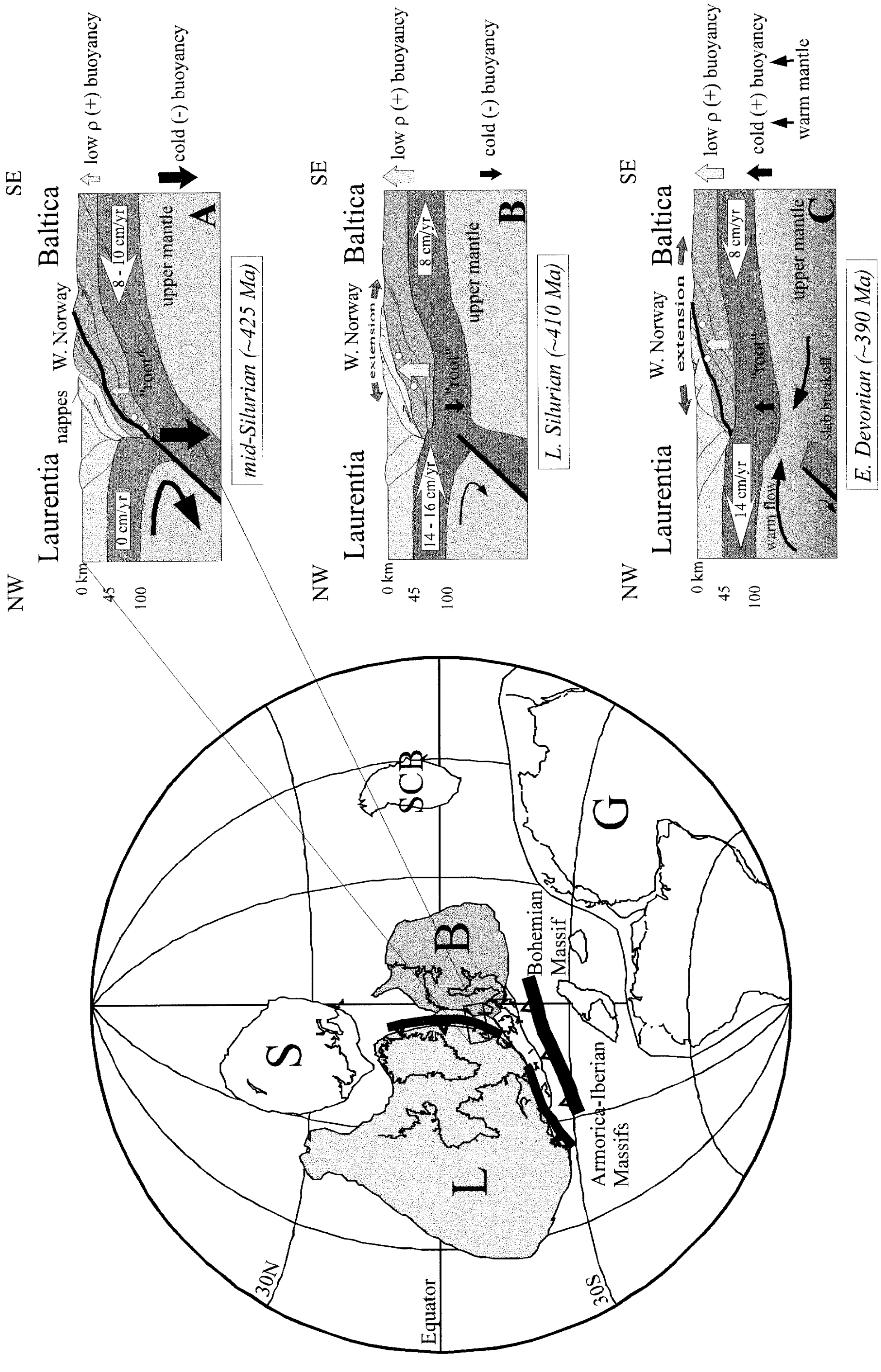
The collision of India with Eurasia in the Palaeocene followed rapid NNE-directed motion of India as the eastern Tethys was consumed. For the period from about 70 to 45 Ma, convergence rates for northward drift of India ranged from 9.5 to 17 cm/yr and dramatically slowed (<10 cm/yr) when full-scale collision commenced after c. 52 Ma [30,33]. Interpretation of deep seismic reflection data through the Himalayas describes crustal thickening achieved via underthrusting of the Indian crust beneath Tibet and genesis/maintenance of crustal thicknesses of c. 75 km [32,34].

Consensus in the literature documents rapid exhumation rates in specific areas of the Himalayas from c. 20 Ma to the present [35,36]. The mechanisms and styles of exhumation, unroofing and uplift of the Himalayan region are debated, but rapid exhumation is closely associated with active normal faults [35,37,38]. Of the various mechanisms, or combinations of mechanisms, proposed for initiation of extensional normal faulting and attendant rapid uplift (e.g. [37,38]), the detachment or convective removal of the lower lithospheric Tibetan mantle during the Miocene [37] is an attractive option. Removal of the TBL provides a means for *regional* exhumation, accords with deep seismic data that imply lack of lithospheric mantle below part of the Tibetan plateau, and satisfies simple physical constraints in a zone where prolonged, rapid subduction was dramatically slowed by continent–continent collision [34,37].

5. Pacific example

Seismic tomography studies of the Pacific region have identified cold anomalies in the mantle that are spatially correlated with positions of Pacific rim subduction zones. Exceptionally wide, cold anomalies imaged at the CMB are strongly correlated with migrating subduction zone positions since the Cretaceous and are associated with areal distribution of subducted plate volume flux in the Pacific region since the Cretaceous. The cold CMB anomalies have been interpreted as probable remnants of subducted oceanic lithosphere incorporated in the lower mantle during the past ~ 120 Myr of Pacific subduction [4,10].

The apparent 'detached' nature of the large, cold masses imaged in the lower mantle has been used as a focal point for modelling both the time scales and mechanisms appropriate to move cold material from the uppermost upper mantle to the CMB. The detached appearance of the cold material at the CMB,


NW
SE
Laurentia
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W. Norway
Baltica
0 km
45
100
0 cm/yr
"root"
8 - 10 cm/yr
upper mantle
A
low ρ (+) buoyancy
cold (-) buoyancy
mid-Silurian (~425 Ma)
NW
SE
Laurentia
W. Norway
extension
Baltica
0 km
45
100
14 - 16 cm/yr
"root"
8 cm/yr
upper mantle
B
low ρ (+) buoyancy
cold (-) buoyancy
L. Silurian (~410 Ma)
NW
SE
Laurentia
W. Norway
extension
Baltica
0 km
45
100
14 cm/yr
warm flow
slab breakoff
"root"
8 cm/yr
upper mantle
C
low ρ (+) buoyancy
cold (+) buoyancy
warm mantle
E. Devonian (~390 Ma)
SCB
G
B
Bohemian Massif
S
L
Armorica-Iberian Massifs
30N
30S
Equator

its large volume and extreme temperature contrasts with the surrounding mantle (anomalies have temperatures >1000 K *below* ambient lower mantle temperatures) have been used to argue for catastrophic ‘flushing’ or frequent ‘avalanching’ of the cold material from the upper into the lower mantle [4,39]. In these models, mantle flushing events are the result of strong gravitational instabilities that develop after large amounts of cold, subducted lithosphere accumulate or ‘pond’ at the 670 km discontinuity [9]. Computer simulations of the flushing process show that the rapidly descending cold material spreads laterally along the CMB and resides in thick layers at the CMB for what is calculated to be >50 Myr [4]. Although the flushing or avalanching episodes vary in frequency and in morphology depending upon the boundary conditions applied, repetition of these events and whole-scale emptying of the ponded cold material above the 670 km discontinuity is demonstrated in three-dimensional simulations [9,39].

These models notwithstanding, controversies abound over the ‘ability’ of subducted slabs to penetrate the 670 km discontinuity. Very recently revised calculations of viscosity changes in the mantle indicate that the phase change at 670 km does *not* preclude slab penetration and mixing in the lower mantle [40] and support the conclusion that phase transition kinetics have consequences for the sharpness of seismic discontinuities in general and, in particular, may affect the driving forces for sinking lithospheric slabs [41]. These studies accord with earthquake data interpretations for the Pacific region that indicate some slabs do penetrate beyond the 670 km discontinuity (e.g. [42,43]). Increasing agreement about slab penetration into the lower mantle does not, however, mandate similar agreement about mantle ‘flushing’ or ‘avalanching’ of slab material from the upper into the lower mantle. Other explanations afforded to account for the presence of cold anomalies in the lower mantle largely depend upon preferences for a whole versus layered mantle mixing scenario [8,44], although it appears from the study by Mitrovica [40] that a probable ‘middle-ground’ between layered and whole-mantle mixing exists and can account for maintained presence of cold anomalies above the CMB, regardless of whether or not these anomalies are induced (as in a mantle flushing model) or are the result of a pre-existing condition [10].

6. Comparison and discussion

The Palaeozoic Era incorporated subduction of comparable (or greater) volumes of oceanic crust over time-frames similar to the Pacific region (170–200 Myr during the Palaeozoic vs. 180 Myr for the modern Pacific), as well as several major continent–continent collisions on scales similar to or larger than the Cenozoic India–Eurasia collision. The mid-Silurian (Scandian) collision between Baltica and Laurentia is a well constrained example that emphasizes the style of crust–mantle interaction

Fig. 4. Plate reconstruction for c. 425 Ma [19] and schematic cross sections for the collision–exhumation–detachment sequence for Baltica and Laurentia from the mid-Silurian to Early Devonian. White horizontal arrows indicate the direction and speed of the plates at that time slice; grey (positive buoyancy) and black (negative buoyancy) vertical arrows indicate the qualitative vertical components of motion as continental crust attempts to subduct and is then exhumed. Two white dots in the Baltican crust represent probable levels of formation and subsequent exhumation of microdiamond- or coesite-bearing rocks found in western Norway; ‘root’ refers to the entire lithospheric slab underlying the oceanic and continental crust. (a) The main collisional event between Baltica and Laurentia occurred at c. 425 Ma and was marked by deep subduction (up to 120 km) of Baltican crust beneath Laurentia with concomitant eastward translation of nappes over the Baltican margin. Deep subduction was a function both of rapid motion of Baltica toward stationary Laurentia and precedence of prolonged subduction of large volumes of cold lithosphere. (b) Shortly after collision, geochronologic and structural evidence indicate the rocks were being exhumed by extensional collapse; the welded continents moved very rapidly southward at this time as the subducted cold lithospheric slab began to delaminate. (c) By the Early Devonian, slab break-off had occurred: warm mantle flowing beneath the welded plates aided the positive buoyancy of the overthickened continental crust and extension of the crustal wedge in exhumation of the orogen. The Laurentia–Baltica plate shifted to rapid northward movement (see also Fig. 3). See text for details.

operative throughout the period of Palaeozoic Pangea assembly and we describe this event in some detail (Figs. 3–5).

Baltica moved at rates well in excess of average latitudinal plate velocities (> 8–10 cm/yr vs. 1–2 cm/yr) prior to its collision with a nearly stationary Laurentia at c. 425 Ma [19,27] (Figs. 3 and 4a). The rapid rate was effected after very long-lived subduction (~ 50 Myr) of Iapetan oceanic crust along the extensive eastern Laurentian subduction axis (Fig. 5). The violent subduction–collision event between Laurentia and Baltica eliminated most of Iapetus and generated HP–UHP metamorphic rocks in western Norway and time-correlative HP rocks in East Greenland, the United Kingdom, and eastern North America (Figs. 2, 4 and 5). During this collision, the combined *negative* buoyancy factors of a cold lithospheric root and mantle downwelling overcame the natural tendency of the low-density continental crustal block to resist subduction; this allowed deep, westward subduction of continental (Baltican) materials and production in western Norway of coesite- and microdiamond-bearing continental crustal rocks (metamorphosed at 85 to > 100 km depths) and regionally extensive eclogitic tracts throughout the Caledonides (metamorphosed at 45–60 km depths) (Figs. 2 and 4a). Rapid exhumation of the HP–UHP sequences is commonly explained by 'extensional collapse', probably triggered by delamination of the cold, downgoing Baltican lithospheric slab shortly after collision [45] (Fig. 4b,c).

The Baltica–Laurentia collisional event followed a period of prolonged subduction beneath the Laurentian margin; the large Baltican continental mass

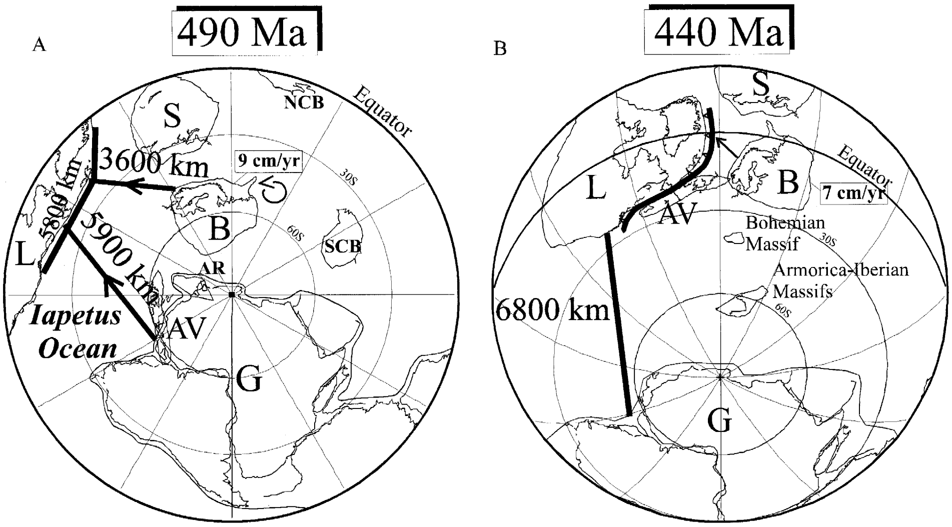


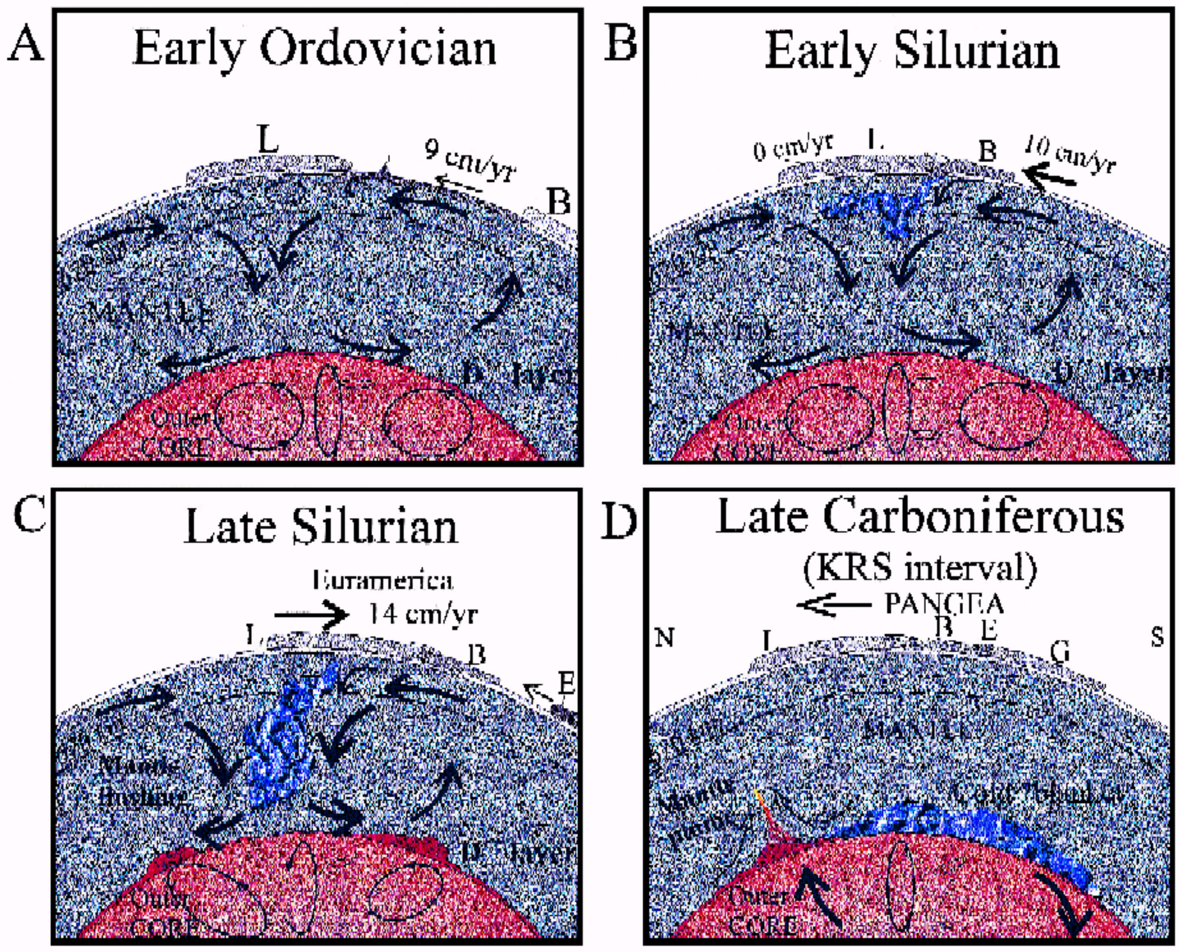
Fig. 5. Ordovician plate reconstructions after [19]. Avalonia and the European Massifs (Armorica) were located close to Gondwana at 490 Ma. Laurentia was positioned in equatorial latitudes during most of the Ordovician; Baltica was initially located at intermediate southerly latitudes and drifted northwards while undergoing rotations, c. 90° anticlockwise, from the Early Ordovician to mid-Silurian (Fig. 4). Avalonia had rifted away from Gondwana by the Llanvirn; the Tornquist Sea, separating Avalonia and Baltica, narrowed gradually during the Ordovician, followed by Late Ordovician 'soft docking' of Eastern Avalonia and Baltica prior to their joint collision with Laurentia. The distances indicated across Iapetus are minima, due to a lack of longitudinal control in the paleomagnetic data. Iapetus was very wide (up to 5900 km) during the early Ordovician, when subduction was established along the Laurentian margin. The subduction axis was up to 5800 km long. The Avalonia–Laurentia and Baltica–Laurentia distances were closed very quickly and attest to rapid subduction of Iapetan oceanic crust through the middle Silurian. The European Massifs and Gondwana closed an additional 6800 km of oceanic crust prior to final Pangea amalgamation at c. 300 Ma. The process of subduction–collision–detachment was repeated rapidly and frequently throughout the Palaeozoic.

was effectively pulled toward a mantle 'cold-spot', generated as cold, downgoing lithosphere amassed beneath the long subduction zone. Rapid plate velocities are a *direct* result of prolonged subduction, a thick cold root, and cold mantle anomalies in the subduction-zone area, and can be inferred from the paleomagnetic data [27]. Rapid collision of a rapidly moving cold, cratonal mass (Baltica) with a stationary continental mass of larger size (Laurentia) facilitated Baltican subduction and attendant high pressure metamorphism. Rapid collision/subduction is one mechanism for maintaining the low geotherms necessary to produce very high pressure metamorphic rocks at very low temperatures. Although slab delamination cannot be documented in absolute terms in any of the Palaeozoic examples, we suggest that, similar to the Himalayan case, delamination addresses the simultaneous needs to return subducted crust rapidly to shallow crustal levels, to facilitate post-orogenic extensional tectonics evident in the Caledonides and, possibly, also to trigger post-collisional magmatism in some parts of the Caledonian sequence.

Slab break-off or delamination in subduction zone settings has been modelled from both geologic and geophysical perspectives [46,47] with similar results: slab delamination occurs as a result of (extensional) strain localization in the zone where the slab subducts beneath the hanging wall plate. The extensional regime can be generated by strong viscosity heterogeneities between the descending cold slab and surrounding mantle [47] or via development of opposing buoyancy forces when continental crust attempts to subduct during a continent–continent collision [46]. In the former case, viscosity heterogeneities are enhanced by fast subduction [47]. Eventually the descending slab decouples from the lithosphere.

Our model of the Palaeozoic crust–mantle–core interplay (Fig. 6) describes repetition of a subduction–collision–delamination–flushing sequence and offers a plausible explanation for change from the predominant 50% distribution of magnetic polarity reversals evident throughout most of the Phanerozoic, to a period of long reverse polarity identified as the KRS. In the Early Ordovician (Fig. 6a), the subduction zone was established along the (present-day) eastern margin of Laurentia and marked the beginning of destruction of the large Iapetus ocean (see also Fig. 5a). North Siberia and the Caledonian margin of Baltica, however, probably formed conjugate margins during the latest Cambrian to Early–Mid Ordovician [48], hence Iapetus destruction was achieved by the combined effects of a rotating and northward moving Baltica, and the rapid northward movement of Avalonia (Fig. 5). By the late Early Silurian, the rapidly advancing Baltican craton collided with a stationary Laurentia and signified elimination of most of the Iapetan oceanic crust: 50 Myr of oceanic crustal subduction ceased, and much of the cold lithospheric material had ponded at the 670 km discontinuity (Fig. 6b). By the Late Silurian–Early Devonian, the HP–UHP rocks and transported nappes of the collision zone were being exhumed, aided in large part by slab delamination. Paleomagnetic data for the Euramerican landmass at this time records first very rapid southeastward movement (12–16 cm/yr), followed by rapid northwestward movement in the Early Devonian (8–12 cm/yr) (Figs. 3 and 4b,cFig. 6c). Delamination in the Late Silurian provides a potential 'trigger' mechanism to invoke mantle flushing: slab delamination is an enticing way to prompt gravitational destabilization of cold lithospheric material ponded in the upper mantle and flush it into the lower mantle (Fig. 6c).

This subduction–collision–delamination–flushing process occurred numerous times prior to final assembly of Pangea as the European land masses and Gondwana advanced toward and collided with Eurasia (Fig. 6c,d). Frequent 'flushing' events may be a natural counterpart to the 'small, frequent avalanches' proposed in three-dimensional models by Tackley et al. [51]. We suggest further that mantle flushing and lateral spreading of cold material along the CMB facilitated long residence times of cold 'blankets' at the CMB well in advance of the onset of the KRS (311 Ma) (Fig. 6d). The upshot of a long residence time for cold Palaeozoic anomalies is an extended period of extreme thermal contrasts at the CMB that affected the normal convective pattern in the outer core. Normally, the outer core adiabat appears to be above that of the lower mantle [52]; therefore, a large thermal contrast at the D″ layer that began to develop in the Silurian–Devonian and was enhanced by continuous subduction throughout the period of Pangea assembly, would compel the outer core to compensate for abnormally cold regions at the ther-



mal boundary layer. One manifestation of this compensation would presumably be increased heat flow at the CMB [50].

7. Words of caution

We link prolonged Palaeozoic subduction preceding supercontinent formation to superchron initiation through the build-up of large volumes of cold, subducted slab material in the lower mantle. We follow with the idea that significant and prolonged thermal anomalies at the D″ layer would perturb the operative convection style of the outer core, and initiate a period of low magnetic reversal rates. We cite here some of the problems our model does not address, in the expectation that researchers investigating present-day data sets for core–mantle–crust processes will begin to incorporate pre-Jurassic data into their calculations and models more seriously.

(1) Current mantle modelling studies are converging upon a blend between a ‘layered’ and a ‘chemically homogeneous’ mantle; our Palaeozoic example does not directly address the debate over the ability of slabs to penetrate the 670 km discontinuity. We rely basically on the facts that the well correlated cold anomalies along the Pacific rim CMB exist as remnants of subducted lithosphere and that their existence requires some mechanism to move large cold masses from the upper into the lower mantle. Many studies indicate that the 670 km phase transition does not preclude slab penetration. The presence

of a phase transition at 670 km and the proposed accumulation of large volumes of cold material over long time periods at the discontinuity, in fact, would enhance a 'gravitational collapse' scenario and subsequent flushing into the lower mantle [9]; this is incorporated in our model, where subduction and ponding at the 670 km discontinuity preceded flushing by up to 90 Myr (Fig. 6).

(2) We do not address the issue of TPW directly in this scenario but, instead, point to some intriguing aspects of our model. Lower mantle thermal anomalies could be related to periods of enhanced TPW [19,27] and mantle instabilities are likely candidates to trigger shifts in the Earth's pole of rotation [53]; an avalanche of cold lithosphere could potentially alter the Earth's inertial moment. Interestingly, an episode of TPW appears to coincide with the India–Eurasia collision [54], although the cause–effect relationship is enigmatic. In the Palaeozoic, an unclarified velocity burst for the welded Baltica–Laurentia–Avalonia landmass occurs immediately after collision and during a period documented on the surface by extensional collapse triggered by lithospheric delamination (see Figs. 3 and 4). APW loops or cusps are normally related to important episodes of divergence or convergence, but Van der Voo [55] has recently suggested a strong component of TPW from late Ordovician to Late Devonian times in order to explain the well known Silurian–Devonian APW cusp (Fig. 3). From a geodynamic point of view, the formation of Euramerica and the subsequent increased velocity implied by APWPs (southward-directed movement of the entire Euramerican crustal mass) are difficult to explain unless we invoke TPW. Prolonged subduction, assembly of Euramerica over an initially low geoid *at the equator* and catastrophic mantle avalanches after continental collision provide plausible mechanisms to trigger rapid TPW in the Late Silurian–Early Devonian (c. 420–410 Ma) (Figs. 3 and 4c).

(3) We still lack the precise mechanism by which the D″ layer affects changes in the circulation pattern

Fig. 6. Time sequence model of subduction–collision–detachment–flushing events in the Palaeozoic that generated a non-reversing state in the geodynamo manifested in the Kiaman Reverse Superchron (311–262 Ma) and the assembly of the Pangean Supercontinent. The model is based on our own data and draws from the mantle flushing simulations of [4]. Ongoing processes in the outer core (orange), at the D″ layer (brick red), in the mantle (blue-grey), and on the surface (plates are different shades of grey) are shown for four different time slices. The subducted and 'flushed' lithosphere (mottled blue) is also shown. Thicknesses of outer core, D″ and mantle are approximately correct, while thickness of the crustal lithosphere is greatly exaggerated to illustrate surface processes. (a) In the Early Ordovician, Baltica was moving rapidly toward Laurentia and Iapetus began to close. Mantle convection was probably in a 'normal' state and we suggest both whole-mantle convection and smaller convection cells above the 670 km discontinuity in association with downflow of the subducting slab. The D″ layer behaves 'normally' as a thin but slightly irregular velocity anomaly just above the CMB; the earth's magnetic field is in its usual state of 50% polarity reversals. (b) By the late Early Silurian, Baltica had collided with Laurentia (see also Fig. 3Fig. 4), and much of the cold, subducted lithospheric material had ponded at the 670 km transition. The large volume of material subducted generated a gravitationally unstable situation at this phase boundary; a triggering mechanism to allow rapid downflow of the material into the lower mantle is suggested in Late Silurian time by slab delamination (c). The surface manifestation of delamination and flushing was rapid (initially) southward movement of the welded Laurentia–Baltica crust. Meanwhile, the European Massifs and, eventually, Gondwana moved northward toward the Eurasian landmass. The consequences for the mantle of this rapid flushing event are based upon the flushing simulations of [4] and [47], which suggest a viscosity 'wave front' ahead of the downrushing cold material. Mantle material slightly colder than ambient mantle is pushed ahead of the cold lithosphere avalanche and alters the morphology of the D″ layer. Like their simulations, we illustrate a thinning of D″ as the convection front pushes toward the CMB, and compensatory thickening of D″ away from the convection cells. (d) The distortion of D″ is magnified throughout the Palaeozoic as continued amalgamation of the Pangean continent and the associated subduction–collision–detachment–flushing processes 'feed' the lower mantle with more cold material. A thick cold 'blanket', a Palaeozoic velocity anomaly, resided above the CMB by the Late Carboniferous. Drastic thermal contrasts at the CMB were thus present in increasing thicknesses for more than 100 Myr prior to the onset of the KRS and Pangea amalgamation. In keeping with the simulations of [4], we show the initiation of a lower mantle plume from one of the overly thickened portions of the D″ layer. Release of plumes from D″ has been previously suggested as a thermal regulating mechanism to conduct heat away from the outer convecting core [1]; experiments of [49,50] similarly demonstrate release of a (simulated) plume from the thermal boundary layer after downflow of cold slab material in a regime of strong mantle convection. Plume release could be induced by increased heat flow from the CMB [50], as core heat flow increases to compensate for the anomalously cold zone between it and the lower mantle (e.g. [51]). In our Palaeozoic case, the D″ layer was so severely altered by the thermal contrasts of the cold, flushed lithosphere that normal outer core convection and the standard 50% magnetic polarity reversal operations were suspended for 50 Myr and the rocks at the surface recorded only reverse polarity during the KRS.

of the core. Our model (Fig. 6) envisages a thick, cold ‘blanket’ that has spread over the CMB and remained there for >100 Myr. The exact mechanism of heat transfer from the outer core to the mantle via such an altered thermal boundary layer is not known. Calculated estimates for the Pacific region today suggest thermal differences between the CMB cold anomalies and the surrounding mantle of >1000 K [4]; the Palaeozoic oceans were areally larger than the Pacific, so it is reasonable to assume that any subduction-related cold anomalies at the CMB in the late Palaeozoic also generated similar lower mantle thermal contrasts. We follow with the fact that large cold masses at the CMB would a priori affect the convection patterns of both the mantle and outer core, regardless of the mechanism, due to the fact that the D″ layer is a critical thermostat for core-to-mantle heat flow.

8. Conclusions

Long-term subduction/destruction of oceanic lithosphere in Palaeozoic time facilitated Pangea assembly *and*, we propose, led to persistent cold anomalies in the lower mantle that caused major thermal contrasts at the CMB (D″ layer), change in outer core convection patterns and, therefore, a change in the geodynamo from a reversing state to a prolonged non-reversing state. The KRS was the product of this series of events. Our analysis relies heavily upon time correlations between global, interior processes and events at the earth’s surface. Other studies have attempted to link Cretaceous surface events with the CNS and have been questioned on the statistical validity of correlating global phenomena; our analysis is equally liable to answer the same critiques. Our model, however, incorporates several pieces of evidence from the rock record that can be addressed in a global framework: we must account for very rapid Palaeozoic plate velocities, continental collisions that generated/preserved numerous high grade Palaeozoic metamorphic orogens, a definitive periodicity to polarity bias throughout the earth’s history, and large cold anomalies present today at the CMB in the Pacific rim region.

A link between high plate velocities, continental collisions and high-grade rocks is obvious. In the Palaeozoic the very large volume of oceanic material subducted is evident from the size of the Palaeozoic oceans. Prolonged subduction of cold slabs, and the corollary of increased cold downwelling in the mantle, provides a ‘sink’ toward which continental plates move with greater than average velocity. A potential consequence of very high velocities prior to continent collision is the production of very high grade rocks: the genesis and preservation of Silurian HP–UHP metamorphic rocks, including microdiamond and coesite in western Norway, for example, document subduction of continental crust to depths >100 km. These rocks necessitate low geothermal gradients; prolonged subduction accompanied by rapid collision are means to fulfil this criterion.

Mantle flushing, or catastrophic descent of cold lithosphere into the lower mantle, in the Palaeozoic is an attractive mechanism to get subducted oceanic lithosphere to the CMB. Mantle flushing models based on the modern Pacific example may have natural counterparts in a system like the Palaeozoic, where prolonged subduction and slab delamination associated with numerous continental collisions could force gravitationally unstable piles of cold material rapidly into the lower mantle.

Further links between the periodicity of reversals and surface plate activity can be made. Neoproterozoic and Palaeozoic plate velocities calculated from well documented APWPs indicate periodic velocity bursts for Baltica, Laurentia, and Avalonia. These documented velocity peaks post-date either periods of massive continental break-up (Rodinia dispersal) or continental collision (e.g., mid-Silurian Caledonian continental collision between Laurentia and Baltica). Conversely, low and stable drift rates correspond to Pangea formation and overlap with the start of the KRS. Extremely rapid latitudinal drift concurs with model calculations of continents with thick crustal roots driven from hot, or alternatively pulled toward cold, anomaly sources in the lower mantle. In this way, the mechanism we advocate for initiation of the KRS does not apply to the CNS because the global tectonic regimes preceding these superchrons were fundamentally different: the KRS corresponded to a period of continental assembly, while the CNS post-dated a prolonged period of supercontinental mantle insulation followed by continental break-up.

Our analysis, while founded in the tangible rock record, leads to further questions about the periodicity of global disturbances in the mantle and the fundamental association, if any, between global tectonics and the phenomenon of TPW. What can be concluded beyond doubt is that crustal lithosphere both *affects* changes in mantle convection and is itself *affected* by deep-seated mantle thermal anomalies in a fundamental feedback process.

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