

The H.O.G. hypothesis for explaining rapid continental motion in the late Neoproterozoic

J.G. Meert and Endale Tamrat, Department of Geological Sciences, University of Florida, Gainesville, FL 32611 (jmeert@geology.ufl.edu)

ABSTRACT

Episodes of extremely rapid ($\geq 20 \text{ cm yr}^{-1}$) plate motion for large continents are known during Late Neoproterozoic to Middle Cambrian time. A number of mechanisms were proposed to explain this rapid motion including true polar wander (TPW), inertial interchange true polar wander (IITPW), warmer mantle conditions (WMC) or a combination of TPW and WMC. The palaeomagnetic data, on which the rapid motion of Laurentia and Gondwana are based, have a poor resolution during the intervals critical to the TPW/IITPW analysis. Here we offer the possibility that the formation of Rodinia created a thermal blanketing effect resulting in a warmer mantle beneath Rodinia and the triggering of lower mantle plumes on a 200-400 Ma time scale. These plumes and warmer conditions provided increased thermal buoyancy and tensional stresses within the supercontinent leading to its breakup. The lower mantle plumes acted in concert with the thick tectosphere to enhance plate motions and drive the continents off the dynamic topographic highs (H.O.G. hypothesis). The resulting motion of

Laurentia away from the geoid high toward a region of colder mantle resulted in the Middle Cambrian transgression. On the other hand, the supercontinent of Gondwana was assembled shortly after this breakup and maintained its effectiveness as a mantle insulator. Due to the continued thermal buoyancy beneath Gondwana, it remained largely emergent during the Paleozoic. Long term subduction and continued mantle insulation by Gondwana may have led to inertial instabilities triggering episodes of Paleozoic TPW. The Mesozoic breakup of Gondwana might have been triggered by the development of mantle plumes beneath the supercontinent on a time scale consistent with proposed geodynamic models.

INTRODUCTION

The notion that large continental plates ($> 2 \times 10^7 \text{ km}^2$) with thick tectospheres might undergo extremely rapid motion ($> 20 \text{ cm yr}^{-1}$) via 'normal' plate driving mechanisms is viewed with scepticism. Available constraints on post-Mesozoic plate motion (for which we also have oceanic floor records) indicate that the best-documented case for rapid motion of a continent with significant size is the $\sim 20 \text{ cm yr}^{-1}$ northward migration of India in late Mesozoic to early Cenozoic time (Klootwijk et al., 1992). However, the Indian continent is a relatively small piece of continental crust (an order of magnitude smaller than Laurentia) and its rapid motion is often

explained by invoking both a warmer mantle beneath India and the increased pull of the ancient Tethyan oceanic slab (Figure 1; see also Forsyth and Uyeda, 1975; Gordon et al., 1979). In fact, the analysis of plate driving forces by Forsyth and Uyeda (1975) indicated that the motion of large continental plates would be 'slowed' by excess asthenospheric drag at the base of the plate (Figure 1; see also Meert et al., 1993; Gurnis and Torsvik, 1994). Recently, Becker and O'Connell (2001) discussed the problems faced by geodynamicists trying to model the relative contributions of each of these forces. Although there must exist a theoretical upper "Plate Tectonic Speed Limit", it is not explicitly stated in the literature. To avoid this problem some authors simply placed a limit on the speeds of continental plates during the development of their palaeogeographic models (e.g. Scotese et al., 1999) or advocate alternative mechanisms to account for the apparent high velocities (Kirschvink et al., 1997; Evans, 1998). While the absolute limits for the rate of plate motion are not explicitly stated, one can imagine that they are ultimately related to the thermal regime underlying the plates. In fact, variations in the thermal regime of the earth (whether due to plumes, mantle insulation or subduction) have all been used in geodynamic models to describe the enhancement or inhibition of plate velocities (Gurnis, 1988; Gurnis, 1990; Gurnis and Torsvik, 1994).

Gordon et al. (1979) analyzed the pre-Tertiary motions of continents using palaeomagnetic data and concluded that Palaeozoic continental plate motions were significantly faster than those observed today. All pre-Mesozoic plate velocity estimates are regarded as minima since we cannot, without correlative seafloor anomaly data, account for longitudinal motion using palaeomagnetism. Gordon et al. (1979) documented motions on the order of $\sim 5\text{-}6 \text{ cm yr}^{-1}$ for Laurentia, Gondwana and Eurasia and argued that the presently observed continental velocities should not be viewed as limits to the maximum speeds of large continental plates. Ullrich and Van der Voo (1981) also noted rapid pulses of latitudinal velocities for several continents, but their analysis was hindered by a lack of well-constrained ages/poles for the continents in the Proterozoic. Nevertheless, they suggested that plate motions in the past might have included pulses of rapid motion. Subsequently, Meert et al. (1993) provided evidence that both Laurentia and Gondwana underwent phases of very rapid plate motion during the late Neoproterozoic and middle Palaeozoic respectively. Later, Meert and Van der Voo (1997) noted that Gondwana's late Neoproterozoic to early Palaeozoic motion approached minimum velocities of up to 24 cm yr^{-1} and Kirschvink et al. (1997) noted that the APWP's from several large continents showed nearly 90

degrees of motion over a 15 Ma time span ($\sim 60 \text{ cm yr}^{-1}$). A number of explanations were proposed to explain this rapid motion including a warmer mantle beneath the Neoproterozoic supercontinent (Gurnis and Torsvik, 1994), true polar wander (TPW; Evans, 1998), inertial interchange true polar wander (IITPW, Kirschvink et al., 1997) and a combination of both TPW and warmer mantle conditions (Meert, 1999). None of the explanations has been wholly satisfying and both the observations and explanations for these fast plate motions are hotly debated. For example, proponents of the IITPW argue that the palaeomagnetic data support rapid motion of nearly 90 degrees during the Tommotian-Toyonian interval (523-508 Ma; Kirschvink et al., 1997; Evans et al., 1998) whilst opponents of the idea note the discordance in length of apparent polar wander paths (APWP's) and the non-synchronicity of the observed motion (Torsvik et al., 1998; Meert, 1999; Torsvik and Rehnström, 2001). Rapid plate motion ($\geq 10 \text{ cm yr}^{-1}$) is observed elsewhere in the Proterozoic record (late Mesoproterozoic; Meert and Torsvik, in review), but is best documented in the late Neoproterozoic interval.

This paper examines the first-order observations supporting the rapid plate motion in the Neoproterozoic and the subsequent evolution of the continents involved in the rapid motion. The argument is made that the rapid motion

resulted from a thermal instability beneath the lithospheric plates generated via a deep-seated mantle plume. We acknowledge that TPW can also generate similar effects, but argue that TPW is not absolutely required to explain the rapid motion of large continents.

PREVIOUS MODELS

True polar wandering

Kirschvink et al. (1997) argued for an episode of extremely rapid apparent polar wander from the Tommotian through Toyonian interval of the Cambrian ($\sim 523\text{-}508 \text{ Ma}$). Their analysis, if correct, indicates a motion of the entire lithosphere at rates of 66 cm yr^{-1} . Kirschvink et al. (1997) did not view this motion in terms of conventional plate tectonics and instead argued that the entire mantle and lithosphere tumbled through 90 degrees as the intermediate and maximum moments of inertia 'interchanged' (See figure 2). They cited, in addition to their analysis of the palaeomagnetic data, the observation that other planets (such as Mars) may also have undergone similar processes based on the large, observable mass excesses located in the equatorial regions (e.g. Olympus Mons). Later, Mound et al. (1999) modeled the effects of IITPW on sea level changes by using a 25 Ma duration for the proposed inertial interchange and the paleogeographic models of Kirschvink et al. (1997). The models suggested that the sea level change was dependent on the location of the continent undergoing the rotation and the duration of the

IITPW event. The models qualitatively supported the IITPW hypothesis although the model itself was limited due to available sea-level change records for the continents and the inability of the model to account for other possible changes influencing sea level.

In more or less the same vein, Evans (1998) argued that true polar wander is an inherent consequence of supercontinental assembly. Evans notes, as have others (Richards et al., 1999; Anderson, 1998) that the prolate contribution of the non-hydrostatic geoid (spherical harmonic degree 2; $\ell=2$) is a long-lived feature associated with supercontinent assembly. In an ideal case, the great-circle trend of TPW could mark the center of the former supercontinent although an offset of nearly 40 degrees exists in the present dataset. Evans (1998) used the extant palaeomagnetic database from Gondwana and Laurentia in support of his hypothesis that rapid TPW occurred in an oscillatory fashion following the breakup of the supercontinent Rodinia.

Meert and Torsvik (in review) also discuss the possibility of TPW during the final assembly of the Rodinian supercontinent (~1100-900 Ma). According to the Evans (1998) hypothesis, this TPW episode may have been triggered by instabilities associated with the pre-Rodinian supercontinent of Columbia (Rogers and Santosh, 2002). The suggestion that subduction around the edges of a large supercontinent surrounding mantle upwellings beneath the

supercontinent (e.g. lower mantle mass excesses) will ultimately draw the supercontinent toward the equator (via TPW) is consistent with the known paleogeographies of Columbia, Rodinia and Pangaea. At the same time, it is important to note that the palaeomagnetic data supporting the older configurations of Columbia and Rodinia along with their latitudinal positions are poorly resolved (Meert, 2002; Meert and Powell, 2001). Kent and Smethurst (1998) proposed that non-dipole contributions to the geomagnetic field would result in a low-latitude bias of palaeomagnetic data; however, they also acknowledge repeated cycling of landmasses to the equator would also produce the same inclination bias. Finally, Torsvik and Van der Voo (in press) assert that the effects of a persistent octupolar geomagnetic field result in artificially high velocities in the Gondwana paleomagnetic dataset. Correcting for these non-dipolar fields actually reduces the magnitude of Gondwana's lower Paleozoic latitudinal motion by 10-12 cm yr⁻¹. Thus, it is unclear whether or not TPW is an inherent consequence of supercontinental assembly or if other explanations can work in concert with TPW to produce the observed rapid motion of continents described above.

Thermal Mechanisms

The thermal budget beneath a supercontinent may also play a role in the 'speed' at which the continents may move during breakup (Gurnis and Torsvik, 1994; Meert, 1999)

although Evans (1998) notes that the observed minimal velocities generated using Neoproterozoic palaeomagnetic data are 'more easily reconcilable with TPW' than arguing for changes in specific mantle conditions. However, Gurnis (1988) showed that these special mantle conditions are the expected expression of a supercontinent that forms an insulating lid on the mantle. Furthermore, Honda et al. (2000) showed that a high-viscosity raft on top of a convecting mantle (i.e. a supercontinent) results in the growth of a mantle plume beneath the supercontinent on time scales ranging from 200-2000 million years. The large variability in the estimates was the result of (a) the type of geodynamic model employed and (b) the initial Rayleigh values. Higher Rayleigh values (10^7) in 3D rectangular box models resulted in the shortest time period for the generation of mantle plumes. Thus, while the temporal arguments regarding the generation of thermal anomalies are debatable, these anomalies appear to be a natural consequence of supercontinental aggregation.

Eide and Torsvik (1996) argued that rapid continental motion could also be driven by the subduction of old oceanic crust during supercontinent formation. They noted that the formation of high-pressure and ultra-high pressure rocks was often preceded by 'bursts' in plate velocities. Thus, in their analysis, the continental plate is pulled towards a cold spot in

the mantle. This argument is similar to the explanation for India's rapid migration towards Asia in that continental plates attached to old oceanic slabs will move at higher relative speeds (see also Forsyth and Uyeda, 1975, Gordon et al., 1979 and Ullrich and Van der Voo, 1981).

Meert (1999) combined the two models and argued that rapid motion away from the long wavelength geoid high produced by mantle upwellings and toward long wavelength geoid lows produced by mantle downwellings might be able to produce the rapid motion observed in the latest Neoproterozoic.

THE H.O.G. HYPOTHESIS

While oscillatory true polar wander remains a viable explanation for the observed speed of continents in the Neoproterozoic (Evans, 1998), it lacks testability on a fine temporal scale because of the current poor resolution of the palaeomagnetic database (Meert, 1999). The proposal made here is that warmer mantle conditions coupled to mantle plume activity can also account for the rapid plate motions observed during the final breakup of the Neoproterozoic supercontinent. Figures 3a-c show the disposition of the continents at 3 distinct times beginning at ~800 Ma again at ~570 Ma and during the middle Cambrian (~510 Ma). While there is some disagreement about the exact configuration of the continents in these reconstructions (see Meert and Torsvik, in review; Meert and

Powell, 2001), they form the starting point for the analysis given herein.

We propose that rapid continental drift (on the order of 15-25 cm yr⁻¹) can be driven by thermal buoyancy generated via mantle plumes and the increased heat beneath the supercontinental lid (Gurnis, 1988; Gurnis and Torsvik, 1994). Figures 4a-d show the hypothetical process for generating this rapid drift. Figure 4a shows the assembly of a supercontinent containing regions of thick tectospheres some 100 Ma after formation. As described in Gurnis (1988), the continent is 'anchored' in place by subduction zones. The 2-D models employed by Gurnis (1988) assumed that the supercontinental lid was either stationary or moving very slowly (1 cm yr⁻¹) prior to its breakup (the assumption was largely used for computational ease). On the real earth, it is likely that the rate of motion is greater than zero although it may have been relatively slow (~2-3 cm yr⁻¹). The slow-moving supercontinent serves to accentuate the thermal regime in the underlying mantle through a blanketing effect and may produce a maximum temperature excess on the order of 200 K (Gurnis, 1988). Anderson (1998) suggests that the thick tectospheres control the tomographic $\ell=6$ geoid whilst the supercontinent and associated subduction zones are mainly responsible for the features of the $\ell=1$ and $\ell=2$ geoids (see also Scrivener and Anderson, 1992). In figure 4b, the supercontinent has

covered the underlying mantle for nearly 200 million years and the mantle plume that began nucleation in Figure 4a now begins its ascent through the heated mantle. This ascent, along with the increased thermal buoyancy beneath the tectosphere enhances the tension in the supercontinent and elevates the $\ell=1,2$ geoid. In figure 4b, some 200-400 million years after supercontinent formation, the plume impinges upon the thickened lithosphere. Large scale volcanism, igneous intrusion and radiating dyke swarms form in zones of weakness which are exploited under the tensional regime generated by the thermal buoyancy (see also Courtillot et al., 1999). In Figure 4d, the supercontinent begins to break apart. Although the tectosphere acts as an inhibiting force during upper mantle convection, the plume 'exploits' the tectosphere and accentuates the motion of the continent off the thermally buoyant geoid high (analogous to the model of Gurnis and Torsvik, 1994). This can be envisioned by assuming the mantle plume acts as a hand which uses the tectosphere to 'grab' the continent and 'throw' it off the superheated region. One can playfully call the plume, "The Hand O' God", or H.O.G. for short. The continent is then pulled toward the $\ell=1,2$ geoid lows.

The models used by Gurnis (1988) indicated peak velocities for supercontinental breakup of up to 7 cm yr⁻¹. This is significantly less than the 15-25 cm yr⁻¹ observed in

the Neoproterozoic interval. In the Gurnis and Torsvik (1994) model, the augmented velocities were dependent on dimensions of the lithospheric root and the lateral temperature contrast arising from a heat source originating in the lower mantle. They estimated a maximum temperature contrast of 160 K over 500 Ma that resulted in a ~ 6 cm/year augmented velocity (i.e. above the background velocity). Gurnis and Torsvik (1994) also noted that if the drift was also driven by the presence of a mantle cold spot, then this might also supply a 10 cm yr^{-1} augmented velocity to the continental plate. The article did not supply an absolute limit to plate velocities but suggested that speeds of up to 20 cm yr^{-1} might be expected. Campbell and Griffiths (1990) calculated that the excess temperatures in plumes could reach temperatures of up to 200-300 K above ambient. Thus, a combination of the thermal anomaly associated with supercontinental insulation (200 K) in addition to the thermal anomaly of the mantle plume (100 K) would produce a total lateral temperature gradient of up to 300 K. According to the analysis made by Gurnis and Torsvik, a 300 K lateral temperature gradient would result in an augmented increase in velocity of $\sim 10\text{-}12 \text{ cm yr}^{-1}$ for a 250 kilometer thick lithospheric root.

Our model is qualitative and is based upon the conclusions of previously published geodynamic models discussed above. The prediction that mantle plumes coupled with an enhanced thermal

regime beneath supercontinents can drive plates rapidly away from the geoid highs and towards the geoid lows can be tested by geodynamic models. Geologic consequences of the model are discussed briefly in the next section.

Neoproterozoic Palaeogeography and H.O.G.

Rodinia (Figure 3b) was thought to have formed largely during the 1100-1000 Ma Grenvillian orogeny (Dalziel, 1997) although parts of the supercontinent may have coalesced earlier. The supercontinent began to break up at ~ 800 Ma (Li et al., 1999; Li et al., 2002) with the arrival of a mantle plume beneath South China (along the present-day western margin of Laurentia). Frimmel et al. (2001) noted that extensive igneous activity in South Africa (Richtersveld Igneous Complex) was broadly coeval with the S. China event. They proposed that a c. 800 ± 60 Ma megaplume stretched from S. Africa through Australia-South China and northernmost Laurentia (see also Wingate et al., 1998; Wingate and Giddings, 2000; Park et al., 1995; Foden et al., 2002). If these estimates are correct, then the mantle plume(s) developed beneath the Rodinia supercontinent some 200-300 Ma after its formation. This timing is in agreement with one of the proposals by Honda et al. (2000).

Unfortunately, we have difficulty estimating minimum plate velocities during the initial breakup of the supercontinent due to a (near-complete) lack of palaeomagnetic

data during the 750-600 Ma interval (see Meert and Powell, 2001). The model given here would predict a short 'burst' of rapid plate motion, but its testing must await further refinement of the palaeomagnetic database.

The supercontinent was not fully disaggregated during this first rifting phase and it was followed some 200 million years later by a second pulse of plume activity (the so-called Sept Îles plume; Higgins and van Breeman, 1998). The presence of this plume has clear manifestations in eastern Laurentia and possible manifestations in Baltica (Bingen et al., 1998; Meert et al., 1998), but there is no clear evidence of the plume in the South American blocks. However, there is some controversy regarding the relationship between the South American cratons and eastern Laurentia (Meert and Torsvik, in review; Tohver et al., 2002).

Palaeomagnetic data from Laurentia during the 570-510 Ma interval is conservatively estimated to give drift rates of 16-20 cm yr⁻¹ (Meert, 1999). Palaeomagnetic data from Gondwana shows rapid motion of western Gondwana over the pole from ~550-500 Ma (~24 cm yr⁻¹; Meert et al., 2001) although the magnitude of this motion may be significantly reduced if non-dipolar fields are considered (Torsvik and Van der Voo, in press).

CONCLUSIONS AND POSSIBLE TESTS

Motion of Laurentia and Gondwana, as constrained by

palaeomagnetic data, during the Late Neoproterozoic through Middle Cambrian interval was rapid. An absolute upper 'speed limit' for large continental plates with thick tectospheres is not established although such a limit must exist. Geodynamic models of supercontinents (Gurnis, 1988; Gurnis and Torsvik, 1994; Honda et al., 2000) indicate that the mantle will warm beneath the supercontinent and plumes can form within 200-400 million years after assembly. Gurnis and Torsvik (1994) estimated that the plate velocity of continents with thick tectospheres can be augmented provided the mechanism was deep-seated. Honda et al. (2000) showed that mantle plumes are a natural result of supercontinent assembly and thus provide the deep-seated mechanism necessary for the rapid drift of continents. The velocity can also be enhanced as the continents drift from the long wavelength geoid highs toward cold (=low) spots produced by subduction.

The presence of large plumes beneath the Rodinian supercontinent and its vestiges are indicated at 800 ± 60 and 585 ± 30 Ma. The temporal development of these plumes is consistent with the models of Honda et al. (2000) and may provide the driving force necessary for the observed rapid drift of Laurentia and Gondwana. Due to a lack of palaeomagnetic data, we are unable to document minimum plate velocities during the initial breakup of Rodinia, but plate velocities

during the Late Neoproterozoic-Early Cambrian interval are consistent with the models of Gurnis (1988) and Gurnis and Torsvik (1994). Long-lived subduction along the assembling (and assembled) margins of Gondwana (eg. closure of the Mozambique, Brasiliano and associated oceans) may have resulted in a region of cold mantle that helped augment the motion of Gondwana.

There are some testable side effects of the H.O.G. mechanism. For example, as noted by Gurnis and Torsvik (1994) flooding of continents (transgression) will occur as the continent moves off the geoid high towards cold regions of the mantle. In the case of Cambrian Laurentia, the Sauk transgression may have resulted from the rapid motion away from a regional of thermal buoyancy toward a geoid low. The lag between continental flooding and rifting in Laurentia is ~50 Ma. We also envision that the earlier phase of rifting (800 ± 60 Ma) in western Laurentia may show a similar lag between the onset of rifting and the development of marine facies. Second order sea level effects, predicted from geodynamic models (Gurnis, 1990) should also be represented in the sedimentary record.

In contrast to Laurentia, the interior of Gondwana remained largely emergent during the Cambrian (Veevers, 1995). As noted by Veevers (1995), assembled Gondwana continued to blanket the mantle until its breakup. The

thermal buoyancy produced by mantle insulation may explain the pulses of rapid motion for Palaeozoic Gondwana and ultimately, the massive outpouring of flood basalts during its Mesozoic breakup (Meert et al., 1993; Veevers, 1995; e.g. the Ferrar-Karoo-Parana provinces). Interestingly, the time period between final Gondwana assembly (~530 Ma) and the Mesozoic igneous events associated with its breakup (Figure 5) is on the order of 400 Ma consistent with the estimates of Honda et al. (2000). Thus, we note, as have many others, that the formation of a long-lived supercontinent may impose a thermal structure on the underlying mantle leading to its ultimate demise.

Finally, we acknowledge that the combination of increased thermal buoyancy and long-lived subduction beneath the margins of the assembled Gondwana continent may have led to inertial instabilities and true polar wander (Van der Voo, 1994 ; Evans, 1998). Excitation of true polar wander during the initial breakup of Rodinia (~750 Ma) is unlikely since the supercontinent straddled the equatorial regions although its equatorial position may have resulted from TPW. Proposed episodes of Vendian-Cambrian TPW are possible given the geodynamic mechanisms proposed elsewhere (Kirschvink et al., 1997; Evans, 1998), but the palaeomagnetic record is currently too sparsely populated to provide a rigorous test of those hypotheses.

Acknowledgements: The authors wish to thank Monika Lipinski for an early review of the manuscript; Rob Van der Voo, Trond Torsvik and David Evans for thorough and critical reviews that helped improve the final version. We also wish to thank Octavian Catuneanu and Pat Eriksson for their editorial work.

Reference List

Anderson, D.L., 1998. The scales of mantle convection, *Tectonophys.*, 284, 1-17.

Becker, T.W. and O'Connell, R.J., 2001. Predicting plate velocities with mantle circulation models, *Geochem. Geophys. Geosys.*, 2001GC000171.

Bingen, B., Demaiffe, D. and van Breeman, O., 1998. The 616 Ma old Egersund basaltic dyke swarm, SW Norway, and Late Neoproterozoic opening of the Iapetus Ocean, *J. Geol.*, 106, 565-574.

Campbell, I.H. and Griffiths, R.W., 1990. Implications of mantle plume structure for the evolution of flood basalts, *Earth Planet. Science Lett.*, 99, 79-83.

Courtillot, V., Jaupart, C., Manighetti, I., Tapponnier, P. and Besse, J., 1999. On causal links between flood basalts and continental breakup, *Earth Planet. Sci. Lett.*, 166, 177-195.

Dalziel, I.W.D., 1997. Neoproterozoic-Paleozoic geography and tectonics: review, hypothesis

and environmental speculation, *Geol. Soc. Am. Bull.*, 109, 16-42.

Eide, E.A. and Torsvik, T.H., 1996. Paleozoic supercontinental assembly, mantle flushing and genesis of the Kiaman superchron, *Earth Planet. Sci. Lett.*, 144, 389-402.

Evans, D.A., 1998. True polar wander, a supercontinental legacy, *Earth Planet. Sci. Lett.*, 157, 1-8.

Evans, D.A., Ripperdan, R.L., Kirschvink, J.L., 1998. Polar wander and the Cambrian-reply, *Science*, 279, 9a

Foden, J., Suck, H.S., Turner, S., Elburg, M., Smith, P.B., Van der Steldt, B., Van Penglis, D., 2002. Geochemical evolution of lithospheric mantle beneath SE South Australia, *Chem. Geol.*, 182, 663-695.

Forsyth, D.W. and Uyeda, S., 1975. On the relative importance of the driving forces of plate motion, *Geophys. J. Roy. Astr. Soc.*, 43, 163-200.

Frimmel, H.E., Zartman, R.E. and Spath, A., 2001. The Richtersveld Igneous Complex, South Africa: U-Pb zircon and geochemical evidence for the beginning of Neoproterozoic continental breakup, *J. Geol.*, 109, 493-508.

Gordon, R.G., McWilliams, M.O. and Cox, A., 1979. Pre-Tertiary velocities of the continents: A lower bound

- from palaeomagnetic data, *J. Geophys. Res.*, 84, 5480-5486.
- Gurnis, M. 1988. Large-scale mantle convection and the aggregation and dispersal of supercontinents, *Nature*, 332, 695-699.
- Gurnis, M., 1990. Ridge spreading, subduction and sea level fluctuations, *Science*, 250, 970-972.
- Gurnis, M. and Torsvik, T.H., 1994. Rapid drift of large continents during the late Precambrian and Palaeozoic: Palaeomagnetic constraints and dynamic models, *Geology*, 22, 1023-1026.
- Higgins, M.D. and van Breeman, O., 1998. The age of the Sept Îles layered mafic intrusion, Canada: Implications for the late Neoproterozoic/Cambrian history of southeastern Canada, *J. Geol.*, 106, 421-433.
- Honda, S., Yoshida, M., Ootorii, S. and Iwase, Y., 2000. The timescales of plume generation caused by continental aggregation, *Earth Planet. Sci. Lett.*, 176, 31-43.
- Kent, D.V. & Smethurst, M.A., 1998. Shallow bias of paleomagnetic inclinations in the Paleozoic and Precambrian. *Earth Planet. Sci. Lett.*, 160, 391-402.
- Kirschvink, J.L, R.L. Ripperdan, D.A. Evans, 1997. Evidence for a large-scale reorganization of Early Cambrian continental landmasses by inertial interchange true polar wander, *Science* 277 541-545.
- Klootwijk, C. T.; Gee, J. S.; Peirce, J. W.; Smith, G. M.; McFadden, P. L., 1992. An early India-Asia contact; paleomagnetic constraints from Ninetyeast Ridge, ODP Leg 121; with Suppl. Data 92-15, *Geology*, 20, 395-398.
- Li, Z.X., Li, X.H., Kinny, P.D. and Wang, J., 1999. The breakup of Rodinia: did it start with a mantle plume beneath South China?, *Earth Planet. Sci. Lett.*, 173, 171-181.
- Li, X.H., Li, Z.X., Zhou, H., Liu, Y. and Kinny, P.D., 2002. U-Pb zircon geochronology, geochemistry and Nd isotopic study of Neoproterozoic bimodal volcanic rocks in the Kangdian Rift of South China: implications for the initial rifting of Rodinia, *Precam. Res.*, 113, 135-154.
- Meert, J.G., 1999. A palaeomagnetic analysis of Cambrian true polar wander, *Earth Planet. Sci. Lett.*, 168, 131-144.
- Meert, J.G., 2002. Paleomagnetic evidence for a Paleoproterozoic supercontinent, Columbia, *Gondwana Res.*, 5, 207-216.
- Meert, J.G. & Van der Voo, R., 1997. The assembly of Gondwana 800-550 Ma, *J. Geodyn.*, 23, 223-235.
- Meert, J.G. and Powell, C. McA., 2001. Introduction to the special volume on the assembly and

- breakup of Rodinia, *Precam. Res.*, 110, 1-8.
- Meert, J.G. and Torsvik, T.H., 2003. The making and unmaking of a supercontinent: Rodinia Revisited, *Tectonophys.*, in review.
- Meert, J.G., Van der Voo, R., Powell, C. McA., Li, Z.X., McElhinny, M.W., Chen, Z. and Symons, D.T.A., 1993. A plate tectonic speed limit?, *Nature*, 363, 216-217.
- Meert, J.G., Torsvik, T.H., Eide, E.A. and Dahlgren, S., 1998. Tectonic significance of the Fen Complex, S. Norway: constraints from geochronology and palaeomagnetism, *J. Geol.*, 106, 553-564.
- Meert, J.G., Nédélec, A., Hall, C., Wingate, M.T.D., Rakotondrazafy, M. 2001. Palaeomagnetism, geochronology and tectonic implications of the Cambrian-age Carion granite, central Madagascar, *Tectonophys.*, 340, 1-21.
- Mound, J.E., Mitrovica, J.X., Evans, D.A.D., Kirschvink, J.L., 1999. A sea-level test for inertial interchange true polar wander events, *Geophys. J. Int.*, 136, F5-F10.
- Park, J.K., Buchan, K.L. and Harlan, S.S., 1995. A proposed giant radiating dyke swarm fragmented by the separation of Laurentia and Australia based on palaeomagnetism of the ca. 780 Ma mafic intrusions in western North America, *Earth Planet. Sci. Lett.*, 132, 129-139.
- Richards, M.A., Bunge, H.P., Ricard, Y. and Baumgardner, J.R., 1999. Polar wandering in mantle convection models, *Geophys. Res. Lett.*, 26, 1777-1780.
- Rogers, J.J.W. and Santosh, M., 2002. Configuration of Columbia, a Mesoproterozoic supercontinent, *Gondwana Res.*, 5, 5-22.
- Scotese, C.R., Boucrot, A.J., McKerrow, W.S., 1999. Gondwanan palaeogeography and palaeoclimatology, *J. Afr. Earth Sci.*, 28, 99-114.
- Scrivener, C. and Anderson, D.L., 1992. The effect of post Pangaea subduction on global mantle tomography and convection, *Geophys. Res. Lett.*, 19, 1053-1056.
- Spada, , G., Ricard, Y., Sabadini, 1992. Excitation of true polar wander by subduction, *Nature*, 360, 425-454.
- Tohver, E., van der Pluijm, B.A., Van der Voo, R., Rizzoto, G., and Scandolaro, J.E., 2002. Paleogeography of the Amazon craton at 1.2 Ga: early Grenvillian collision with the Llano segment of Laurentia, *Earth Planet. Sci. Lett.*, 199, 185-200.
- Torsvik, T.H. and Rehnström, E.F., 2001. Cambrian paleomagnetic data from Baltica: Implications for true polar wander and Cambrian paleogeography, *J. Geol. Soc. Lond.*, 158, 321-329.

Torsvik, T.H., Meert, J.G. and Smethurst, M.A., 1998. Polar wander and the Cambrian, *Science*, 279, 9a.

Torsvik, T.H. and Van der Voo, R., 2002.

Ullrich, L. and Van der Voo, R., 1981. Minimum continental velocities with respect to the pole since the Archean, *Tectonophys.*, 74, 17-27.

Van der Voo, R., 1994. True polar wander during the middle Palaeozoic?, *Earth Planet. Sci. Lett.*, 122, 239-243.

Veevers, J.J., 1995. Emergent, long-lived Gondwanaland vs. submergent, short-lived Laurasia: Supercontinental and Pan-African heat imparts long-term buoyancy by mafic underplating, *Geology*, 23, 1131-1134.

Wingate, M.T.D., Campbell, I.H., Compston, W., Gibson, G.M., 1998. Ion microprobe U-Pb ages for Neoproterozoic basaltic magmatism in south-central Australia and implications for the breakup of Rodinia, *Precam. Res.*, 87, 135-159.

Wingate, M.T.D. and Giddings, J.W., 2000. Age and palaeomagnetism of the Mundine Well dyke swarm, Western Australia: implications for an Australia-Laurentia connection at 750 Ma, *Precam. Res.*, v.100, pp. 335-357.

Figure Legends

Figure 1: “Normal” plate driving/inhibiting forces. The figure is modified from Forsyth and Uyeda, 1975 and Becker and O’Connell, 2001). Positive (=driving) forces are in green and negative (=inhibiting) forces are in red.

Figure 2: True polar wander and inertial interchange true polar wander explanations adapted from Meert (1999). Top figure shows normal true polar wander (after Spada et al., 1992) for both an isoviscous and stiff lower mantle case. The shaded ball represents a mass excess (subduction) and the migration of the spin axis is shown for both cases. The bottom figure shows inertial interchange true polar wander (Kirschvink et al., 1997) with a view along the I_{\min} axis. If the magnitude of the I_{int} axis exceeds the I_{\max} axis, the mantle and lithosphere will tumble through 90 degrees as the axes interchange.

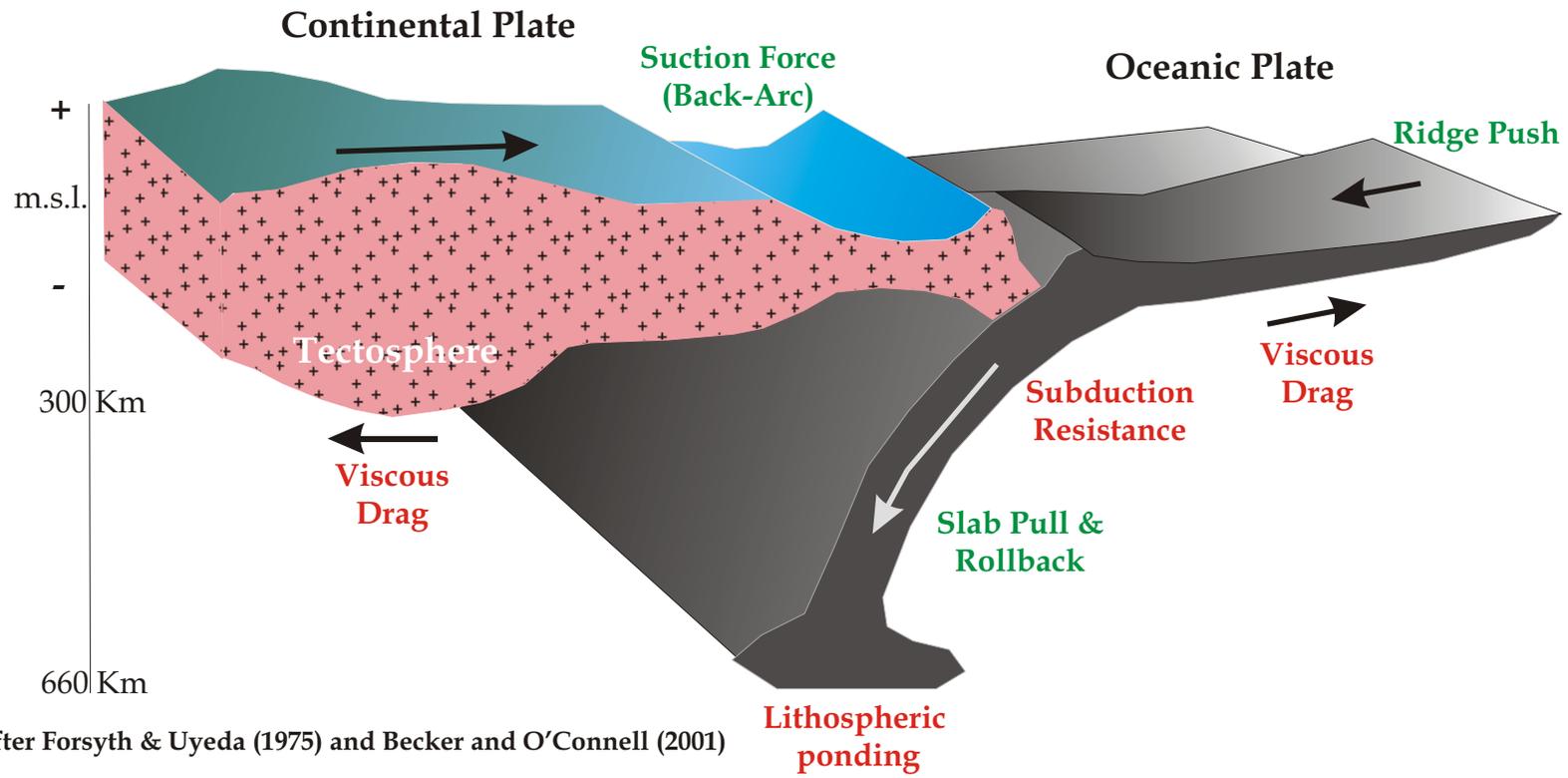
Figure 3: (a) Supercontinent Rodinia at ~800 Ma. The areal extent of plume volcanism at 800 and 600 Ma are shown by the shaded orange regions. (b) 580 Ma reconstruction showing the south polar location of eastern Laurentia and southern South America and (c) ~500 Ma reconstruction showing the eastern margin of Laurentia at ~30° S and southern south America at ~30° S.

Figure 4: Note: The figures are not to true scale; LM represents a segment of the Lower Mantle and UM represents a segment of the upper mantle; the white-dashed line represents missing mantle between the UM and LM. (a) Supercontinent +100 Ma after formation with increased sublithospheric temperatures. Plume nucleation at the Core-Mantle Boundary (CMB) begins and a region of cold mantle downwellings may appear at the boundaries of the supercontinent as well as in regions of old oceanic crust. The $\ell=1,2$ geoid is shown in idealized fashion next to the figure. (b) The supercontinent +200 Ma after formation. The plume is now formed and is ascending in the warm mantle region beneath the supercontinent. The supercontinent is now under increased tension due to the elevated geoid caused by the thermal anomaly beneath the supercontinent. (c) The supercontinent at +400 Ma. The plume has now impinged upon the tectosphere and exploited previous weak zones (former sutures) producing flood basalts and an elevated $\ell=1,2$ geoid. The increased tension coupled with the ‘cold’ mantle downwellings begins to break apart the supercontinent. (d) initial breakup of the supercontinent and rapid drift towards geoid lows. The plume becomes entrained in the moving continent and effectively ‘throws’ the continent off the geoid high.

A large piece of the supercontinent may exist and serve to generate a second episode of thermal buoyancy and rifting.

Figure 5: APWP for Gondwana during the three intervals of Neozoic rapid APW (550-520 Ma; Meert et al., 2001), 475-420 Ma (Meert et al., 1993) and 420-340 Ma (Meert et al., 1993). Major flood basalt provinces are shown, the Parana-Etendeka (133-131 Ma); the Karoo-Ferrar (184 Ma) and the Deccan (65 Ma) after Courtillot et al., 1999. The interval from final Gondwana assembly (taken here as 530 Ma) and the observed volcanism ranges from 350-465 Ma in line with the estimates of Honda et al., 2000.

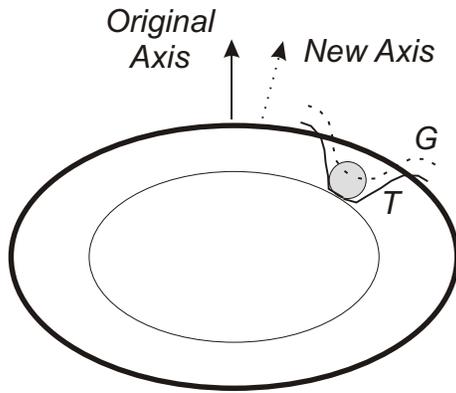
PLATE DRIVING FORCES



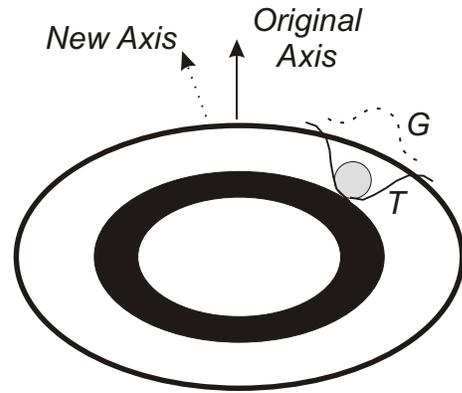
After Forsyth & Uyeda (1975) and Becker and O'Connell (2001)

Fig 1

“Normal True Polar Wander”



**Ioviscous Mantle TPW Model
Positive Mass Anomaly**



**Stiff lower Mantle TPW Model
Positive Mass Anomaly**

**Inertial Interchange True
Polar Wander (IITPW)**

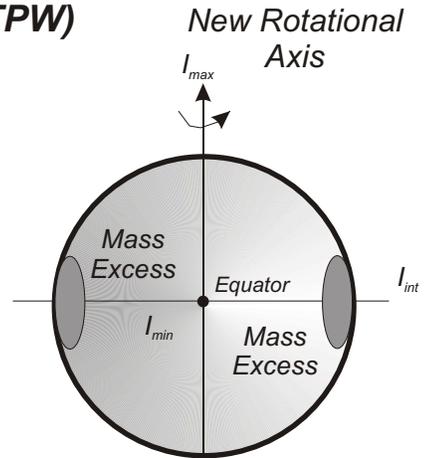
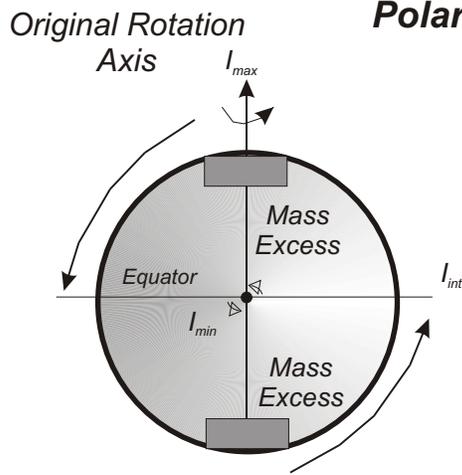
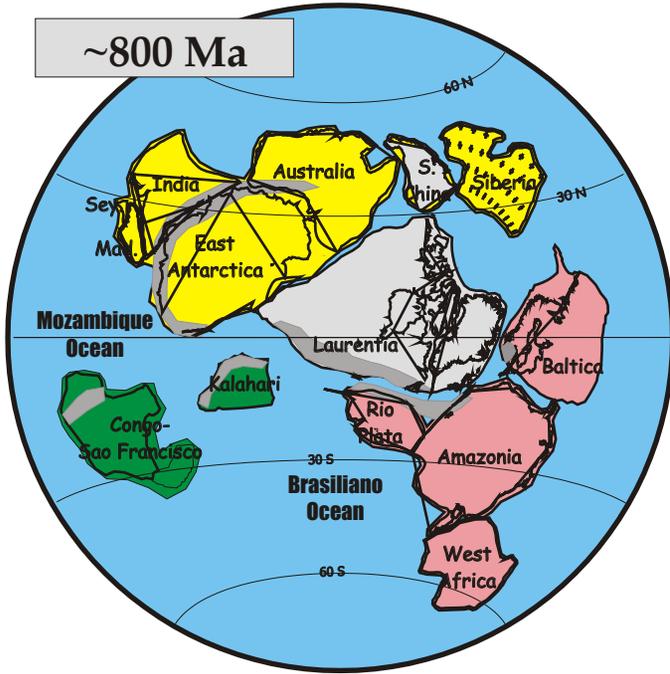
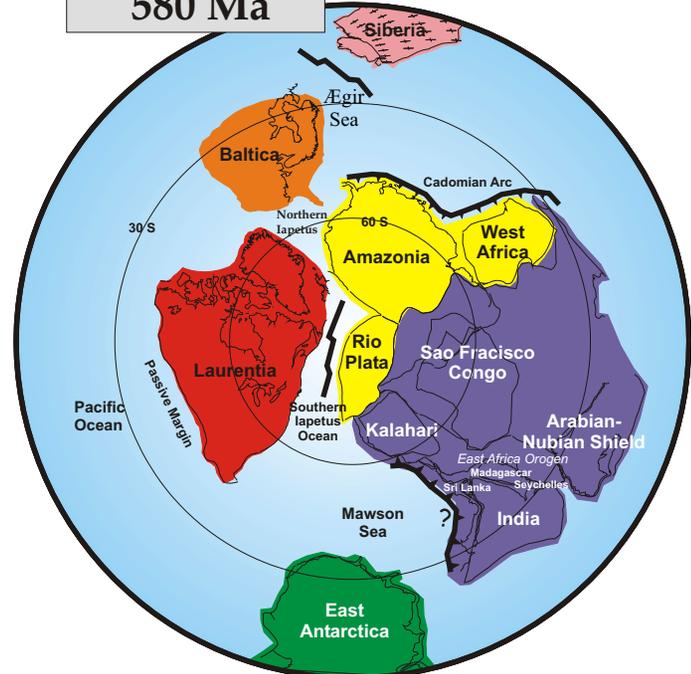


Fig 2

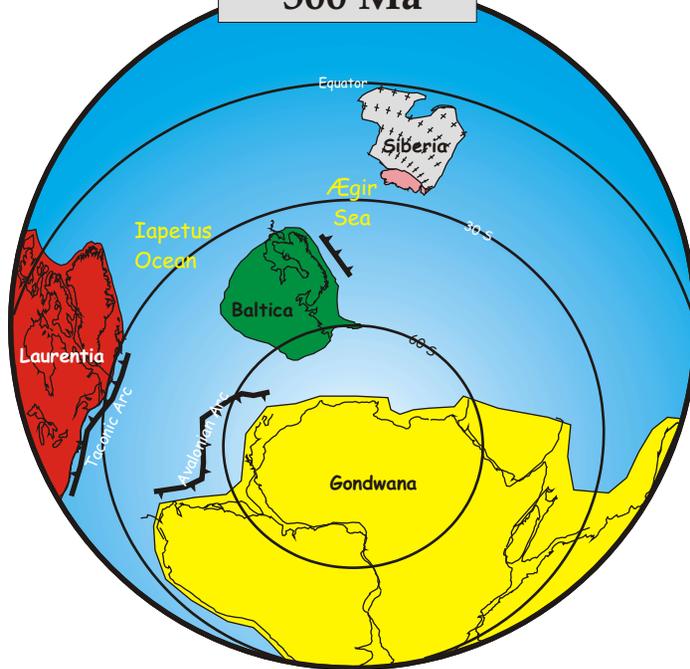
~800 Ma

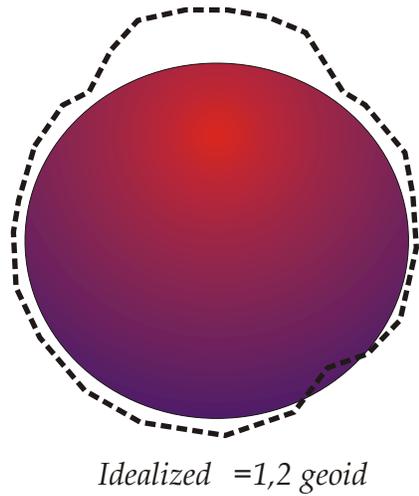
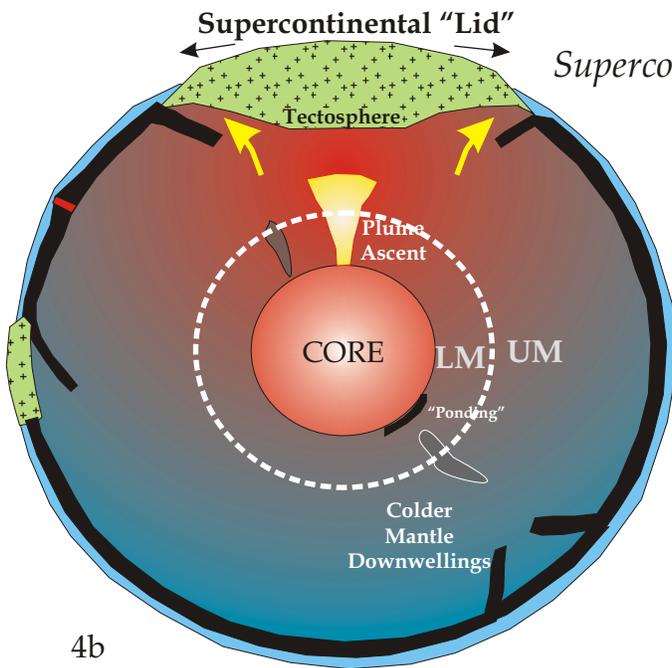
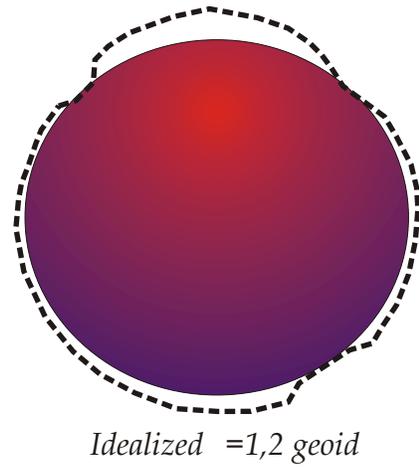
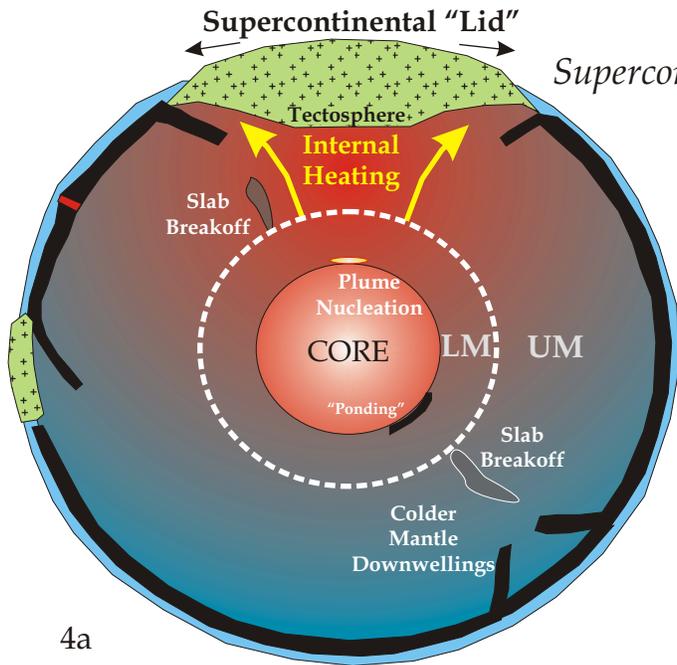


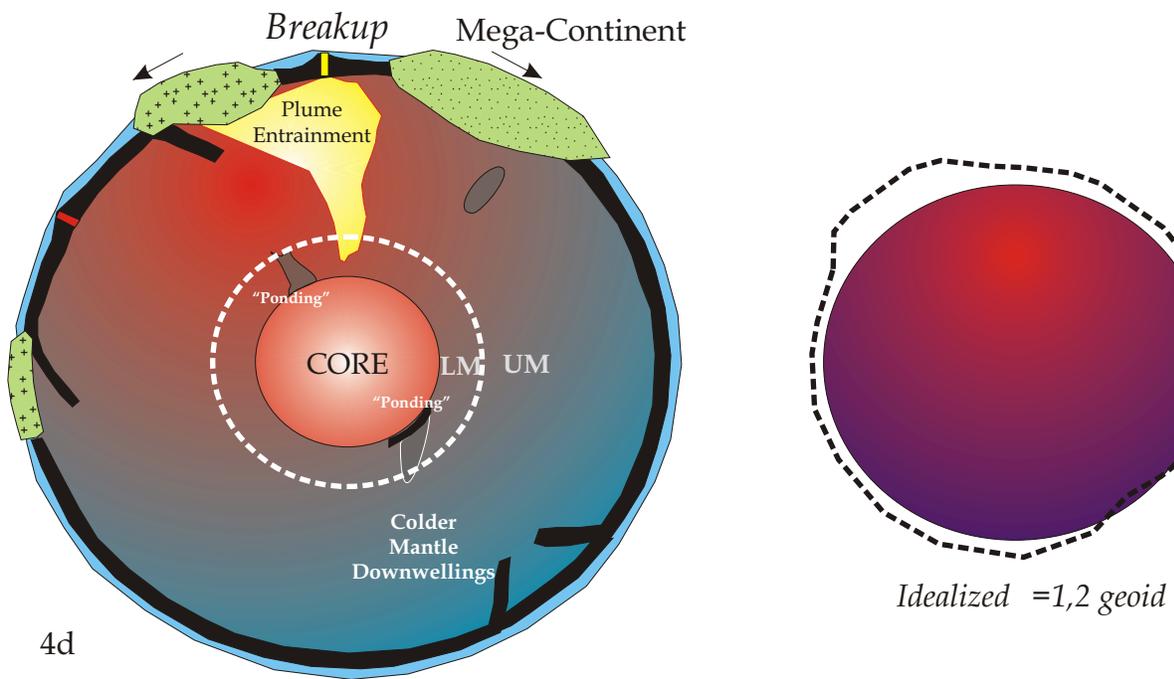
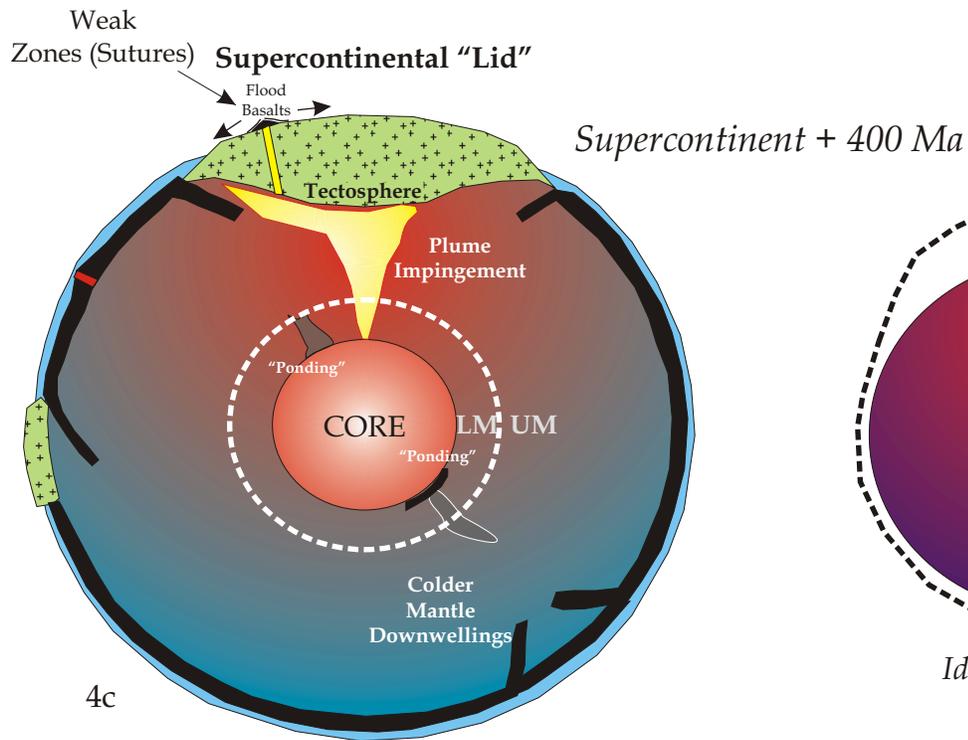
580 Ma



500 Ma







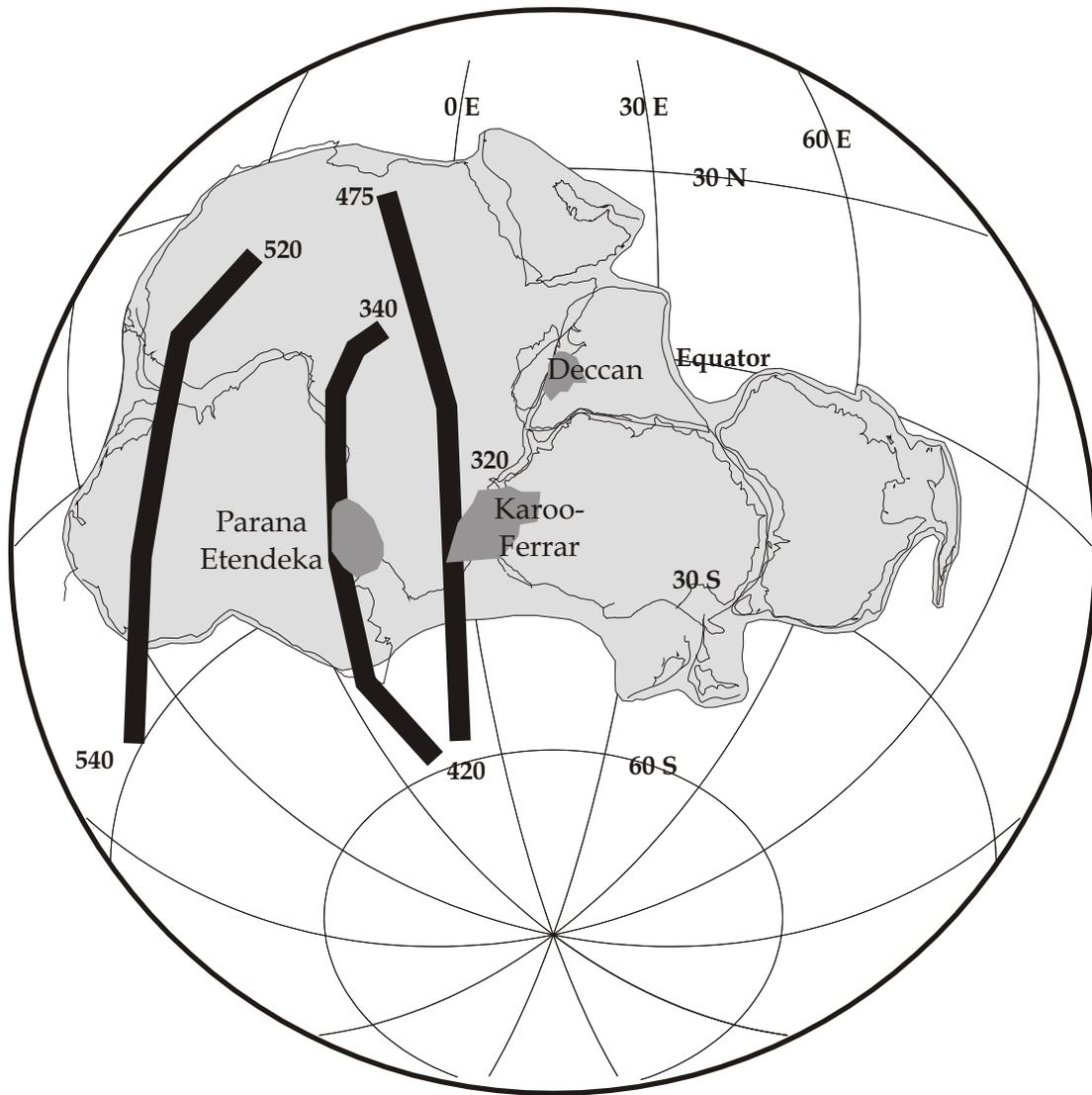


Fig 5