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Notes

Rapid drift of large continents during the late Precambrian and Paleozoic: Paleomagnetic constraints and dynamic models

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ABSTRACT

During the late Precambrian and early Paleozoic, Laurentia and Baltica moved at minimum drift rates of up to 23 cm/yr. These drift rates are computed from paleomagnetic apparent-polar-wander paths and represent minimum velocities, because there could have been significant undetected longitudinal motion. A pronounced burst in latitudinal velocity followed the breakup of the supercontinent Rodinia, which had been assembled for about 400–500 m.y. Finite-element models with tectonic plates show that the presence of deep continental roots can strongly influence the velocity of continents if the driving source of buoyancy is located in the lower mantle. When plates are driven by lithospheric cooling and subducted slabs, the presence of a root is less important. We argue that Laurentia and Baltica were either pushed off of a hot lower-mantle source or pulled toward cold lower-mantle anomalies and that the presence of continental roots enhanced this motion.

INTRODUCTION

Since the seminal work of Forsyth and Uyeda (1975), who showed that plates with attached continents move slower than purely oceanic plates, there has been a reluctance to accept the possibility that large continents could have moved with velocities greatly exceeding present-day rates. Rapid latitudinal motion of continents is often judged unreasonable. Recent paleomagnetic observations now seem to indicate that the drift rates of Laurentia, Baltica, and Gondwana greatly exceeded both present-day and post-Pangea-breakup drift rates of large continental blocks.

Does the observation of rapid continental velocities provide support for the absence of a continental tectosphere, as suggested by Schult and Gordon (1984)? Is there any basis for the hypothesis that the presence of deep roots attached to continents will significantly slow continents? What may have caused continental blocks to move significantly faster in the late Precambrian and Paleozoic in comparison to the slower-moving fragments after the breakup of Pangea? In light of recently determined high-quality apparent polar-wander paths (APWPs) for Baltica and Laurentia, we consider these questions with a set of finite-element calculations of continental plates with deep roots.

APPARENT POLAR-WANDER PATHS FOR LAURENTIA AND BALTICA

Paleomagnetic data provide quantitative estimates for the latitudinal and rotational movements of continental plates. Along with biogeographic and sedimentary facies data, paleomagnetic studies form the basis for developing paleogeographic reconstructions. The reliability of APWPs, most notably for Baltica, Laurentia, and Avalonia,

have improved considerably over the past few years, and the late Precambrian and Paleozoic drift history for these blocks and the development of the intervening oceans are now constrained to a first order (Van der Voo, 1988, 1993; Torsvik and Trench, 1991; Torsvik et al., 1992). Laurentia and Baltica probably formed part of the Rodinia supercontinent (Dalziel, 1991; Hoffman, 1991), which was assembled at ca. 1100 Ma and broke up during late Precambrian time. Laurentia, which formed the core in the Rodinia supercontinent, and Baltica were situated at low to equatorial latitudes during most of Riphean time but drifted southward during Vendian time (Fig. 1A) and occupied polar latitudes at ca. 580–600 Ma. In early Paleozoic time, Laurentia and Baltica represented individual continental units, whereas Avalonia was attached to the northwest margin of Gondwana. Avalonia rifted off Gondwana during Early Ordovician time (Torsvik and Trench, 1991) and merged with Baltica by Late Ordovician time. Baltica-Avalonia subsequently collided with Laurentia by Middle Silurian time (425 Ma) to form Euramerica (Laurasia). Later collisions with Gondwana and the European massifs formed Pangea by Permian time.

In order to calculate latitudinal and rotational velocities for Baltica and Laurentia, we fitted a spherical spline (Jupp and Kent, 1987) to the original paleomagnetic data in order to generate a smooth APWP. The paleomagnetic data were graded according to the Q factor of Van der Voo (1988). We excluded magnetic overprints and paleomagnetic poles that we suspected were not in tectonic coherence with Laurentia or Baltica.

APWPs for Baltica and Laurentia were generated for times from late Precambrian

to early Tertiary. The Baltica APWP is based on data listed in Torsvik et al. (1992) for Vendian to Permian time and upgraded with late Riphean data (Torsvik et al., 1994). The Mesozoic extension of the Baltic APWP is based on European mean values listed in Van der Voo (1992). Cambrian to Permian data for Laurentia are listed in Mac Niocail and Smethurst (1994), the Vendian data are from Meert et al. (1994), and the post-Permian data for North America are listed in Van der Voo (1992).

On the basis of these synthetic APWPs, we have calculated latitudinal drift rates and rotational velocities for a specific reference location averaged over a 10 m.y. time window (Fig. 1). Drift rates computed from paleomagnetic data represent minimum rates, because longitudinal movements remain undetected. From this analysis, it is clear that there were high drift rates and rotational velocities for both Baltica and Laurentia from late Precambrian (Vendian) to Devonian time that clearly exceeded modern plate velocities for plates with large attached continents. Particularly important were drift rates for Laurentia of 18 cm/yr during Vendian time (when Laurentia was moving rapidly from the South Pole to a stable equatorial position) and 23 cm/yr during Silurian time (when Laurentia was moving southward as the Iapetus ocean closed). Baltica showed significant peaks of 16 cm/yr during the Vendian-Cambrian, 9 cm/yr during the Late Ordovician when Baltica merged with Avalonia, and 12 cm/yr in the Silurian during destruction of the Iapetus ocean and collision with Laurentia.

DYNAMIC MODELS OF PLATES WITH DEEP ROOTS

On the basis of our understanding of how plates are driven, these rapid drift rates of large continental blocks pose serious problems. At present, plates are driven primarily by the negative buoyancy of subducting slabs and the cooling of the oceanic lithosphere as it spreads away from mid-ocean ridges; subduction is the more important of the two processes (Forsyth and Uyeda, 1975; Hager and O'Connell, 1981). If there were no differences between the structure of continental and old oceanic lithosphere, continental plates would only move more slowly because of a reduced push from the cooling oceanic

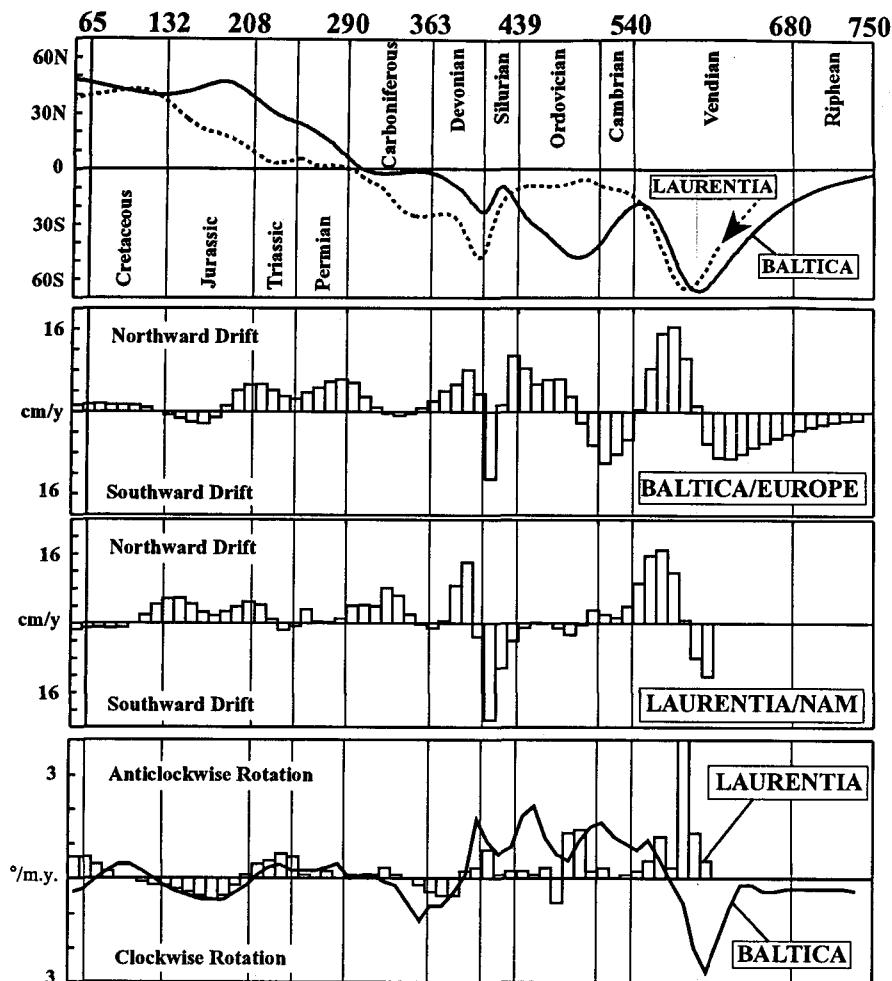


Figure 1. A: Latitudinal velocity of Baltica-Europe (reference location: 60°N, 10°E) and Laurentia-North America (NAM) (reference location 40°N, 270°E) as function of geologic time. Time scale after Harland et al. (1989), except age for Vendian-Cambrian boundary, which was originally 570 Ma in Harland et al. (1989). B and C: Latitudinal drift rates for Baltica and Laurentia separated into southward and northward movements. D: Angular rotation rates separated into clockwise rotations for Baltica and Laurentia.

Figure 2. A: Rheological structure; black is high-viscosity lithosphere and root; w_r is root width, X_c is position of left corner of root, and wz is location of two weak plate-margin zones. B: Location of buoyancy forces. Cold slab (right) has constant dip of 45° and depth of 670 km; cooling oceanic lithosphere is along top; ellipse shape is lower mantle anomaly. Shading is schematic. Lithospheric temperatures are from standard boundary-layer cooling model with spreading rate of 6 cm/yr. Average temperature within slab corresponds to that with age of 20 m.y. Lower mantle temperature is defined as $T_o \sin(\pi x/7500 \text{ km}) \sin(\pi z/D)$ where T_o is temperature of anomaly given in text, z is measured downward from top of lower mantle, and D is thickness of lower mantle, 2300 km.

lithosphere. However, continents—in particular, Archean cratons—may be underlain by deep roots as much as 300 km thick (Jordan, 1975, 1988). The roots are probably

neutrally buoyant and hence essentially passive, except for a significantly stiffer rheology (Pollack, 1986). The root under the Canadian Shield is particularly evident in

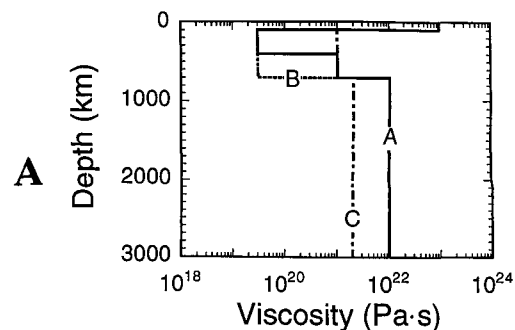


Figure 3. The three viscosity models used in flow calculations.

seismic tomography and locally may be as much as 400 km thick (Grand, 1987). It has been suggested that the presence of continental roots would appreciably slow down those plates that have embedded continents (Schult and Gordon, 1984). Here we demonstrate the effect of deep roots on plate velocity for two different driving forces: a shallow one due to lithospheric cooling and subduction and a deep one involving a large-scale lower mantle source.

The strong lateral variations in lithospheric strength that probably accompany deep roots are easily handled with a finite-element analysis of mantle flow (King et al., 1990). Our strategy has been to define the magnitude and pattern of buoyancy and compute the instantaneous flow velocities for the coupled plate-mantle system. The geometry of the two-dimensional flow model (Fig. 2) has a box with an aspect ratio of 5:1 and a depth of 3000 km. The box is further divided into viscosity layers (Fig. 3). The viscosity models used bracket recent estimates from studies of postglacial rebound and the geoid.

The lithosphere has two weak zones representing diverging and converging margins (Fig. 2). The lithosphere has a viscosity of 10²³ Pa·s and narrow weak zones of 10²⁰ Pa·s. The upper mantle also has variations in viscosity with a root of width w_r . The viscosity of the root is conjectural but is set here to 10²³ Pa·s. From glacio-isostatic analysis, Nakada and Lambeck (1991) suggested that there is an order-of-magnitude difference in viscosity of the upper mantle between continents and the Pacific Ocean. However, the rheological difference between root and upper mantle is likely to be much larger, $\sim 10^2$, in order for the roots to have survived since the Archean (Gurnis, unpublished calculations).

For lithospheric sources of buoyancy, the lithosphere thermally thickens according to the standard boundary-layer model with a half-spreading rate of 6 cm/yr. The slab al-

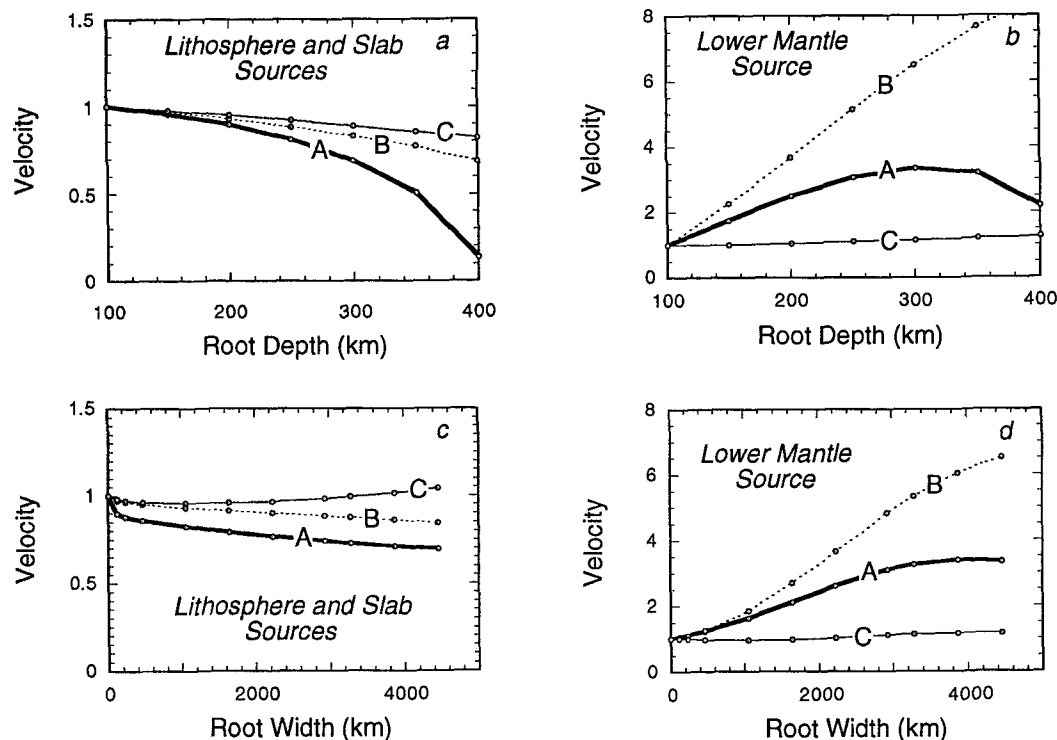


Figure 4. Velocities of continent as function of root parameters. A, B, and C refer to three radial viscosity models shown in Figure 3. Absolute velocities (cm/yr) of cases with no roots used to normalize curves are as follows: lithospheric source, viscosity model A—6.78, B—9.71, C—1.2; deep source of buoyancy, viscosity model A—1.3, B—0.8, C—3.05.

ways has the same dip (45°) and age (20 m.y.). The magnitude of the driving source remains invariant as the width and depth of the continental root vary. When the root depth, d_r , is varied from 100 to 400 km, w_r is held at a constant 4450 km; when w_r is varied from 0 to 5625 km, d_r is set to a constant 300 km.

Continental velocity changes as the root under the plate thickens and widens. The velocity (Fig. 4) is defined as the average horizontal velocity along the top from $x = X_c$ to $X_c + w_r$ and is normalized by the continental velocity when a root is absent (see Fig. 4 caption). Plate velocity is only a mild function of the characteristics of the root, but the details are sensitive to the radial viscosity.

When the driving forces are shallow, continental velocity only decreases slightly as the root thickness increases (Fig. 4a). When the whole mantle is essentially isoviscous (model C, Fig. 3), the upper mantle and transition zone are dragged along with the plate with only a small decrease in strain rate with depth, and consequently, as the root thickens, the continental velocity decreases only marginally (Fig. 4a). There is little difference as the root thickens when the upper mantle and transition zone have the same viscosity (C in Fig. 4a). There is a larger decrease in velocity when there is a large jump in viscosity from the upper mantle to the transition zone (A in Fig. 4a); for small root thicknesses, most of the strain ef-

fects driven by the shallow sources of buoyancy are located within the weak upper mantle, but when the root becomes embedded in the stiff transition zone, the continent slows appreciably because the shallow source attempts to turn the whole mantle layer over. Much of the same physics is evident when the width of the root is increased; the plate velocity decreases for shallow sources of buoyancy.

When the source of buoyancy driving the flow is located below the root, continental velocity increases with root dimensions. As for shallow sources of buoyancy, when there is no appreciable viscosity contrast between the upper and lower mantle (model C), there is little change caused by the lateral variations in viscosity (Fig. 4, b and d). When there is a significant increase in viscosity from the upper mantle to the lower, continental velocity increases rapidly with root thickness (Fig. 4b) and width (Fig. 4d). The lower-mantle source of buoyancy driving the continental plate is caused by the increased coupling to the surface when the roots become embedded in the stiff lower mantle. Without roots, plates become less tightly coupled with the driving buoyancy source.

For example, the presence of a 250-km-thick continental root would not significantly affect the velocity of a continent if the plate was driven by lithosphere cooling and subduction (Fig. 4a), but if the source of buoyancy was located in the lower mantle,

then such a root could have a profound effect and push the continental plate 3 to 5 times faster compared to a rootless plate. The absolute increase in velocity increases linearly with the lateral temperature contrast in the lower mantle because the equation of motion is linear. A temperature contrast of 100 K leads to an absolute continental velocity of 1.3 cm/yr (viscosity model A) to 0.8 cm/yr (B) (see Fig. 4). This result implies that if the temperature contrast was 500 K, then the augmented increase in velocity would be 19.5 cm/yr to 20.0 cm/yr for viscosity models A and B, respectively.

DISCUSSION

Rapid latitudinal drift rates of Laurentia and Baltica in Vendian time (Fig. 1) occurred during the break-up of the long-lived Rodinia supercontinent (Dalziel, 1991; Hoffman, 1991). Proto-east Gondwana (Antarctica-Australia) may have rifted off western Laurentia (present coordinates) at 725 Ma (Powell et al., 1993) or alternatively at 600 Ma (Meert and Van der Voo, 1994). This movement was followed by the at least ~ 20 cm/yr velocity peak (Fig. 1) of the combined remains of Rodinia (including Laurentia and Baltica). At the end of this burst in latitudinal velocity, Laurentia and Baltica moved away from each other as well as from the Gondwana block. How could such major continental blocks move so fast if they were surrounded by rifted margins? The lower-

mantle heat source could provide a logical explanation: Rodinia may have been assembled from ca. 1100 to at least 725 Ma, and Laurentia was at the center of this supercontinent (Dalziel, 1991; Hoffman, 1991). An alternative possibility that we do not consider is a component of true polar wander (TPW). If lower-mantle thermal anomalies cause rapid bursts in plate velocity, we would expect that this could also be a time of enhanced TRW because of the commensurate changes in the Earth's moment of inertia.

The increase in temperatures under a supercontinent arising from continental insulation can be found if the rest of the mantle is completely cooled by subduction and the mantle under the continent warms with the mid-oceanic ridge basalt value of radioactive heating (1.5×10^{-12} W/kg). These assumptions yield a temperature rise of 33 K after 500 m.y., also assuming that the heating rate during Rodinia assembly was 30% higher than today. This value is not an upper limit because it ignores the secular cooling of Earth and plume heating. An upper limit is obtained by assuming that all the heat that is emerging from the mantle is made in the mantle (7.5×10^{-12} W/kg), for a temperature rise of 160 K. Using this upper limit, we calculate a 6 cm/yr augmented velocity for a continent with a 250-km-thick root.

An alternative possibility is that Laurentia-Baltica moved toward a cold spot in the mantle generated by a prolonged period of subduction; a localized cold spot of a few hundred kelvins can be generated in a few hundred million years (Gurnis, 1993) and thereby create the necessary buoyancy for an augmented velocity in excess of 10 cm/yr. An implication of moving toward a cold spot is that a significant sea-level rise would be expected to follow the burst in continental velocity as the continent settled into the dynamic topographic low overlying the cold spot (Gurnis, 1990). Laurentia underwent a sea-level rise coincident with its slowing down during the Middle Cambrian (cf. Kominz and Bond, 1991) and underwent a period of rapid basin subsidence far in excess of the sea-level rise immediately following the Silurian-Devonian 23 cm/yr peak in drift rate.

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