The Lithospheric Structure of Pangea

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Abstract

Lithospheric thickness of continents, obtained from Rayleigh wave tomography, is used to make maps of the lithospheric thickness of Pangea by reconstructing the continental arrangement in the Permian. This approach assumes that lithosphere moves with the overlying continents, and therefore that the arrangement of both can be obtained using the poles of rotation obtained from magnetic anomalies and fracture zones. The resulting reconstruction shows that a contiguous arc of thick lithosphere underlay most of eastern Pangea. Beneath the western convex side of this arc there is a wide belt of thinner lithosphere, underlying what is believed to have been the active margin of Pangea, here named the Pangeides. On the inner side of this arc is another large area of thin lithosphere beneath the Pan-African belts of North Africa and Arabia. The arc of thick lithosphere is crossed by bands of slightly thinner lithosphere that lie beneath the Pan-African and Brasiliano mobile belts of S. America, Africa, India, Madagascar, and Antarctica. This geometry suggests that lithospheric thickness has an important influence on continental deformation and accretion.

keywords; Pangea, lithospheric thickness, cratons, Pan-African orogenesis.

1. Introduction

Writing more than 100 years ago Dana (1875) recognized that many continents consisted of an interior shield that had resisted deformation, surrounded by mobile belts. Often the belts become successively younger toward the continental margins. Because old continental regions are often underlain by thick lithosphere, it is likely that continental growth is associated with accretion around regions of thick lithosphere. A variety of different definitions of lithospheric thickness have been used by different authors (see Priestley and McKenzie, 2013). That used here depends on a thermal model of the crust and upper mantle, consisting of a crust, underlain by a mechanical boundary layer (MBL) in which heat is transported by conduction alone, underlain by a thermal boundary layer (TBL) and an isentropic mantle. The temperature and temperature gradient are required to be continuous everywhere, and the TBL is part of the convecting upper mantle. The model is parameterised using the thickness of the MBL, determined by fitting the estimates of temperature at given depths. The lithospheric thickness is then determined as the depth at

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which the conductive geotherm in the MBL reaches the temperature of the isentropic interior, and falls in the middle of the TBL. There is no reason to expect other definitions of lithospheric thickness to give similar values to those used below. Until recently the only method of estimating lithospheric thickness of continents depended on the mineralogy of garnet-bearing nodules, which are only found in rare alkaline rocks. Another method is now available which depends on Rayleigh wave tomography. The Rayleigh wave velocity is primarily controlled by V_{SV}, the velocity of vertically polarized shear waves, which is in turn principally controlled by temperature and only weakly by composition (Priestley and M^{c}Kenzie, 2006). Rayleigh wave tomography can therefore be used to determine the temperature as a function of depth, and hence the lithospheric thickness, by fitting a geotherm to temperature estimates greater than 1173 K at depths greater than 100 km (Priestley and M^{c}Kenzie, 2013). At present, the various approximations required limit the analysis to waves with periods greater than $\sim$ 50 s, and therefore to lithospheric thicknesses greater than $\sim$ 110 km. There is now good agreement between the maps of V_{SV} from different authors who used a variety of different methods to analyze the data and to carry out the inversions (see Priestley and M^{c}Kenzie, 2013). The maps show that the regions of lithosphere thicker than $\sim$ 150 km are considerably more extensive than the surface outcrops of Archaean and Proterozoic rocks which form the shields. They also show that continental regions of Asia that are now undergoing active shortening are underlain by lithosphere with a thickness >200 km. Because the structures involved are now producing thick lithosphere, Priestley and M^{c}Kenzie (2006) suggested that such regions should be called 'cores' rather than 'cratons'. The method that Priestley and M^{c}Kenzie used to estimate lithospheric thicknesses does not provide reliable values for continents when the thickness is less than about 110 km, because the limited vertical resolution of the surface wave tomography smears the low crustal velocities into the uppermost mantle.

Pangean Lithosphere

All of the continents have regions of thick lithosphere associated with Precambrian cratons, which are now distributed around the globe. However, in the Permian, all the major continental regions were joined together as Pangea, and we were curious to see what was the distribution of thick lithosphere before Pangea was fragmented. Figure 1 shows the continental reassembly, carried out using the rotation poles in Table DR1 in the GSA Data Respository. The maps were produced by rotating the values of lithospheric thickness from model PM_v2_2012 (Priestley and M^{c}Kenzie, 2013), then contouring the resulting values. Thick lithosphere associated with present active continental shortening was removed, as were the large values along the Pacific margin of South America that result from the high V_{SV} velocity in the subducting slab, and not from thick lithosphere. Several features of Figure 1 are striking and show a correlation with surface features that have been interpreted through many years of regional geological mapping. In particular, Pangea consists of three large regions, shown with different colors in Figure 1: an outer arc of thinner lithosphere, which we call the Pangeides active margin; a central arc of thick lithosphere; and an area of thinner lithosphere that underlies what is now North Africa, Arabia, and western Europe. These and other features discussed below offer insights into the formation and deformation of continental lithosphere.

A Pangean arc of thickened lithosphere

The most striking feature of Figure 1 is the contiguity of the regions of thick lithosphere throughout Pangea. Because thick lithosphere is considerably more extensive than is the surface outcrop of Archaean cratons, this feature of the reconstructions is less obvious from the surface geology. The contiguity of the thick lithosphere in Figure 1 also suggests that the lithospheric thicknesses determined from Rayleigh wave tomography are reasonably accurate, since there is otherwise no reason why a continuous arc should appear in the reconstruction. Many present-day continental margins are marked by zones of thinner lithosphere in Figure 1. It is unclear whether this feature is real. Because the lithospheric thickness of old oceanic regions is only about 100 km, the limited spatial resolution of model PM_v2_2012 of about 250 km smears the boundary between thin oceanic and thick cratonic lithosphere. The contiguity of thick lithosphere in Figure 1 can result only if thick lithosphere was produced or deformed (or both) during the assembly of Pangea. Before Pangea was assembled, its separate pieces must in general have had different shapes which would not fit together. At present, regions of thick lithosphere are widely scattered and have irregular boundaries. As the fits in Figure 1 show, they can have undergone little deformation during their dispersion after the Permian. If they had undergone deformation during the dispersion, they would no longer fit together when Pangea was reconstructed by rigid rotations. If future motions again result in the formation of a new Pangea, they will, in general, not bring the rifted margins back together in exactly the same configuration as they had in the Permian. Therefore, regions of thick lithosphere can only form contiguous regions if thick lithosphere is formed in the gaps, or if the regions themselves are deformed. Probably both processes are involved. The resistance to continental shortening must also depend on lithospheric thickness, because otherwise shortening would stop before the thick lithosphere became contiguous. Figure 2A shows the details of equatorial Pangea (or western Gondwanaland). The Atlantic fits show that the thick lithosphere of North America and South America and of Africa formed a continuous belt before the Atlantic opened, and that the thin lithosphere beneath northeast Brazil is part of a more extensive region of thin lithosphere in East Pangea. Figure 2B shows the major structural domains on the southern continents using the same scale and projection as in Figure 2A, and largely agrees with the reconstructions of Vaughan and Pankhurst (2008) and of Tohver et al. (2006). Their Arabian-Nubian and Nile Shields are shown as Pan-African in Figure 2B. Much of the region shown as Pan-African probably also contains large amounts of reworked older rocks. The region of Laurasia in Figure 2C shows that the reconstruction does not close the Arctic Basin, which forms the only interruption in the entire length of thin lithosphere in Figure 1. This misfit may result from relative motion between the regions east and west of the Ural Mountains since the Permian.

Thickened lithosphere and Pan-African orogenesis

Within the arc of contiguous thick lithosphere, several belts of thinner lithosphere occur. These are particularly clear in Gondwanaland, both along the continental margins and within the present-day continents of Africa and South America. Along the margins, it is difficult to know if these features result from later stretching during continental breakup, or are caused by smearing owing to the limited spatial resolution of the surface wave tomography. However, within the continents, they show a strong correlation with the mapped presence of Pan-AfricanâĂŞaged (650âĂŞ550 Ma) orogenic belts (Kennedy, 1964; Miller et al., 1996; Bizzi et al., 2003; Harley, 2003; Milesi et al., 2010). These linear belts of Pan-African age between the older shields are weak zones that have controlled the locations of the rifts formed when Gondwanaland broke up (Daly et al., 1989) (Fig. 2B). Figure 2A shows a region of thin lithosphere to the east of the West African craton and to the north of the Congo craton and its southerly continuation into South America along the eastern margin of the Amazonian craton. This region underlies the Neoproterozoic Pan-African and Brasiliano belts (Fig. 2B), a complex orogenic system that resulted in the formation of the North African and South American parts of West Gondwanaland (de Almeida et al., 1981; Caby, 1987; Bizzi et al., 2003; Daly et al., 2014). The throughgoing crustal-scale fault and shear zones of western Africa, known as the Kandi fault, and the corresponding Transbraziliano Lineament in Brazil show that these orogenic zones extended from Africa to South America before the south Atlantic rift formed (Fig. 2C). A band of lithosphere that is slightly thinner than that beneath the Archaean cratons on either side crosses Africa from Nambia to Tanzania, separating the Congo craton from the Zimbabwe craton (Figs. 2A and 2B). This band underlies the Pan-African orogenic zones of Damaran, Lufilian, and Zambezi deformation resulting from collison of the Congo and Zimbabwe cratons (Kröner, 1977; Coward and Daly, 1984). Though this band is slightly thinner than the lithosphere on either side, it is considerably thicker than that beneath northeast Africa and the arc further west, and forms the southern part of the Pangean arc of thickened lithosphere. This geometry shows that the Pan-African collisional processes must have resulted in widespread orogenic strain on a lithospheric scale to create the observed contiguity of thickened lithosphere in our reconstruction.

The Pangeides active margin

The reconstruction shows that Pangea consisted of an arc of contiguous thick lithosphere with an arc of thin lithosphere comprising Phanerozoic mobile belts on its convex side. The southern part of this area of mobile belts was named the Samfrau Geosyncline by Du Toit (1937). Our Fig. 1 shows a much more extensive zone of mobile belts, interpreted as an active plate margin stretching from Northern Australia to NE Asia (Dalziel & Grunow 1992, Dickinson 2004, Scotese and Langford 1995) and incorporating Du Toit?s Samfrau Geosyncline A more suitable name for this long and complex zone of Late Paleozoic Early Mesozoic active margin tectonics is therefore the Pangeides. Presumably oceanic lithosphere of Panthalassa, none of which remains today, was being subducted along this margin. In addition the accretion of a number of continental and oceanic fragments occurred as shown in several paleogeographic reconstructions.

The Pan-African active margin

The reconstruction of Pangea also shows a large region of thin lithosphere on the concave side of the arc of thick lithosphere. Much of this region was either remobilized or accreted (or both) in the Late Neoproterozoic to form the terranes of the Pan-African age Mozambique belt (Stern, 1994; Shackleton, 1996). Sadly, these maps of the lithospheric thickness beneath Pangea are no obvious help in understanding why the Pan-African lithosphere is so thin and why such extensive remobilization occurred.

Discussion

Geologists have long been aware that continental deformation is strongly affected by the distribution of cratons. Maps of lithospheric thickness based on Rayleigh wave tomography now make this control even more obvious than it is from the surface geology. The lithospheric thickness beneath the Pan-African belts formed by the collision between Archaean cratons is greater than the extensive Pan-African terranes of northeast Africa and Arabia. This difference suggests that the Central African and Brasilian Pan-African belts have been thickened by shortening in the past, in the same way as is now occurring in central Asia (Priestley and McKenzie, 2006, 2013). The distribution of thick lithosphere, beneath both Pangea and Asia, implies that the forces resisting shortening increase strongly when two such regions come in contact with each other. Variations in lithospheric thickness determined from surface wave tomography correlate with variations in the overlying crustal structure, and are therefore not likely to be artifacts of the inversion process.

Acknowledgements

We thank C. Sengor for his help, and L. Lawver and L. Gahagan for supplying many of the poles used for the reconstructions.

GSA Data Repository item 2015xxx, xxxxxxxx, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

http://doi.pangaea.de/10.1594/PANGAEA.847325

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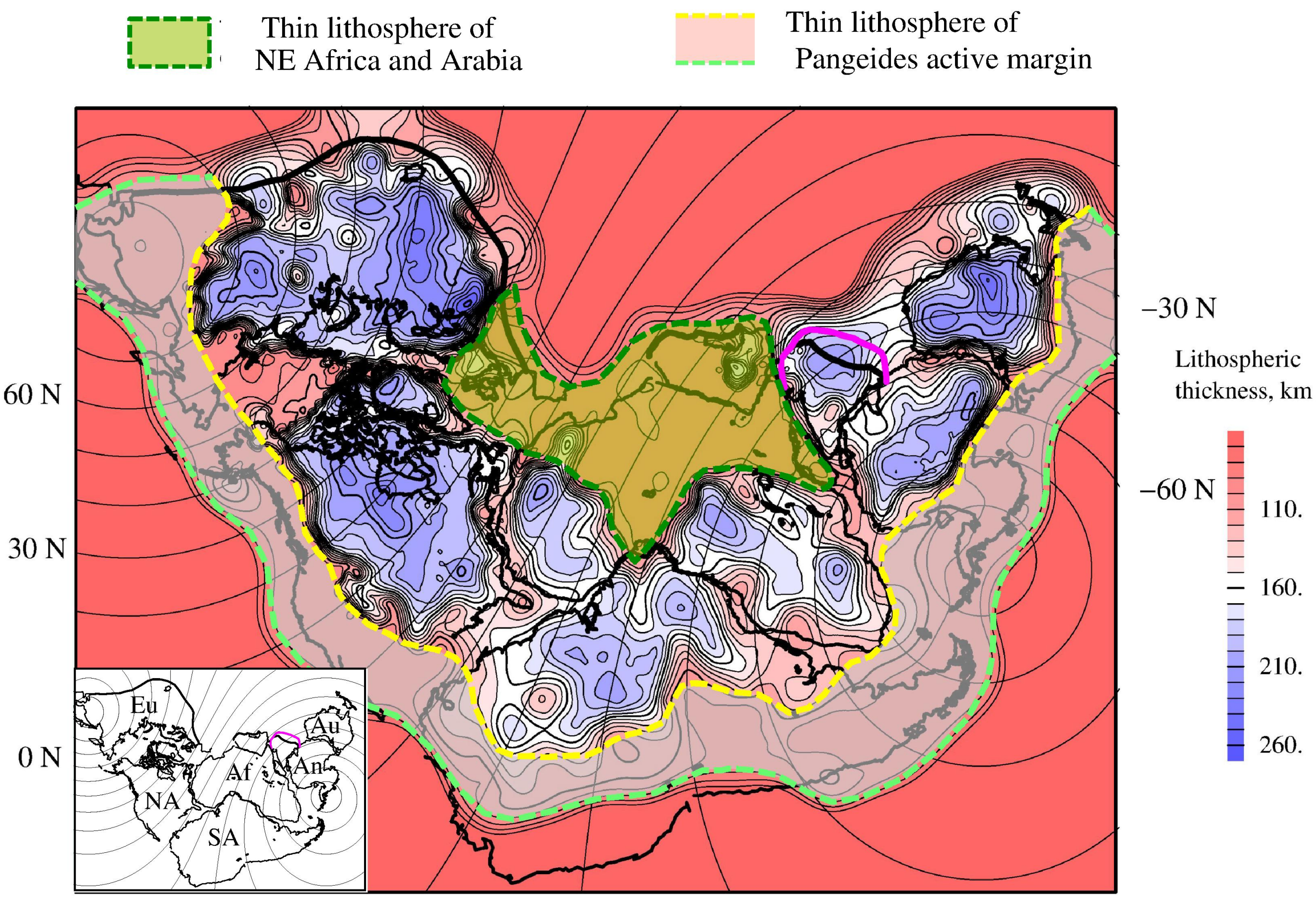

Figure 1: Pangea reconstruction. Thick black and magenta lines show the northern boundaries of India and Arabia and the southern boundary of the Eurasian craton. Dashed light-green line marks the outer margin of the Pangeides active margin. Dashed yellow line shows approximate boundary between the active margin and the arc of thick lithosphere. Dashed dark-green line outlines the area underlain by the thinner lithosphere that now underlies North Africa, Arabia, and western Europe. The inset shows the same reconstruction without any lithospheric thickness contours. The labels in the inset are NA North America, Eu Eurasia, SA South America, Af Africa, An Antarctica, Au Australia. Oblique Mercator projection with axis 30°N, 80°E.

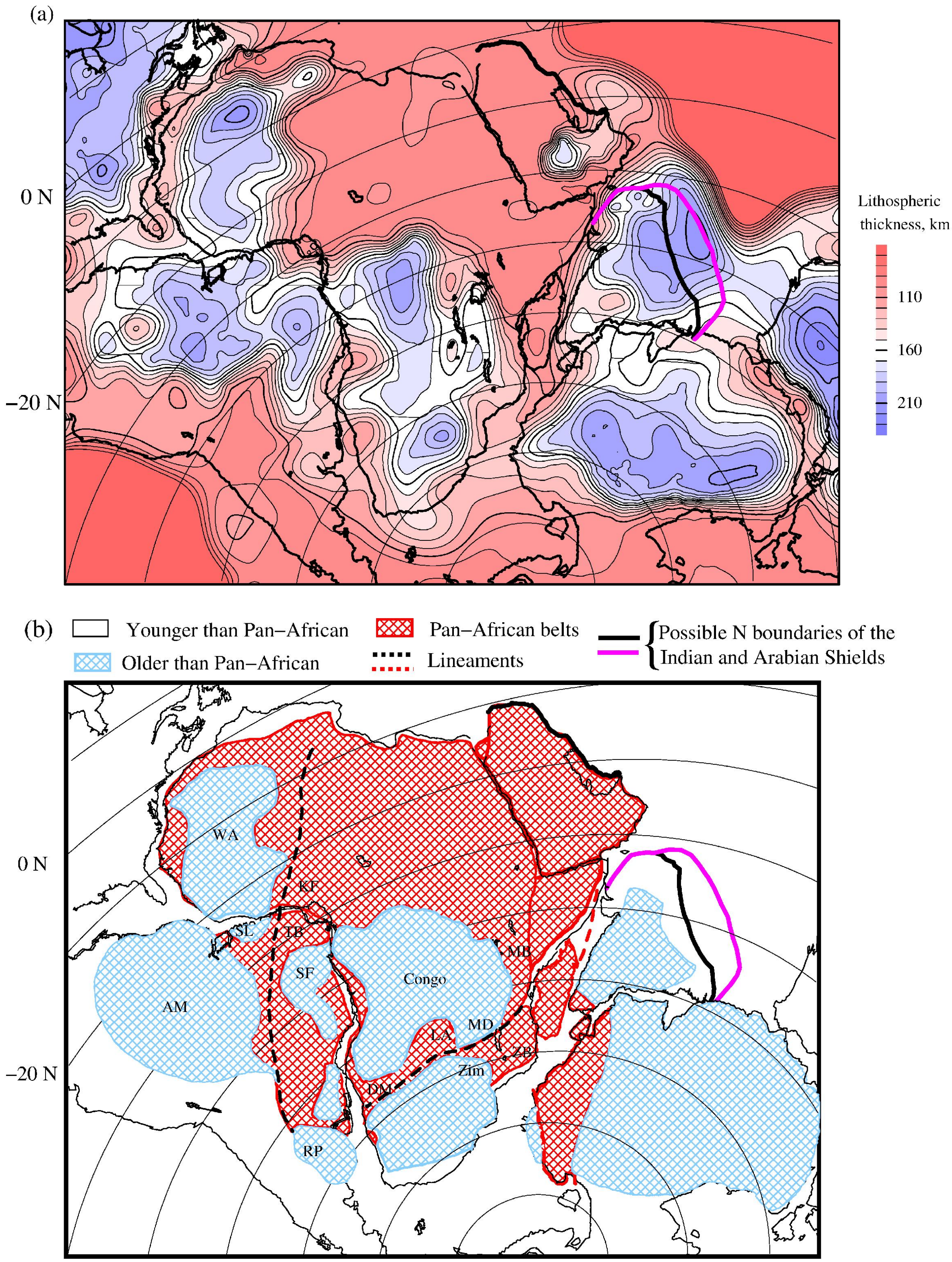
(a)
0 N
−20 N
Lithospheric thickness, km
110
160
210
(b)
Younger than Pan−African
Older than Pan−African
Pan−African belts
Lineaments
Possible N boundaries of the Indian and Arabian Shields
0 N
−20 N
WA
KF
SL
IB
SF
AM
Congo
MB
MD
LA
ZB
Zim
DM
RP

Figure 2:

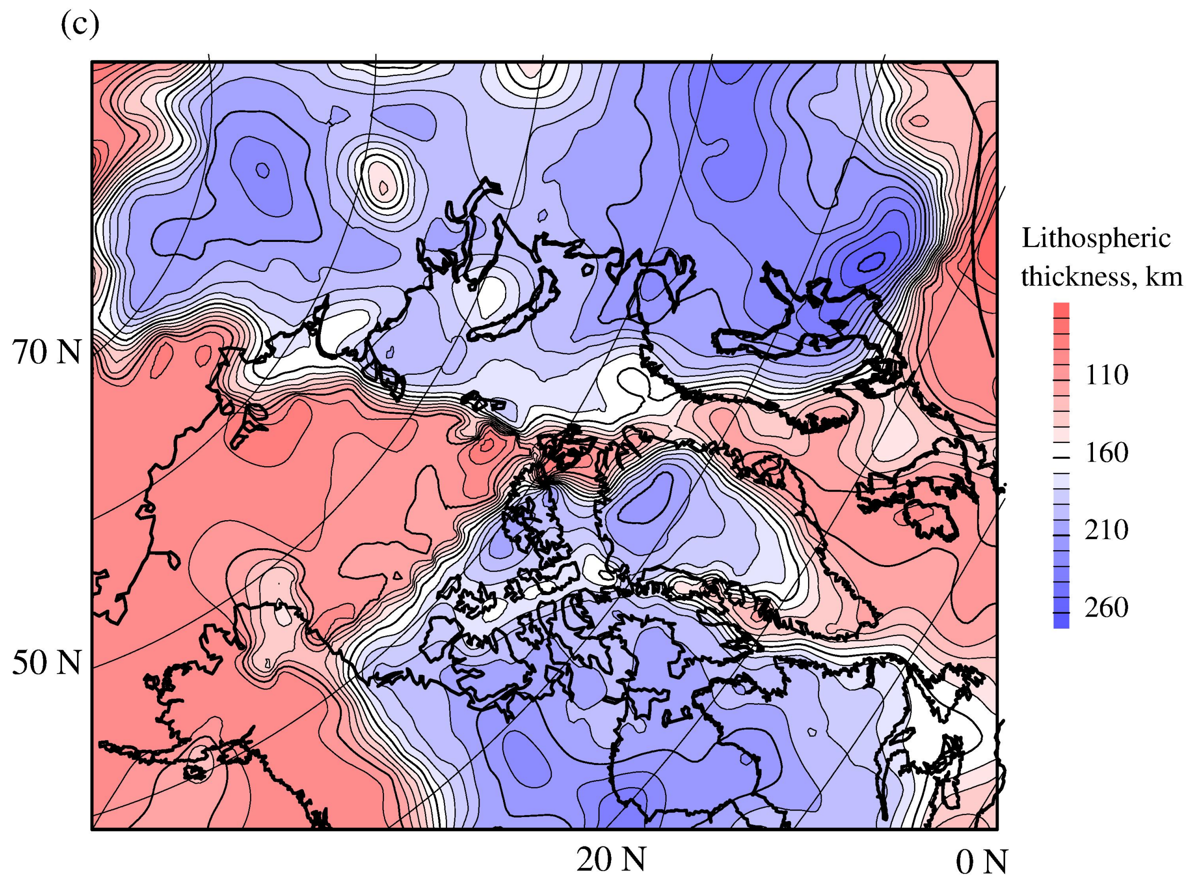

Figure 2:

A: Detail from Figure 1 of West Gondwanaland; Airy projection with pole at 0°N, 10°E and $\beta = 30°$. B: A reconstruction of West Gondwanaland showing outline of the major Pan-African orogenic belts in red, major regions that are older than the Pan-African crust in blue, and areas of post Pan-African crust in white. Red lines denote the boundary of pervasive Pan-African orogenic deformation, and dashed black lines show major continental-scale structural lineaments. In South America, TB is the Transbrasiliano lineament, AM the Amazonian craton, RP the Rio de la Plata craton, SL the São Luis craton, LA the Luis Alves craton, and SF the São Francisco craton. In Africa KF is the Kandi fault; MD is the Mwembeshi dislocation; DM is the Damaran Matchless belt; MB is the Mozambique Belt; LA is the Lufilian Arc; ZB is the Zambezi Belt, and Zim is the Zimbabwe craton, Congo the Congo craton, and WA the West African craton. The projection is the same as Fig. 2a. C: Detail from Fig. 1 of Laurasia, Airy projection with pole at 30°N, 20°E and $\beta = 30°$.