

Why is the areoid like the residual geoid?

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[1] The equipotential figures of Earth (residual geoid), and of Mars (areoid) are characterized by pairs of elevated and pairs of depressed antipodal equatorial regions. Elevated regions of the residual geoid lie vertically above the two Large Low Shear Wave Velocity Provinces (LLSVPs) on the Core Mantle Boundary (CMB). There is evidence that the LLSVPs are dense, physicochemically distinct, and have been stable in their positions with respect to each other and to the Earth's spin axis for at least ~ 550 My. The final event in the planetary-scale development of the Earth's structure was the moon-forming event and the comparable event on Mars is thought by many to have been the Borealis basin-forming impact. We attribute the formation of the LLSVPs and postulated comparable masses underlying the elevated regions of the areoid on the CMB of Mars, to the immediate after-effects of those two giant impacts. **Citation:** Burke, K., S. C. Werner, B. Steinberger, and T. H. Torsvik (2012), Why is the areoid like the residual geoid?, *Geophys. Res. Lett.*, 39, L17203, doi:10.1029/2012GL052701.

1. History

[2] The Residual Geoid (RG) [Hager, 1984] and the Areoid (AR) [Konopliv *et al.*, 2006], the equipotential figures of the Earth and Mars, are characterized by similar features of elevated and depressed antipodal equatorial regions relative to the hydrostatic figure of a spinning planet (Figure 1). The expectation of a hydrostatic figure led to a useful model of the Earth's figure for ~ 150 years from Newton's time. Later, Gauss, George Darwin and others showed that a better approximation of the figure is given by the geoid [Bruns, 1878]. Mapping the geoid progressed rapidly after the acquisition of satellite orbital data began in 1957. Following the plate tectonic revolution, Hager [1984] was able to distinguish between parts of the low degree geoid attributable to slabs of subducted lithosphere within the mantle which form part of "the dynamic geoid", and the remainder that he called "the residual geoid" (the RG, Figure 1a). Dziewonski [1984] among others recognized coincidence between the RG and volumes of perturbed P-wave velocities that later became even more obvious in

S-wave models and came to be called the two Large Low Shear-wave Velocity Provinces (LLSVPs) of the deep mantle [Garnero *et al.*, 2007]. When those two bodies, which lie vertically below the two RG elevations, were first identified it was considered that they were hot and buoyant because their seismic velocities are relatively slow, but evidence began to emerge by the end of the last century (see reviews by Lay and Garnero [2011, p. 115] and by Tackley [2012]) that the material within the LLSVPs is dense and iron-enriched [Ishii and Tromp, 1999; Kellogg *et al.*, 1999; van der Hilst and Kárason, 1999].

2. The Two LLSVPs and Their Coincidence With the Residual Geoid Highs

[3] Three critical implications of the dimensions, mass distributions and locations within the mantle [Burke *et al.*, 2008, Table 1] for understanding LLSVP origin and history are:

[4] 1. The LLSVPs lie on the CMB which is consistent with seismological evidence that they are composed of about 2–3% denser material than the rest of the mantle (compare review by Tackley [2012]).

[5] 2. Antipodal LLSVP locations coinciding with two elevated regions of the residual geoid and centered close to the equator [Burke *et al.*, 2008, Table 1] are consistent with the idea that the equator of a revolving planet will rotate to overlie elevated regions of the degree-two geoid, because in that way the moment of inertia around the spin axis is maximized [Goldreich and Toomre, 1969]. The centers of mass of the LLSVPs are at 11°S and 15°S [Burke *et al.*, 2008, Table 1], close to but not on the equator. This asymmetry corresponds to spherical harmonic degree one, but by definition there cannot be a degree one geoid component. Therefore, corresponding geoid highs have to be further north, more centered on the equator.

[6] 3. The centers of mass of the two LLSVPs lie $\sim 176^\circ$ apart, when measured along the equator. That antipodal disposition limits the motion of the spin axis relative to the mantle, so that it stays close to the great circle 90° away from the centers of the antipodal RG highs associated with the LLSVPs [Steinberger and Torsvik, 2010].

[7] In summary, the observed LLSVP configuration consisting of two similar antipodal masses on the equator overlain by corresponding geoid highs is a stable configuration to the extent that these masses will remain at the equator even though the spin axis may move.

3. Stability of the LLSVPs and the Residual Geoid Highs

[8] The LLSVPs have been fixed in their positions with respect to each other and the spin axis of the Earth for hundreds of millions of years [Burke and Torsvik, 2004;

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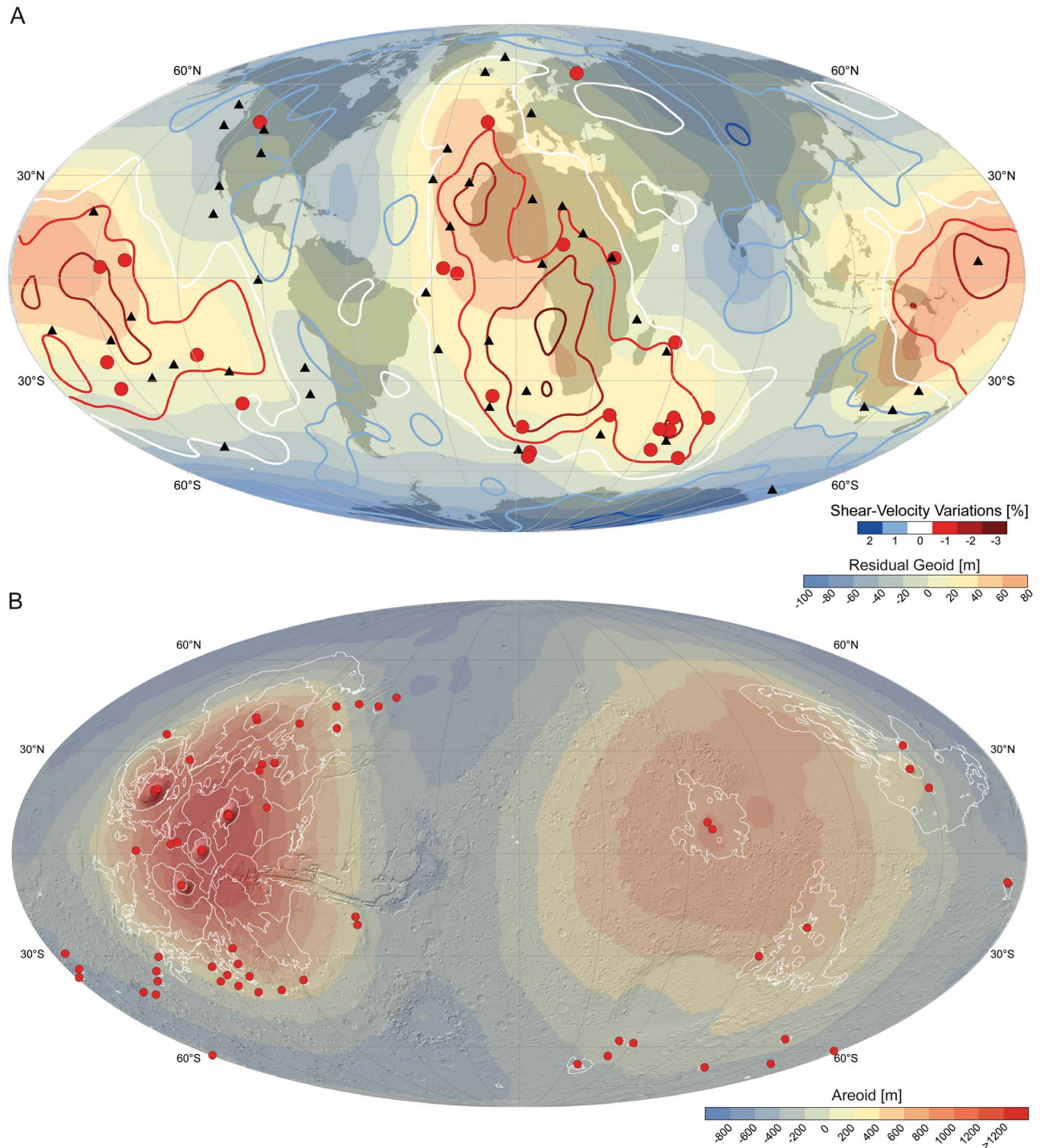


Figure 1. (a) The residual geoid (color shading of 20 m spacing, red is high and blue is low [Hager, 1984]), the Large Low Shear wave Velocity Provinces (LLSVPs; contour lines with a separation of 1%, white is zero, red is low and blue is high; velocities from the SMEAN model of Becker and Boschi [2002]), the distribution of hotspots (black triangles [Steinberger, 2000]) and of Large Igneous Provinces (LIPs) restored palaeo-magnetically to their eruption sites (red circles [Torsvik et al., 2010]). The two LLSVPs are located antipodally on the Earth's equator at the CMB. Plumes mainly from the Plume Generation Zones (PGZs) at the margins of LLSVPs led to the generation of LIPs and hotspots. Residual geoid highs match the LLSVPs quite well and LIPs and hotspots are concentrated closer to the +20 m level than to other levels shown, as well as being on the edge of the LLSVPs on the CMB. (b) The areoid (color shading, red high, blue low [Konopliv et al., 2006]), volcanic geological units (white outline [Tanaka et al., 1986]) and volcano eruption sites (red dots). Many (eleven volcanoes in the western and five in the eastern hemisphere) eruption sites are concentrated at the edges of the areoid highs.

Torsvik et al., 2006; *Burke et al.*, 2008; *Torsvik et al.*, 2010; *Burke*, 2011]. Evidence of the long term stability of the LLSVPs, and therefore presumably also the RG highs above them, comes from the observation that over the past 550 million years large igneous provinces and kimberlites have been erupted vertically above Plume Generation Zones (PGZs) at the edges of the LLSVPs on the CMB [*Torsvik et al.*, 2010], which lie close to the +20 m contour of the RG (Figure 1a). This finding, which establishes the long-term stability of the LLSVPs, has together with accruing seismological, geochemical and mineral physics understanding, contributed to growing interest in the geodynamic character of the two LLSVPs.

[9] No attempt can yet be made to test whether the two LLSVPs were fixed in their stable positions at times before 0.55 Ga. That is because the distribution of continent-sized objects on the Earth's surface for earlier times is as yet too poorly known to allow meaningful tests [see, e.g., *Burke*, 2007, 2011]. Nevertheless, the assumption that the positions of the two LLSVPs were as they are now back to ~ 4 Ga is realistic because Wilson-Cycle processes reflecting the operation of plate tectonics and for that reason the same as the tectonic processes that have operated since 0.55 Ga are recognized from geological evidence to have been in operation back to 4.0 Ga [e.g., *Bowring et al.*, 1989] and 4.3 Ga [*Harrison*, 2009], or at least back to around 3 Ga [*Sizova et al.*, 2010; *Shirey and Richardson*, 2011; *Dhuime et al.*, 2012]. No perturbation to the Earth System, such as an impact large enough to lead to the formation of isolated masses of the sizes of the two LLSVPs (in sum $\sim 2\%$ of mantle mass) has been recognized since the much earlier moon-forming event at ~ 4.5 Ga, which was ~ 100 My into the history of the solid Earth. *Mukhopadhyay* [2012] gives new Xe evidence, showing that, if noble gases in plumes are derived from the LLSVPs, they have existed since the formation of the Earth.

4. Is the Areoid, Like the Residual Geoid, Related to Antipodal Equatorial Masses on the CMB?

[10] We suggest that the areoid resembles the residual geoid in its two antipodal equatorial elevations (Figure 1) because it too is underlain by equatorial and antipodal masses on the CMB. Evidence consistent with this idea comes from the observation that deeply-sourced volcanic eruption sites at the time of their eruptions on the Earth lay close to a specific contour (+20 m) of the residual geoid (Figure 1a) and many Martian volcanic eruption sites (Figure 1b) overlie the margins of the areoid highs [*Werner et al.*, 2006]. These Martian volcanoes are for that reason inferred to have also been erupted above plumes that rose from the edges of two postulated antipodal masses on the CMB that underlie the areoid highs. If, on the other hand, we consider the volcanic geological units (white outlines in Figure 1b), we can only see a general tendency of these units to occur in regions of high areoid, but not specifically along the margins of such regions. Previous models [*Zuber and Smith*, 1997; *Phillips et al.*, 2001] argue that the shape of the Martian gravity field and thus areoid is related to the surface load caused by the Tharsis province. Both models indicate that with the removal of the Tharsis load the

antipodal gravity anomaly vanishes. *Steinberger et al.* [2010] have postulated that, in a dynamic Martian mantle, long-wavelength (up to spherical harmonic degree 5) areoid highs should be underlain by an overall low-density mantle that is dynamically upwelling. This does not contradict the idea proposed here that the areoid highs are underlain by dense masses near the core-mantle boundary. Volcanic activity on Mars occurred at least episodically over the past 4 billion years (based on crater count statistics), which indicates long-lived volcanic and magmatic activity on Mars [*Werner*, 2009], and implies a longevity of the postulated underlying equatorial and antipodal mass distribution on the CMB. A strong test of the idea that the postulated antipodal equatorial masses on the Martian CMB exist must, however, await the deployment and operation of seismometers on the Martian surface.

[11] One feature distinguishes the areoid from the residual geoid: Compared to the eastern hemisphere, the gradient of the western elevated region of the areoid is steeper, and that region reaches a greater elevation (Figure 1b). The region with the steeper gradient corresponds to the area of the huge Tharsis basaltic province (Figure 1b). We concur with, e.g., *Grott and Breuer* [2010] that the additional occurrence of an area of relatively dense basalt at the surface of the western elevated region and its absence from the eastern elevated region of the areoid accounts for the steeper gradient and greater elevation of the areoid in the west.

5. Why Are the Figures of the Earth and Mars Not Hydrostatic?

[12] The antipodal arrangement of the two LLSVPs on the equator is a stable configuration and observations indicate that stability to have persisted for at least the past 0.55 Gy but there remains a question because a spinning planet can be expected to have a hydrostatic figure. Why then do the LLSVPs exist? How and when did they form? Why have they survived instead of being assimilated into an Earth with a hydrostatic figure?

[13] To address these questions we focus on the similarity of the areoid to the residual geoid. If that similarity results from formation by similar processes of mass concentration beneath areoid and geoid highs on the CMB, some mechanisms of origin that have been postulated for the formation of these masses may be eliminated from consideration. For example: Models have been constructed that suggest the formation of the two LLSVPs under plate tectonic conditions. The basic idea of those models is that slabs of subducted lithosphere push material in the thermal boundary layer (TBL) immediately above the CMB to build the two LLSVPs as "thermochemical piles" and afterwards to move those piles about on the CMB. But because there is no evidence that plate tectonics has ever operated on Mars [see, e.g., *Solomon et al.*, 2005; *Nimmo and Tanaka*, 2005] there is no evidence that the pushing of TBL material by subducted slabs could ever have happened on that planet. Making "thermochemical piles" by pushing mantle material along the CMB is not a phenomenon that could have happened on Mars and could therefore have been common to the two planets. If areoid and the residual geoid are formed by similar processes, then plate tectonics involving

subduction can be eliminated from consideration as a process for making the two LLSVPs and the postulated similar bodies on Mars.

[14] By contrast large body impacts early in solar system history were, unlike plate tectonics, common to Mars and the Earth. A scenario in which masses underlying areoid and geoid highs formed in catastrophic episodes on the two planets following their greatest impacts, the Moon-forming impact on the Earth [Canup, 2008a, 2008b] and a giant impact on Mars, which may have formed the Borealis basin [Andrews-Hanna et al., 2008; Marinova et al., 2008, 2011; Nimmo et al., 2008] or alternatively caused thick crust in the southern highlands [Golabek et al., 2011; Reese et al., 2010, 2011], can be envisaged to have operated in this way: (i) The two planets developed hydrostatic figures very early in their histories while their cores were forming and their mantles were convecting rapidly. (ii) The catastrophic impacts on the two planets that led to the formation of the Earth's moon and of the Borealis impact basin or southern highland crust on Mars established short-lived high energy convection regimes and at least partial melting of the mantle on a vast scale. Following Tackley [2012], iron-rich materials from several sources, including a basal magma ocean [Labrosse et al., 2007], upside-down differentiation [Lee et al., 2010] and overturn of early crust [Tolstikhin et al., 2006] could have accumulated in the deep mantle. To give an order of magnitude estimate of energies provided by an impact we take 10 km/s as a typical velocity and a heat capacity 1250 J/kg/K. With a mass of the impactor of about 10% of the planet, we find that the energy of the impact would be sufficient to heat the entire planet by ~ 4000 K. This would lead to significant melting of the mantle, e.g., Canup [2008b] infers from smooth particle hydrodynamics (SPH) models melting of the entire mantle after the moon-forming impact. Thus, even if only a fraction of the impact energy was converted to heat, or if – in the case of Mars – the impact velocity was somewhat less, corresponding to the smaller escape velocity [Agnor et al., 1999], it is clear that it can lead to a substantial increase in temperature, decrease in viscosity and increase in vigour of convection. For comparison, Reese et al. [2011] consider impact energies of $1\text{--}3 \cdot 10^{30}$ J on Mars, which would correspond to 1250–3750 K temperature rise, while Marinova et al. [2011] considered smaller impact energies. (iii) We envision that, in the aftermath of the impact, the vigour of convection gradually decreased, leading to gradually longer and longer wavelengths and finally a predominant degree-two areoid pattern that survived until today. Because the areoid highs are not aligned with the crustal dichotomy symmetry axis, we do not think that the effect of antipodal heating caused by the impact played a role in establishing this pattern as an immediate consequence. (iv) The iron-rich material was not remixed but survived in the deep mantle as pairs of masses associated with residual geoid and areoid highs. On the Earth that iron-rich material forms the surviving antipodal and equatorial LLSVPs on the CMB. On Mars similar bodies are suggested to have formed after a giant impact and to have survived to be associated with the present high elevation of the areoid.

[15] Clearly, this scenario is only a hypothesis, and numerical modeling will be required to show that it is viable,

building upon existing work [Spohn and Schubert, 1991; Watters et al., 2009; Golabek et al., 2011; Reese et al., 2010, 2011].

6. Conclusions

[16] Mars and the Earth do not have the hydrostatic figures that are to be expected in spinning planets but they do appear to have stable figures with the residual geoid on Earth matching two stable LLSVPs, which are masses that occupy equatorial antipodal positions on the CMB. Mars is inferred to have similar equatorial antipodal masses on its CMB, although that suggestion cannot be fully tested until after a seismometer network is operational on the Martian surface. The structure of the deep mantle in the two planets is suggested to result from having been generated by the moon-forming event and a Martian giant impact event and subsequently insufficient energy to disperse the two LLSVPs and the two equivalent postulated Martian bodies. Viscous flow in the planetary mantles is suggested to have declined rapidly after the giant impacts and to have been unable to re-establish planetary hydrostatic figures because the energy of the two impacts was dissipated very quickly by the viscous flow. The figures of the two planets might therefore be better thought of as metastable rather than as stable. That metastable state may be influencing long-term planetary surface evolution and rotational dynamics. A limitation of our study is that it is not yet possible to accommodate the postulated giant impact event into established Martian crater forming chronologies.

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