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Mantle Anchor Structure: An argument for bottom up tectonics

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ABSTRACT

Close examination of the long wavelength shear velocity signal in the lowermost mantle in the wavenumber domain ties several geophysical observations together and leads to fundamental inferences. When mantle shear velocity model S362ANI at a depth of 2800 km is expanded in spherical harmonics up to degree 18, more than one half of the seismic model's total power is contained in a single spherical harmonic coefficient: the "recumbent" Y_{20} spherical harmonic; a Y_{20} with its axis of symmetry rotated to the equatorial plane. This degree 2 signal, which continues with decreasing amplitude for more than 1000 km above the core–mantle boundary (CMB), is characterized by two antipodal regions of low velocities, separated by a circum-polar torus of higher than average velocities. If the slow regions are associated with net excess mass, then any axis of rotation located in the plane of the circum-polar torus will be close to the maximum moment of inertia axis; this includes, of course, the current axis of rotation. We suggest that the recumbent Y_{20} is a very stable feature: once established, it is difficult to erase, and only relatively small departures from this equilibrium configuration are possible. This anomaly correlates strongly with the degree 2 terms of the residual geoid expansion, distribution of the hot spots above the slow regions, high attenuation in the transition zone, and position of subduction zones above the fast band during the last 200 Ma. Also, the preferred paths of the virtual geomagnetic pole and true polar wander locations for the last 200 Ma lie within the fast band. Since the non-hydrostatic perturbation of the moment of inertia tensor depends only on degree-2 anomalies in the density distribution and deformation of discontinuities, it is natural to infer that rotational dynamics of the Earth have influenced the distribution of heterogeneities in the Earth's deep interior. We propose that the large-scale heterogeneity at the base of the mantle, which we name Mantle Anchor Structure (MAS) may have formed early in the history of the convecting mantle, remained locked in place with respect to the Earth's rotation axis ever since, and is currently imposing the planform of flow in the mantle and of plate tectonics at the surface.

1. Introduction

The motivation for the first attempt to map seismic velocity anomalies in three dimensions on the global scale (Dziewonski et al., 1977) was to identify the driving mechanism of plate tectonics. Even this initial, very low resolution study detected significant correlation between degree 2 and 3 velocity anomalies in the lowermost mantle and the corresponding geoid coefficients, demonstrating the capability of the tomographic approach to resolve an otherwise nonunique inverse problem. Furthermore, that study, as well as that of Masters et al. (1982), motivated Busse (1983) to propose a degree-2 (quadrupole) layered convection in the mantle with the lower mantle pattern being that of the "recumbent" Y_{20}, even though this pattern was not that clear in the seismic models available then; Busse has also suggested that this pattern could be very stable.

Le Pichon and Huchon (1984) reached a similar conclusion, and pointed out the correspondence of geoid lows with subduction and geoid highs with the seafloor spreading. Cazenave et al. (1989) pointed out the correlation at degree-2 of regions of elevated surface topography, geoid highs, low seismic velocities and the hotspot distribution.

Some correlations between geodynamic observables were noted even without tomographic information. For example, Crough and Jurdy (1980) note the correlation between the distribution of hotspots and the geoid corrected for the effect of slab subduction. Improved seismic models (Dziewonski, 1984; Woodhouse and Dziewonski, 1984) stimulated geodynamic research on the quasi-static response of a viscous Earth to internal loads in order to elucidate the relationship between velocity anomalies and the geoid (Forte and Peltier, 1987; Hager, 1984; Richards and Hager, 1984). The main objective was to determine the variation of viscosity with depth, although there is another unknown radial function involved: the coefficient of proportionality of velocity and density variations. There are tradeoffs, but the need for an increase in viscosity in the lower mantle by a factor

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between 10 and 100 times over that in the upper mantle seems to be robust. In general, these studies did not investigate how the seismic anomalies originated; for a detailed review, see Forte (2007).

Richards and Engebretson (1992) demonstrated that the geographical distribution of the mass of slabs subducted during the last 200 Ma agrees, for spherical harmonic coefficients of degrees 2 and 3, with the geoid signal, seismic velocities and hot spot distribution. This study was extended by Ricard et al. (1993), who reconstructed the history of subduction during the Cenozoic and Mesozoic periods, and, assuming that slabs sink vertically with imposed velocities, calculated the present day 3-D model of mass anomalies in the mantle. They found good agreement between a geoid computed for this model and the observed one. However, if this model was correct, then assuming a proportionality between density and velocity anomalies, it should predict travel time anomalies of phases such as *S* or *ScS*; regardless of the selection of the coefficient of proportionality, the pattern of the predicted and observed *ScS* residuals was entirely different (Guy Masters, personal communications). The sinking slab model was further developed by Lithgow-Bertelloni and Richards (1998) and we shall be using their slab model represented by a spherical harmonic expansion of density anomalies in 20 layers, spanning the depth range from Moho to CMB; we shall refer to this model as L-B&R.

The popularity of the sinking slab model was enhanced by images of unimpeded penetration of slabs into the lower mantle (Grand et al., 1997; van der Hilst et al., 1997). As a result, this slab-centric conceptual model has been widely accepted in the Earth Science community in the late 1990s. There were, however, serious reasons to doubt its completeness. The foremost was the absence of the intense, large-scale anomalies associated with the low velocity regions: the so-called African and Pacific Superplumes (Dziewonski et al., 1991, 1993) and more recently Large Low Shear Velocity Provinces, LLSVP (Garnero and McNamara, 2008). The other was that many of the slabs seemed to become stagnant in the upper mantle, or to stop at the depth of about 1000 km (Fukao et al., 2001) and that the global spectrum of lateral heterogeneity changed dramatically across the 650 km discontinuity (Gu et al., 2001; Ritsema et al., 2004).

Forte et al. (2002) have modeled mantle convection using as starting point density anomalies inferred from a tomographic study; they observed that the strong degree-2 pattern remained stable over a billion years. Some recent convection models (Bull et al., 2009; Foley and Becker, 2009; Zhong et al., 2007) match the redness of the spectrum in the lower mantle, but they do not capture the very particular distribution of anomalies observed seismically in the lowermost mantle, as well as the inferred stability in time. In a very recent paper, Zhang et al. (2010) present mantle convection calculations for the last 600 Ma which indicate that the Pacific and African superplumes changed their size and position during that time, but end with a thermal structure similar to that seen in the velocity anomalies near the CMB. On the other hand, the fixity of hotspots (Morgan, 1972) and the correlation of their long-wavelength distribution with the LLSVP prompted Davaille (1999) and Jellinek and Manga (2004) to experimentally study the relationship of large upwellings and plumes, of which hotspots may be the surface expression. In particular, Jellinek and Manga (2004) show how plumes originating in the deep mantle can cluster and be stabilized within major upwellings under specific composition, density and viscosity conditions.

Expanding data sets, improved model parameterizations, and more sophisticated modeling procedures have contributed to significant progress in tomographic studies of the mantle. In general, 3D models of shear velocity are better constrained than those of compressional velocity because surface waves, which control the upper mantle structure, are dominated by shear energy. There is, also, remarkable agreement among models obtained by different (not all) research groups (see, e.g. Becker and Boschi, 2002); this is particularly true of the models obtained using combined subsets of data that have good resolving power at all depths within the mantle.

In what follows, we summarize the seismic constraints on the pattern of heterogeneity, discuss their probable relation to the non-hydrostatic moment of inertia tensor and compare them with the predictions of the L-B&R model, separate radial correlation functions for the slow and fast velocity anomalies as well as the distribution of hotspots. We then draw conclusions from these comparisons and outline future directions of research necessary to explain the dynamic behavior of the Earth on a planetary scale. Some of our inferences have been made previously by various authors, who are credited with citations. The synthesis presented here leads us to the suggestion that the giant degree 2 anomaly imposes control on mantle circulation and is very long-lived; this is novel and may lead to new efforts to improve our understanding of the Earth's dynamics.

Even though we focus here on the very large wavelength component of the seismic model, there is copious evidence for the existence of shorter wavelength anomalies, particularly at the bottom of the mantle (for a review, see Lay, 2007). These may or may not be a part of this super-long wavelength dynamics; for example, Hartlep et al. (2003) present a model of convection in which large and small-scale flows can be separated by a gap in the power spectrum.

2. Seismic constraints

Global models of mantle shear velocity anomalies have reached “maturity”. This does not mean that all structures of potential interest have been resolved; for this we do not have sufficient data coverage. Rather, it means that we have resolved, on the global scale, the dominant large-wavelength anomalies, because of the red nature of the power spectrum. In practice, this means that truncation of the spectrum at a range of order numbers at which the spectral power is rapidly decreasing does not alias the long-wavelength image of heterogeneities in the space domain significantly.

By “maturity” we also mean that all global 3D models of S-velocity anomalies obtained with data sets allowing good control over the structure from the top to the bottom of the mantle (i.e. including body wave and overtone data) show very similar features (Gu et al., 2001; Kustowski et al., 2008; Masters et al., 2000; Mégnin and Romanowicz, 2000; Panning and Romanowicz, 2006; Ritsema et al., 1999, which from here on will be referred to as KED). We shall use here S362ANI of KED as representative of this class of models; we refer the reader to Figures 8 and 9 in KED and Figures 4.7, 4.10–15 and 4.17–18 in Kustowski (2007) for direct comparison with other models. Specifically, the longest wavelength structure is nearly identical between the cited models. The advantage of global models is that they and their properties, such as power spectra, reflect the behavior of the system as a whole, rather than selected regions such as velocity anomalies near subduction zones; a spectrum of velocity anomalies also takes into account the vast areas away from subduction zones.

Figure 1 shows the r.m.s. amplitude of the isotropic part of model S362ANI compared to S362D1 (Gu et al., 2001) as a function of depth, power spectrum of the isotropic part of model S362ANI as a function of depth and harmonic degree, and horizontal slices through the model at five different depths. The intervals in which the power is high are seen at 100 km depth, 600 km depth and 2800 km depth; they are separated by regions of low amplitude, white spectrum. The near surface features are well understood: they are dominated by surface tectonics with very slow mid-ocean ridges, faster old oceans and very fast continental cratons and platforms. The maximum spectral power is at degree 5 and begins to decrease rapidly after degree 6. The r.m.s. of the model decreases threefold between 200 and 250 km depth range; this may be contrasted with a smoothly changing r.m.s. curve for an earlier model, S362D1 (Gu et al., 2001). The additional data and less radial smoothing explain the higher radial resolution of KED. This depth range contains both lithosphere and asthenosphere, yet has a unique signature in terms of the level of heterogeneity; we propose a new term “heterosphere” to indicate the