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GR Focus Review

# The long-wavelength mantle structure and dynamics and implications for large-scale tectonics and volcanism in the Phanerozoic

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ABSTRACT

The Earth's lower mantle structure, as revealed by seismic tomography studies, is best characterized by two large low seismic velocity provinces (i.e., LLSVP) beneath Africa and Pacific and their surrounding, circum-Pacific seismically fast anomalies. This mantle structure, sometimes called degree-2 structure, has been the most robust feature of all the seismic tomography models for the last 30 years. The dominantly degree-2 mantle structure explains the long-wavelength geoid anomalies including the geoid highs over Africa and Pacific. The LLSVPs are suggested to be the source regions for hotspot volcanism and large igneous province (LIP) events that are compositionally distinct from that for mid-ocean ridge basalts, thus holding the key to understanding mantle geochemistry. The degree-2 structure and LLSVPs have also been used as a reference frame to reconstruct paleogeography and true polar wander (TPW) history of the Earth for the Phanerozoic (i.e., for the last 500 Ma). This paper presents a comprehensive review of studies on the degree-2 mantle structure. While seismic tomography inversion and models are discussed, the main focus of the paper is on the dynamics of long-wavelength mantle convection, plate tectonics and large-scale volcanism. Important topics in the paper include: 1) the long-wavelength seismic structure for the present-day mantle, its possible relation to the long-wavelength geoid anomalies, volcanism and magmatism, and plate motion history, 2) the time evolution of the long-wavelength mantle structure in the Phanerozoic and its relations to Pangea assembly and breakup and history of volcanism/LIP events, and 3) the physics that controls the dynamics of long-wavelength mantle convection. The paper also provides a critical assessment on the validity of the hypothesis of spatially stationary Africa and Pacific LLSVPs since the early Paleozoic and its implications.

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## 1. Introduction

The first global seismic tomography model of the Earth's mantle was published about 30 years ago (Dziewonski, 1984; Woodhouse and Dziewonski, 1984) and it has profoundly shaped our understanding of the Earth's dynamics. The seismic model demonstrated that the Earth's lower mantle is characterized by two major seismically slow anomalies below Africa and Pacific that are surrounded by circum-Pacific seismically fast anomalies, i.e., a spherical harmonic degree-2 structure. This seismic imaging of the mantle has made it possible to integrate and understand a variety of observations including plate tectonics, long-wavelength gravity and topography anomalies, true polar wander, hotspot volcanism, and geochemical anomalies. It has also posed challenging questions to geodynamics regarding the origin and dynamics of such long-wavelength mantle structure. While the seismic structure represents a snapshot of the present-day Earth's mantle, recent studies have also started to explore time-evolution of mantle structure in Earth's geological history.

This paper presents a review of studies on long-wavelength mantle structure and its dynamics. This paper intends to address the following questions. What are the general characteristics of present-day's mantle structure as seen from seismic studies? What is the relationship between the long-wavelength, degree-2 mantle structure and hotspot volcanism and large igneous province events (LIP)? How is the long-wavelength mantle structure related to the positive gravity/geoid and residual topographic anomalies in the African and Pacific regions? What are the dynamic origins of and controls on the long-wavelength mantle structure? What are the possible scenarios of time evolution of mantle structure in the geological history? How can the time evolution of mantle structure be constructed and constrained? The paper is divided into three main sections. The first section is on the present-day mantle structure as seen in seismic tomography studies and its implications for other geophysical and geological observations and for geodynamics. The second section is on convection models of long-wavelength mantle structure. The third section discusses possible scenarios of time-evolution of long-wavelength mantle structure in recent geological history (i.e., since the early Paleozoic for the last 500 Million years) and its implications for the geological observations.

## 2. Long-wavelength Structure and Dynamics of the Present-day Earth's Mantle

### 2.1. Seismic observations of the long-wavelength mantle structure

Dziewonski (1984) and Woodhouse and Dziewonski (1984), published about 30 years ago, are the two seminal papers on the three-dimensional (3-D) structures of the Earth's mantle. In Dziewonski (1984), P-wave travel time residual data from the International Seismological Center (ISC) bulletins were used to construct a 3-D P-wave model for the lower mantle. In Woodhouse and Dziewonski (1984), surface wave seismograms from International Deployment of Accelerometers (IDA) and Global Digital Seismograph Network (GDSN) were used in waveform modeling to construct a 3-D S-wave model for the upper mantle. These models had relatively low resolution due to the limited data available at the time. The upper mantle S-wave model was represented by spherical harmonic functions up to degree and order 8 in the azimuthal directions (i.e., a resolution of ~5000 km) and by cubic polynomials in depth (i.e., a resolution of ~200 km) (Woodhouse and Dziewonski, 1984). The P-wave model for the lower mantle had up to degree and order 6 in spherical harmonics (i.e., a horizontal resolution of ~7000 km) and 4-th order Legendre functions in the radial direction (i.e., ~500 km resolution) (Dziewonski, 1984). Despite the coarse resolution, the upper mantle S-wave model showed clearly signatures of surface tectonic provinces: seismically fast anomalies in continental shields and slow anomalies beneath the mid-ocean ridges, which are consistent with early studies on regional scales (e.g., Brune and Dorman, 1963). Distinct features of the P-wave model for the lower mantle include the circum-Pacific fast speed anomalies from a depth of 1000 km to the core-mantle boundary (CMB), and slow speed anomalies below Africa and Pacific near the CMB (i.e., a spherical harmonic degree-2 structure) (Dziewonski, 1984). Although the upper mantle S-wave and lower mantle P-wave models employed entirely different techniques and data, the upper mantle and lower mantle structures showed some continuities from the upper to lower mantles (Woodhouse and Dziewonski, 1984).

Tanimoto (1990) constructed a 3-D global S-wave model for the whole mantle by using long-period body waves and surface waves, and the model was represented by 11 layers in the radial direction and spherical harmonics up to degree and order 6. The general characteristics of mantle structure in Tanimoto's model were consistent with those from Woodhouse and Dziewonski (1984) and Dziewonski (1984), for example, the association of mantle structure with surface tectonic settings. However, Tanimoto (1990) highlighted the predominance of the degree-2 structure throughout the mantle, although the power of seismic anomalies was relatively small in the mid-mantle, compared with that at shallow depths and near the CMB. The degree-2 lower mantle structure in the S-wave model in Tanimoto (1990) was similar to that revealed in the P-wave model in Dziewonski (1984). The degree-2 structure was also found to exist in the transition zone in a study of Earth's free oscillations and overtones (Masters et al., 1982). Remarkably, such a degree-2 mantle structure and its dominance in the mantle have been one of the most robust features in all the subsequent seismic tomography models that have employed larger datasets, higher resolutions and more advanced techniques (Su et al., 1994; Li and Romanowicz, 1996; Grand et al., 1997; Su and Dziewonski, 1997; van der Hilst et al., 1997; Ritsema et al., 1999; Masters et al., 2000; Grand, 2002; Montelli et al., 2004; Zhao, 2004; Panning and Romanowicz, 2006; Houser et al., 2008; Ritsema et al., 2011). This dominantly degree-2 mantle structure and its depth-dependent spectra are shown in Fig. 1a-c from a recent high-resolution S-wave model (Ritsema et al., 2011).

Although this paper focuses on the long-wavelength (e.g., degree-2) mantle structure, it is helpful to discuss briefly some general characteristics of the seismic models. More thorough reviews can be found in Thurber and Ritsema (2007), Romanowicz (2003) and Garnero (2000). Three different inversion approaches have been used, and they are to invert separately for P-wave and S-wave speed models (e.g., Dziewonski, 1984; Tanimoto, 1990) and jointly for S-wave, P-wave or bulk-sound speed models (e.g., Su and Dziewonski, 1997; Masters et al., 2000; Houser et al., 2008). These models have been parameterized using either mathematical basis functions (e.g., spherical harmonic functions or polynomials) (e.g., Dziewonski, 1984) or cells (e.g., Grand, 2002). The most recent high resolution S-wave model used spherical harmonics up to degree and order 40 (~1000 km horizontal resolution) (Ritsema et al., 2011) or cells with horizontal spacing of ~300 km (e.g., Grand, 2002; Houser et al., 2008), and had vertical resolution of ~150 km. Some recent P-wave models were parameterized in cells with horizontal spacing as small as ~100 km (Fukao and Obayashi, 2013).

The P-wave models, similar to Dziewonski et al. (1977), Dziewonski (1984), were constructed using the ISC and also hand-picked travel time data for direct arrivals, reflected phases and differential phases (e.g., P and PP). Due to the large number of data (e.g., ~10 million travel times in Fukao and Obayashi (2013)), the P-wave models tend to have high spatial resolution in well-sampled regions of the mantle, such as subduction zones, thus providing insights into associated physical processes such as subduction dynamics (e.g., Zhou, 1996; van der Hilst et al., 1997; Zhao, 2004). For example, some P-wave models suggest that subducted slabs might have stalled at least temporarily in the upper mantle or around ~1000 km depths (Fukao et al., 2001; Fukao and Obayashi, 2013), although some other slabs extend to the CMB (e.g., van der Hilst et al., 1997; Grand, 2002).