Earth and Planetary Science Letters 450 (2016) 108–119

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

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Electrical conductivity as a constraint on lower mantle thermo-chemical structure

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ARTICLE INFO

Article history:
Received 21 December 2015
Received in revised form 30 May 2016
Accepted 17 June 2016
Available online 1 July 2016
Editor: J. Brodholt

Keywords:
Earth's mantle
electrical conductivity
mantle composition
mantle structure
eletromagnetic C-responses

ABSTRACT

Electrical conductivity of the Earth's mantle depends on both temperature and compositional parameters. Radial and lateral variations in conductivity are thus potentially a powerful means to investigate its thermo-chemical structure. Here, we use available electrical conductivity data for the major lower mantle minerals, bridgmanite and ferropericlase, to calculate 3D maps of lower mantle electrical conductivity for two possible models: a purely thermal model, and a thermo-chemical model. Both models derive from probabilistic seismic tomography, and the thermo-chemical model includes, in addition to temperature anomalies, variations in volume fraction of bridgmanite and iron content. The electrical conductivity maps predicted by these two models are clearly different. Compared to the purely thermal model, the thermo-chemical model leads to higher electrical conductivity, by about a factor 2.5, and stronger lateral anomalies. In the lowermost mantle (2000–2891 km) the thermo-chemical model results in a belt of high conductivity around the equator, whose maximum value reaches ∼120% of the laterally-averaged value and is located in the low shear-wave velocity provinces imaged in tomographic models. Based on our electrical conductivity maps, we computed electromagnetic response functions (C-responses) and found, again, strong differences between the C-responses for purely thermal and thermo-chemical models. At periods of 1 year and longer, C-responses based on thermal and thermo-chemical models are easily distinguishable. Furthermore, C-responses for thermo-chemical model vary geographically. Our results therefore show that long-period (1 year and more) variations of the magnetic field may provide key insights on the nature and structure of the deep mantle.

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1. Introduction

Global models of seismic tomography are converging towards a coherent picture of the mantle in the sense that different datasets and methods agree on large-scale structures (*e.g.* Ritsema et al., 2011). In the lowermost mantle (2400–2891 km), the seismic structure is dominated by two large low shear-wave velocity provinces (LLSVPs) beneath the Pacific and Africa, where shear-wave velocity drops by a few percent compared to its horizontally averaged value. The exact nature of LLSVPs is still unclear, but several hints suggest that they result from both thermal and chemical anomalies (*e.g.*, van der Hilst and Kárason, 1999; Trampert et al., 2004). Alternatively, a thermally dominated origin, implying the presence of post-perovskite outside LLSVPs, has also been advocated (*e.g.* Davies et al., 2012). Chemical anomalies, if present, may result either from early differentiation of the Earth's mantle, or from the recycling of oceanic crust (MORB). Calculations based on mineral physics database suggest that LLSVPs are better explained by material enriched in iron and silicate than by recycled oceanic crust, which would require temperatures in excess of 1500 K relative to average temperature at these depths (Deschamps et al., 2012). This supports a primordial origin related to early differentiation of the mantle. Following the "Basal mélange" (BAM) hypothesis (Tackley, 2012), these primordial reservoirs may however be regularly re-fed with small fractions of MORB. A major difficulty when inferring the thermo-chemical structure from seismic models, is that temperature and composition strongly trade off with one another. Efforts have been made to obtain independent constraints on the density structure from seismic normal modes (Ishii and Tromp, 1999; Trampert et al., 2004; Mosca et al., 2012), allowing the determination of large scale 3D thermo-chemical models of the mantle.

Unlike density and seismic velocities, electric conductivities of mantle minerals increase with temperature (*e.g.* Poirier, 1991). Earth's mantle electrical conductivity further depends on compositional parameters, in particular mineralogical composition and

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http://dx.doi.org/10.1016/j.epsl.2016.06.027
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iron content. Radial profiles and 3D maps of electrical conductivity in the mantle may thus provide important information on its thermo-chemical structure (*e.g.* Khan et al., 2015). Such variations can be recovered from inversions of magnetic field variations recorded at geomagnetic observatories and by satellites (for a detailed treatment, see Kuvshinov and Semenov, 2012). Variations with periods from a few days to 1 year have been used to build 1D radial models of conductivity (Olsen, 1999; Kuvshinov and Olsen, 2006; Velímský, 2010; Civet et al., 2015; Puethe et al., 2015) that show an increase by 2 to 3 orders of magnitude between the top of the mantle and the core-mantle boundary. Regional and global tomographic models of mantle electrical conductivity have also been obtained (Kelbert et al., 2009; Semenov and Kuvshinov, 2012; Koyama et al., 2014). However, the 3D conductivity structures observed in these models strongly differ both in amplitude and distribution, and are limited to depths of 1600 km.

The direct approach, which consists of calculating synthetic electrical conductivity models from observed or *a priori* thermo-chemical models, provides valuable information, if these models can be tested against observations. For instance, assuming a mantle geotherm and mineralogical model, Xu et al. (2000) computed a radial conductivity profile for the entire mantle that agrees with the radial conductivity model beneath Europe obtained by Olsen (1999). More recently, Deschamps (2015) reconstructed 3D maps of conductivity from the global 3D thermo-chemical models of Trampert et al. (2004). A natural extension of the direct approach is the inversion of magnetic field data in combination with other observables for thermo-chemical models using Monte-Carlo algorithms (*e.g.* Khan et al., 2006; Verhoeven et al., 2009). This approach allowed recovering the radial thermo-chemical structure of the mantle at global (Verhoeven et al., 2009) and continental (Khan et al., 2006) scales. Here, using a direct approach, we calculate new 3D maps of electrical conductivity for both purely thermal and thermo-chemical models of the lower mantle, and electromagnetic response functions (C-responses) associated with these maps. Our calculations show that anomalies in electrical conductivity predicted by thermo-chemical models are stronger than those predicted using purely thermal models by a factor 2.5. At periods larger than one year, C-responses for purely thermal and thermo-chemical models are different, suggesting that long-period magnetic field variations can be used to discriminate between purely thermal and thermo-chemical models of lower mantle.

2. Modeling lower mantle electrical conductivity

At lower mantle temperature and pressure, three transport mechanisms are thought to contribute to electrical conductivity (*e.g.* Yoshino et al., 2009): ionic, small polaron, and proton conduction. Each mechanism involves a different charge carrier. Ionic conduction is related to the migration of Mg-site vacancies. Small polaron conduction and proton conduction involve the hopping of an electron from Fe^{3+} to Fe^{2+} ions, and the hopping of protons amongst point defects, respectively. In all three cases, however, the charge migration is a thermally activated diffusion process that follows a Boltzmann distribution, and can be described by

$$\sigma = \sigma_0 T^m \exp\left(-\frac{E_a + PV_a}{kT}\right), \tag{1}$$

where P is pressure, T is temperature, and $k = 8.617 \times 10^{-5}$ eV/m Boltzmann's constant. The exponent m appears in polaron models only (*e.g.* Goddat et al., 1999). The values of the pre-exponential factor σ_0, and of the activation energy and activation volume, E_a and V_a, are different for each of the three mechanisms, and the electrical conductivity of the aggregate may be obtained by summing these three contributions. In the lower mantle, however, several arguments indicate that small polaron conduction is the dominant mechanism, and that other mechanisms may be neglected to a good approximation. First, as pointed by Goddat et al. (1999), the activation energies of lower mantle minerals for the small polaron mechanism are small, typically a few tenths of eV, whereas for ionic conduction $E_a > 1$ eV, implying (Eq. (1)) that ionic conductivity is much smaller than small polaron. Second, because it strongly depends on the water content (Yoshino et al., 2009), proton conduction may be much less efficient in the lower mantle than in the upper mantle, since the former is thought to be dry. In this context, Xu and McCammon (2002) identified two possible mechanisms controlling the electrical conductivity of bridgmanite: ionic and small polaron. However, the conductivity obtained by summing the contributions from these two mechanisms can be parameterized with a single law (Vacher and Verhoeven, 2007). For ferropericlase, Dobson and Brodholt (2000) identified only one regime for temperatures larger than 1000 K. Finally, Vacher and Verhoeven (2007) showed that the changes in electrical conductivity due to variations in the iron content, which may be of particular importance for the Earth's lower mantle, are much stronger than the changes induced by accounting for mechanisms with different temperature dependence.

2.1. Model and data sets

We estimated the electrical conductivity of the lower mantle aggregate following the approach underlined in Vacher and Verhoeven (2007), with some modifications. This approach considers variations due to pressure, temperature, and composition. Compositional changes include two sources: variations in mineralogical composition of the aggregate, and variations in iron fraction in each mineral composing the aggregate.

We considered a lower mantle aggregate consisting of two minerals, bridgmanite, (Mg, Fe)SiO_3, and ferropericlase, (Mg, Fe)O. For each mineral i, the individual conductivity σ_i is given by

$$\sigma_i = \sigma_0^i \left(\frac{x_{\mathrm{Fe}}^i}{x_{ref}^i}\right)^{\alpha_i} \exp\left[-\frac{E_a^i + \beta_i\left(x_{\mathrm{Fe}}^i - x_{ref}^i\right) + PV_a^i}{kT}\right], \tag{2}$$

where T and P are temperature and pressure, and x_{Fe}^i, σ_0^i, and E_a^i iron fraction, pre-exponential factor, and activation energy for mineral i, respectively. The fraction of iron influences both the pre-exponential factor and the activation energy, and its effects are controlled by two parameters, α_i and β_i. Vacher and Verhoeven (2007) assume that the fractions of iron in bridgmanite and ferropericlase, x_{Fe}^{bm} and x_{Fe}^{fp}, are equal. Here, we control these fractions by fixing the iron partitioning between bridgmanite and ferropericlase according to

$$K_{\mathrm{Fe}} = \frac{x_{\mathrm{Fe}}^{bm}/\left(1 - x_{\mathrm{Fe}}^{bm}\right)}{x_{\mathrm{Fe}}^{fp}/\left(1 - x_{\mathrm{Fe}}^{fp}\right)}. \tag{3}$$

Given the volume fraction of bridgmanite in the assemblage, X_{bm}, and global iron fraction in the aggregate,

$$X_{\mathrm{Fe}} = X_{bm} x_{\mathrm{Fe}}^{bm} + (1 - X_{bm})\, x_{\mathrm{Fe}}^{fp}, \tag{4}$$

the individual iron fractions x_{Fe}^{bm} and x_{Fe}^{fp} can be calculated by solving Eqs. (3) and (4). Eq. (4) indicates that x_{Fe}^{bm} increases and x_{Fe}^{fp} decreases with increasing iron partitioning. Solving Eqs. (3) and (4) further shows that for $K_{\mathrm{Fe}} < 1.0$ both x_{Fe}^{bm} and x_{Fe}^{fp} increase with increasing fraction of bridgmanite, whereas for $K_{\mathrm{Fe}} > 1.0$ both decrease (Supplementary Fig. S1).

To compute the bulk conductivity of the aggregate, we need to define an appropriate averaging scheme for a multiphase system.

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