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Estimating the electrical conductivity of the melt phase of a partially molten asthenosphere from seafloor magnetotelluric sounding data

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ABSTRACT

Seafloor magnetotelluric soundings provide models of electrical conductivity distributions in the Earth's oceanic mantle. By inverting the sounding results, a high-conductivity (typically 0.01–0.1 S/m) layer is often obtained in the oceanic upper mantle, which is referred to as the electrical asthenosphere. The obtained high conductivity is then interpreted in terms of the amount of additional conduction that accounts for the conductivity value based on a physical model of the asthenosphere. There are two major candidates that are considered as the cause of the asthenosphere: the effect of water and partial melting. In this paper, we consider the partial melting hypothesis. We propose a method to estimate the electrical conductivity of the melt phase that is responsible for high conductivity by assuming the melt fraction distribution in the asthenosphere. We applied this method to one-dimensional conductivity profiles recently obtained from three regions of different seafloor age, and the results indicate that the proposed approach, combined with other approaches such as seismology and mineral physics, will provide useful information in testing a partial melting hypothesis for the cause of the asthenosphere.

1. Introduction

The cause of the asthenosphere's weakness is still a matter of debate. Although the effect of water in mantle minerals is regarded as a possible cause (e.g., Hirth and Kohlstedt, 1996; Karato, 2012, the classical idea for the cause of the asthenosphere being partially molten is also considered as one of the most plausible candidates (Holtzman and Kohlstedt, 2007). The asthenosphere is characterized as a layer of low velocity and low Q in terms of seismic wave propagations and as a layer of high electrical conductivity (Karato, 2012). A combination of different geophysical methods such as seismic and electromagnetic methods is essential to separate the effects from different causes. We need to seek a model for the origin of the asthenosphere that satisfies geophysical observations and mineral physics in as consistent a way as possible. This paper aims to show an example of such an approach.

The presence of partial melt was first thought to be a plausible candidate for the cause of the seismic (e.g., Anderson and Sammis, 1970) and electrical (e.g., Shankland and Waff, 1977; Honkura, 1975) properties of the oceanic asthenosphere soon after the establishment of the theory of plate tectonics. However this idea was considered unlikely, because an unrealistically large fraction of silicate melt is required to account for the observed physical properties. For example, Shankland and Waff (1977) showed the melt fraction necessary to account for the asthenospheric high conductivity to be greater than 3–5%, which is inconsistent with the mineral physics requirement (e.g., Langmuir et al., 1992). Meanwhile Karato (1990) pointed out the importance of the effect of water (hydrogen) on the high electrical conductivity of olivine, as well as its effect of weakening the material. Later, the effect of water was also shown to account for the low velocity and high attenuation of the oceanic asthenosphere (Karato and Jung, 1998) and the decrease in mantle viscosity (Mei and Kohlstedt, 2000).

Seafloor electromagnetic (EM) soundings have shown that the oceanic asthenosphere can be characterized by a high conductivity of approximately 0.01–0.1 S/m (e.g., Filloux, 1980). Evans et al. (2005) showed that the electrical conductivity of the uppermost asthenosphere below the East Pacific Rise may be anisotropic, higher by one order of magnitude in the direction parallel to the plate motion than that in the perpendicular direction. They interpreted this anisotropic feature to be caused by a wet a-axis aligned olivine to the plate motion direction. A recent observation (Naif et al., 2013) off Nikaragua subduction zone showed a similar anisotropic feature. Considering the depth variations of the electrical anisotropy in these two recent results, Naif et al. (2013) suggested that melt in aligned tubes in the direction of plate motion distributes in the uppermost asthenosphere of relatively young oceanic mantle.

One recent result of seafloor magnetotelluric (MT) observations (Baba et al., 2010) from a relatively young seafloor (the Philippine Sea) and an old seafloor (the northwestern Pacific Ocean) suggested that the mean depth to the electrical asthenosphere is

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apparently dependent on the age of the plate. Based on the resulting one-dimensional (1-D) electrical conductivity profiles, Baba et al. (2010) estimated the thermal structure or water content, assuming either of the two parameters, in the oceanic asthenosphere with reference to experimentally determined values of the electrical conductivity of olivine with controlled water contents at a high temperature and pressure. It was shown that obtained conductivity profiles can be explained by the effect of water (hydrogen) with an assumption of age-dependent temperature profile based on the half-space cooling model. They also showed that their estimation of the thermal structure under the assumption of dry conditions or realistic water content may exceed the solidus at a certain depth range for the asthenospheric mantle beneath the Philippine Sea, suggesting that a silicate partial melt may exist. On the other hand, the estimated temperature is shown to be significantly lower than the solidus in the asthenosphere beneath the northwestern Pacific Ocean even for a highly wet condition, implying that partial melting is unlikely to occur in this case.

However, the possible presence of carbonatite melt at lower temperatures in the oceanic upper mantle has been recently recognized (e.g., Dasgupta and Hirschmann, 2006, 2007). The discovery of "petit-spot" volcanoes (Hirano et al., 2006) proved the occurrence of melting beneath the old Pacific plate. Recent seismological evidence (Kawakatsu et al., 2009) also indicates that the observation is more compatible with a partially molten asthenosphere than with a hydrous sub-solidus asthenosphere. Gaillard et al. (2008) measured the electrical conductivity of a carbonatite melt to be higher than the measured values of silicate melts by several orders of magnitude. Hirschmann (2010) proposed a model of melt distribution in the oceanic upper mantle to account for the seismic low-velocity layer. According to this work, the H_2O and CO_2 contents in silicate melt are supposed to be continuously variable as a function of the degree of partial melt. A combination of recent results of mineral physics (Gaillard et al., 2008; Hirschmann, 2010) suggests that even a small amount of melt would be able to explain the asthenospheric high conductivity (Yoshino et al., 2010).

Earlier studies estimated the melt fraction that is responsible for the observed conductivity profiles, by assuming the electrical conductivity of the silicate melt at a certain H_2O content, temperature and pressure (Shankland and Waff, 1977; Park and Ducea, 2003). However, such an approach is not appropriate when the CO_2 content has to be taken into consideration, as the melt conductivity in the oceanic upper mantle depends also on the amount of CO_2. The ratio of H_2O and CO_2 and their amounts are variable in accordance with the degree of partial melting and degree of oxidization in the asthenosphere (Dasgupta et al., 2013), and therefore the melt conductivity is supposed to be similarly variable. The conductivity of carbonatite melts depends on the CO_2 content (Yoshino et al., 2012), as the conductivity of hydrous silicate melts depends greatly on the H_2O content (Ni et al., 2011). Therefore, in this paper, we attempt another approach to translating electrical conductivity profiles to profiles of electrical conductivity of melt that is responsible for the high conductivity anomaly, by assuming the melt fraction. It will be shown that such an interpretation combined with other approaches is useful in constraining the physical state of the upper mantle.

2. Method

We assume that the partially molten upper mantle consists of two phases, fluid and solid, and denote their volume fraction as x and 1-x, respectively. The Hashin–Shtrikman (H–S) model (Hashin and Shtrikman, 1962) is used for an evaluation of the physical properties of such a two-phase system, in which the medium consists of spheres occupied by either of the phases (Fig. 1). There are two kinds of H–S model, providing the upper and lower bounds from the model. When modeling a partially molten mantle rock, the small dihedral angle between the mantle minerals and melts (e.g., Yoshino et al., 2009b) permits us to use the H–S upper-bound model or the H–S+ model where the solid and liquid phases are assumed to occupy the sphere and the rest of the space, respectively. This model allows the conducting fluid phase to form a well-connected network even for small fractions. The bulk electrical conductivity is given by,

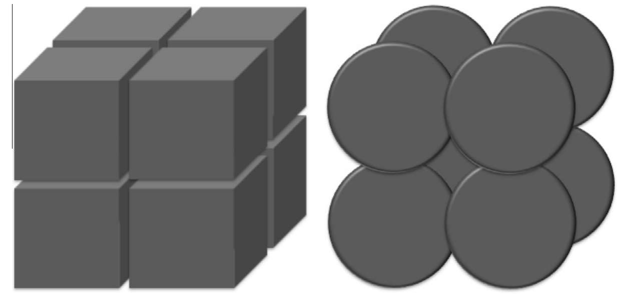

Fig. 1. Two models of two-phase systems. One phase is expressed by spheres in the Hashin–Shtrikman (H–S) model (right) and by cubes in the cube model (left). In each model, the bulk conductivity becomes high when the sphere or cube is occupied by the solid (resistive) phase. They are called the H–S+ and cube+ models, respectively. The opposite case in which the sphere or cube is occupied by the fluid (conductive) phase is called the H–S- or Cube- model, respectively.

$$\sigma_{HS}^{+} = \sigma_f + \frac{1-x}{\left(\frac{x}{3\sigma_f} - \frac{1}{\delta\sigma}\right)} \tag{1}$$

where σ_f and σ_s are the electrical conductivity of the fluid and solid phases, respectively, and $\delta\sigma = \sigma_f - \sigma_s$.

The bulk conductivity at a given depth range in the mantle can be estimated by an electromagnetic sounding. Here we assume the observed value, σ_{obs}, is related to the properties (σ_f, σ_s, and x) of a partially molten system by Eq. (1). It is obviously impossible to determine all three properties by simply fitting the theoretical estimation to the observation. In most studies, therefore, the melt fraction was estimated from this equation by assuming σ_f and σ_s (Pommier and Le-Trong, 2011). However, volatile (H_2O and CO_2) contents in the melt phase strongly affect the bulk conductivity of partially molten material, which can vary by several orders of magnitude (e.g., Yoshino et al., 2012). Therefore, such an approach is not appropriate.

Here we consider a different approach. Assuming the melt fraction x is independently estimated and the bulk conductivity in Eq. (1) is obtained by observation and denoted as σ_{obs}, we derive an equation for the electrical conductivity of melt as,

$$\sigma_f = \frac{1}{4x}\left[\{(3-2x)\sigma_s + (3-x)\sigma_{obs}\} + \sqrt{\{(3-2x)\sigma_s + (3-x)\sigma_{obs}\}^2 + 8x^2\sigma_s\sigma_{obs}}\right] \tag{2}$$

Note that the conductivity of the solid phase has also to be assumed to estimate the fluid phase conductivity by using this equation. However, this assumption does not greatly affect the estimation because solid phase conductivity is normally much lower than that of the fluid phase and is often ignorable.

Another simple model of a partially molten material is the so-called cube model (Waff, 1974; ten Grotenhuis et al., 2005), in which one phase occupies the cubes and the other phase fills the rest of the space (Fig. 1). In order to consider the high conductivity of the asthenosphere, we take a case in which the solid phase occupies the cubes so that the fluid phase forms a well-connected network (hereafter called the cube+ model). Denoting the grain size