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# An upper bound on the electrical conductivity of hydrated oceanic mantle at the onset of dehydration melting

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ABSTRACT

Electrical conductivity soundings provide important constraints on the thermal and hydration state of the mantle. Recent seafloor magnetotelluric surveys have imaged the electrical conductivity structure of the oceanic upper mantle over a variety of plate ages. All regions show high conductivity (0.02 to 0.2 S/m) at 50 to 150 km depths that cannot be explained with a sub-solidus dry mantle regime without unrealistic temperature gradients. Instead, the conductivity observations require either a small amount of water stored in nominally anhydrous minerals or the presence of interconnected partial melts. This ambiguity leads to dramatically different interpretations on the origin of the asthenosphere. Here, I apply the damp peridotite solidus together with plate cooling models to determine the amount of $H_2O$ needed to induce dehydration melting as a function of depth and plate age. Then, I use the temperature and water content estimates to calculate the electrical conductivity of the oceanic mantle with a two-phase mixture of olivine and pyroxene from several competing empirical conductivity models. This represents the maximum potential conductivity of sub-solidus oceanic mantle at the limit of hydration. The results show that partial melt is required to explain the subset of the high conductivity observations beneath young seafloor, irrespective of which empirical model is applied. In contrast, the end-member empirical models predict either nearly dry ($<20$ wt ppm $H_2O$) or slightly damp ($<200$ wt ppm $H_2O$) asthenosphere for observations of mature seafloor. Since the former estimate is too dry compared with geochemical constraints from mid-ocean ridge basalts, this suggests the effect of water on mantle conductivity is less pronounced than currently predicted by the conductive end-member empirical model.

## 1. Introduction

The upper mantle is composed of rigid lithospheric plates that slide on ductile asthenosphere. The depth interval over which the rheological transition from rigid to ductile behavior occurs is known as the lithosphere–asthenosphere boundary (LAB). The mechanism responsible for the viscosity reduction at the LAB is often attributed to temperature, mineral hydration, or partial melting (Anderson and Sammis, 1970; Karato and Jung, 1998; Stixrude and Lithgow-Bertelloni, 2005; Faul and Jackson, 2005). Geophysical observations sensitive to all three mechanisms provide constraints on the origin of the LAB and the asthenosphere.

Magnetotelluric (MT) and seismic studies of oceanic plates both show contrasting material properties above and below the LAB. The lithosphere often exhibits high seismic velocity and low electrical conductivity, while the asthenosphere exhibits low seismic velocity, strong seismic anisotropy, and high electrical conductivity (Kawakatsu and Utada, 2017). Seismic studies have identified a sharp velocity reduction below oceanic plates at depths thought to coincide with the LAB. Regions characterized by a sharp LAB typically experience a 5–10% shear wave velocity reduction over a depth interval less than 30 km thick, requiring unrealistic temperature gradients that are inconsistent with a thermal origin (Fischer et al., 2010). Although a thermal origin alone is less likely, debate persists over which mechanism, partial melting or mineral hydration, best explains the geophysical observations (Beghein et al., 2014).

Here, I focus on the electrical conductivity signature of the LAB beneath oceanic plates. The conductivity structure of the oceanic upper mantle has been observed by a relatively limited number of independent marine MT studies, each located in a unique tectonic setting. Since mantle conductivity varies as a function of temperature, water content, and partial melt fraction, MT data provide unique constraints on the origin of the asthenosphere (Yoshino and Katsura, 2013; Kawakatsu and Utada, 2017).

Most studies consider olivine as a proxy for the electrical properties of the bulk upper mantle since it is the primary mineral phase in peridotite (∼60%) and laboratory measurements on dry

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olivine, pyroxene, and garnet show similar conductivity behavior (Xu and Shankland, 1999). Generally, the asthenosphere is $10^{-2}$ to $10^{-1}$ S/m. As is the case with seismic observations, this range of asthenospheric conductivity values also requires unrealistic temperatures for dry mantle olivine. Several independent laboratory studies have reported distinct empirical models for the electrical conductivity of hydrous olivine (Gardés et al., 2014). The model discrepancies have led to conflicting interpretations of either hydration or partial melting as the cause of the electrical asthenosphere (Wang et al., 2006; Yoshino et al., 2006).

A global approach that assumes the mantle conductivity is controlled by olivine, however, masks the heterogeneity among MT studies, ignores the role of pyroxenes, and precludes considering the thermodynamic stability of a multiphase sub-solidus mantle in a regional context. Furthermore, due to the prominent effect of $CO_2$ on the solidus, recent studies suggest sub-solidus LAB is unable to explain conductivity observations for hydrous carbonated source mantle regardless of plate age, whereby incipient melts may be a ubiquitous feature of the LAB (e.g., Katsura et al., 2017). Since the gravitationally stability of incipient volatile-rich melts remains an open question, there is an inherent non-uniqueness when inferring hydration or partial melt from MT observations. Here, I demonstrate that when temperature and hydration are parameterized in a thermodynamically consistent framework and the mantle is treated as a two-phase mixture of olivine and pyroxene, none of the existing empirical conductivity models for hydrated mantle minerals can explain the high conductivity signature at LAB depths in MT observations made on young seafloor. Therefore, partial melting is the only viable mechanism to explain highly conductive LAB. By ignoring the role of $CO_2$, the present study clarifies when hydration is not a viable mechanism to account for the observed mantle conductivity and, in such cases, resolves the previously noted issue of non-uniqueness.

## 2. Mantle conductivity

### 2.1. Conduction in nominally anhydrous minerals

Peridotite rock is the primary constituent of the upper mantle and is made up of the nominally anhydrous minerals (NAMs) olivine, pyroxene, and garnet. In the absence of well-connected conductive phases such as metal oxides or fluids/melts, the electrical conductivity signature of the upper mantle is controlled by the concentration and diffusion of point defects through the crystal lattice structure of silicate minerals, both of which are thermally-activated processes (Yoshino and Katsura, 2013). Therefore, the conductivity behavior of mantle minerals can be described by empirical fitting of experimental conductivity data to an Arrhenius relation.

The dominant conduction mechanism for dry olivine is a combination of small polaron hopping (charge exchange between ferrous and ferric iron) and diffusion of magnesium vacancies (Schock et al., 1989)

$$\sigma_{dry} = A_{vac} \exp\left(\frac{-\Delta H_{vac}}{RT}\right) + A_{pol} \exp\left(\frac{-\Delta H_{pol}}{RT}\right) \tag{1}$$

where $\sigma_{dry}$ is the anhydrous olivine conductivity, $A_{vac}$ and $A_{pol}$ are preexponential factors, $\Delta H_{vac}$ and $\Delta H_{pol}$ are activation enthalpies, $R$ is the gas constant, and $T$ is absolute temperature. In addition to temperature, mantle conductivity varies as a function of oxygen fugacity, iron content, and (to a lesser extent) pressure due to changes in defect concentration. For a quartz-fayalite-magnetite oxygen fugacity buffer representative of upper mantle conditions, dry olivine conductivity increases from approximately $10^{-6}$ S/m at 700 °C to $10^{-2}$ S/m at 1400 °C (Constable, 2006).

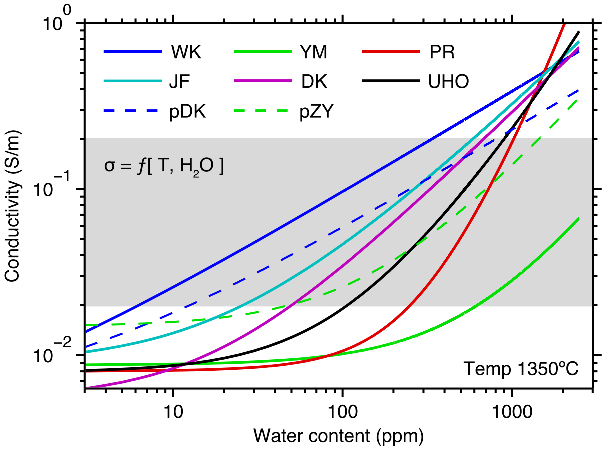

**Fig. 1.** Comparison of six hydrous olivine and two hydrous pyroxene conductivity laws. Solid and dashed lines show predicted electrical conductivity of olivine and pyroxene as a function of water concentration at 1350 °C, respectively. Predictions vary by up to one order of magnitude. The shaded region represents the typical range of observed asthenosphere conductivity. WK = Wang et al. (2006). YM = Yoshino et al. (2009). PR = Poe et al. (2010). JF = Jones et al. (2012). DK = Dai and Karato (2014). UHO = Gardés et al. (2014). pDK = Dai and Karato (2009). pZY = Zhang et al. (2012).

### 2.2. Hydrogen conduction

The electrical conductivity of the upper mantle is also dependent on the concentration of hydrogen defects (commonly referred to as water content) in NAMs due to the high chemical mobility of hydrogen that is incorporated as a charged species ($H^+$) (Karato, 1990). Experimental studies have confirmed that hydrated NAMs are significantly more conductive than their dry counterpart. However, there are significant inter-study disagreements regarding the degree to which water enhances conductivity (Gardés et al., 2014). Furthermore, it is not yet clear which hydrogen conduction mechanism is responsible for the enhancement and whether a single or multiple species of hydrogen are operating (Du Frane and Tyburczy, 2012; Karato, 2013).

The conduction mechanism for hydrated NAMs has been expressed in one of two forms. Wang et al. (2006) developed an Arrhenian relation for olivine conductivity that takes into account hydrogen speciation

$$\sigma_{wet} = A_{wet} C_w^r \exp\left(\frac{-\Delta H_{wet}}{RT}\right) \tag{2}$$

where $C_w$ is the water content and exponent $r$ is a constant. For $r = 1$ all of the hydrogen contributes equally to conduction and when $r$ is less than one it implies the concentration of hydrogen that influences conductivity is some fraction of the total concentration. Yoshino et al. (2009) proposed an alternative relation that treats hydrogen as a single species

$$\sigma_{wet} = A_{wet} C_w \exp\left(\frac{-\Delta H_{wet} - \alpha C_w^{1/3}}{RT}\right) \tag{3}$$

where $\alpha$ is a constant. The exponent $r$, which is not included in the equation, is implicitly assumed to equal unity, such that all of the incorporated hydrogen contributes equally to the conductivity. The $\alpha$ and $C_w$ terms were included in the exponential function to account for the water concentration dependence of the activation energy seen in their experimental data. This has the net effect of increasing the contribution of hydrogen conduction to the bulk conductivity at higher water concentrations.

Fig. 1 shows a comparison of several existing hydrous conductivity models for olivine and pyroxene at 1350 °C. Since conduc-