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# Laboratory-based electrical conductivity at Martian mantle conditions

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## ABSTRACT

Information on temperature and composition of planetary mantles can be obtained from electrical conductivity profiles derived from induced magnetic field analysis. This requires a modeling of the conductivity for each mineral phase at conditions relevant to planetary interiors. Interpretation of iron-rich Martian mantle conductivity profile therefore requires a careful modeling of the conductivity of iron-bearing minerals. In this paper, we show that conduction mechanism called small polaron is the dominant conduction mechanism at temperature, water and iron content conditions relevant to Mars mantle. We then review the different measurements performed on mineral phases with various iron content. We show that, for all measurements of mineral conductivity reported so far, the effect of iron content on the activation energy governing the exponential decrease in the Arrhenius law can be modeled as the cubic square root of the iron content. We recast all laboratory results on a common generalized Arrhenius law for iron-bearing minerals, anchored on Earth's mantle values. We then use this modeling to compute a new synthetic profile of Martian mantle electrical conductivity. This new profile matches perfectly, in the depth range [100,1000] km, the electrical conductivity profile recently derived from the study of Mars Global Surveyor magnetic field measurements.

## 1. Introduction

Induced magnetic field analysis offers a unique opportunity to sound planetary interiors. Indeed the electrical conductivity derived from the induced magnetic field represents a signature of the interior which is complementary to seismological data. Such complementarity has been demonstrated for more than ten years on Martian synthetic data (Mocquet and Menvielle, 2000; Verhoeven et al., 2005) and will be used to interpret future seismological data in combination with the recently derived MGS conductivity profile (Civet and Tarits, 2014). To obtain a successful joint inversion, a preliminary step consists in a precise identification of the temperature and composition effects on geophysical data, in particular on the electrical conductivity.

Electrical conductivity of mantle minerals depends on internal structure through pressure, temperature, oxygen fugacity and composition. Composition includes not only the constituent mineral phases but also the chemistry of the phase such as iron content and minor phases such as partial melt and water. Recent laboratory measurements of minerals conductivity (see e.g. the reviews (Yoshino, 2010; Karato, 2011)) have identified the sensibility of the conductivity to all these parameters and allows therefore a precise modeling of the conductivity in terms of internal structure. For example, Khan and Shankland (2012) have recently used this modeling to evaluate the water content in the Earth's mantle from a bayesian inversion of electromagnetic induction data.

The first synthetic profile of Mars mantle electrical conductivity based on laboratory measurements of the conductivity of iron-bearing minerals was computed by Vacher and Verhoeven (2007), hereafter called VV07. As the Martian mantle is much more iron rich than the Earth's mantle (Bertka and Fei, 1997), VV07 had to estimate the effect of iron on the conductivity on all mantle minerals. At that time, laboratory measurements of the conductivity of iron bearing minerals were scarce and the authors supplemented assumptions to estimate the conductivity of some iron bearing minerals. Starting from a mantle mineralogy reproduced by Bertka and Fei (1997) from a Dreibus and Wanke (1985) composition based on SNC meteorites, VV07 computed a synthetic conductivity profile which turned out to be by one order of magnitude more conductive than terrestrial estimations. This effect was mostly due to the higher iron content of the Martian model with respect to the Earth's mantle. These results are now challenged by the recent measurements of the electrical conductivity of individual mineral phases. Different research groups (Wang et al., 2006; Yoshino et al., 2009; Poe et al., 2010) have succeeded to perform complex high pressure and high temperature measurements of minerals electrical conductivities. Unfortunately, their results differ, mainly on the conductivity of hydrous minerals.

A first attempt to reconcile these studies was conducted by Jones et al. (2012) by testing the different conduction models on cratonic

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lithosphere from two locations in southern Africa where temperature and composition are well known. Unfortunately, the results were that none of the models were consistent with the field observations, highlighting the difficulty to select reference values among the different database for the electrical conductivity of hydrous minerals. A recent review of the experimental measurements of hydrous olivine conductivity by Gardés et al. (2014) suggest that most of the discrepancies between the conductivity laws derive from the experimental uncertainties and biases on the water concentration of the olivine samples.

Very recently, Wang et al. (2014) have studied the electrical conductivity of peridotite xenoliths from the North China Craton. Such peridotites are characterized by Fe-poor olivine and pyroxenes. Their measurements could not be adequately modeled by the law proposed by VV07 to model the effect of iron on conductivity. Wang et al. (2014) proposed to modify this law to take into account the recent highlight of the distance between ferrous and ferric atoms as a key parameter governing the conductivity of iron-bearing minerals. Such relationship was proposed for the first time by Yoshino and Katsura (2009) to model the effect of iron on the electrical conductivity of upper mantle minerals.

In this paper, we show that, due to the very high iron content of the Martian mantle, conduction mechanism called small polaron is the dominant conduction mechanism at temperature and water content conditions relevant to Mars mantle. This overcomes the difficulties associated to discrepancies between the different measurements of the conductivity of hydrous mineral phases. Focusing on the effect of iron on electrical conductivity, we propose to recast the new measurements performed on all minerals phases with different iron contents on a common law. This law generalizes the work of VV07 and has been proposed by Wang et al. (2014) for olivine and pyroxenes on the basis on the model of Yoshino and Katsura (2009) for the effect of iron on activation energy. We then apply this new law to update the laboratory-based model of the electrical conductivity of the Martian mantle.

Let us emphasize that the aim of the paper is not to provide a precise and conclusive computation of the electrical conductivity of iron-bearing mineral phases at all iron content but to present a laboratory-based modeling of the effect of iron on mineral electrical conductivity, anchored on Earth's mantle values and reasonably extrapolated at Martian conditions.

## 2. Electrical conductivity of mantle minerals at Martian conditions

### 2.1. Charge transport mechanisms

Laboratory measurements of the electrical conductivity $\sigma$ of a hydrogen-iron bearing mantle silicate mineral have allow to identify three different charge transport mechanisms (e.g. (Yoshino, 2010)):

$$\sigma = \sigma_i + \sigma_h + \sigma_p \tag{1}$$

where $\sigma_i$ is the contribution of ionic conduction (migration of Mg-vacancies sites), $\sigma_h$ the contribution from small polaron conduction (electron holes hopping between ferrous and ferric iron) and $\sigma_p$, the contribution from the migration of protons. All these three different conduction mechanisms increase with temperature according to an Arrhenius law:

$$\sigma_{i,h,p} = \sigma_0^{i,h,p} \exp\left(\frac{-\Delta H^{i,h,p}}{kT}\right) \tag{2}$$

where $\sigma_0$ is the pre-exponential factor, $\Delta H$ activation enthalpy, $k$ Boltzmann's constant and $T$ absolute temperature. Each charge transport mechanism becomes dominant at a given temperature range (Yoshino, 2010). Proton conduction is governed by water content whereas iron content governs small polaron conduction. By measuring the amount of water in the mineral apatite in two shergottites, McCubbin et al. (2012) estimated that the Martian interior contains between 73 and 290 ppm water. We therefore consider that 200 ppm of water, or 0.02 wt% is a reasonable estimate of the water content of the Martian mantle. From a study of SNC meteorites, Dreibus and Wanke (1985) have estimated an iron content of the order of 25%. Fig. 1 shows a comparison between electrical conductivities of San Carlos olivine associated to the three different transport mechanisms for iron content equal to 10% and 25% at temperature range and water content relevant to the Martian mantle. Ionic, small polaron and proton conduction were computed from the results of Yoshino et al. (2009) with an effect of iron on the small polaron conduction modeled from Wang et al. (2014). These results show that, for water content equal to 0.02% and iron content equal to 10% (representative Earth's mantle value), proton conduction dominates the olivine conduction for temperature smaller than 1500 K whereas ionic conduction becomes dominant at higher temperatures. On the contrary, for iron content equal to 25% (representative Martian mantle value), small polaron conduction clearly dominates the electrical conductivity at conditions relevant to Martian mantle. The Martian mantle conductivity can therefore be adequately modeled by the sole small polaron conduction, which overcomes the difficulty associated to the measurements of the effect of water content on proton conduction.

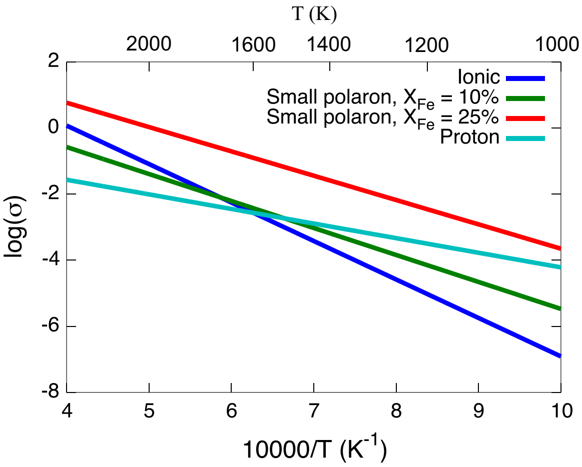

**Fig. 1.** Comparison between electrical conductivities of olivine associated to ionic, small polaron and proton conduction for iron content equal to 10% and 25% at temperature range and water content relevant to the Martian mantle. Ionic and proton conduction are computed according to the results of Yoshino et al. (2009) with enthalpy values equal to 2.31 eV and 0.92 eV for ionic and proton conduction, respectively. Small polaron conduction was computed from Eq. (4) and olivine electromagnetic parameters of Table 1.

In a recent paper, Dai and Karato (2014) have investigated the influence of iron and hydrogen on the electrical conductivity of olivine. On the contrary to many studies, their measurements suggest only a modest effect of iron on the electrical conductivity at Martian mantle temperature. As their measurements on the conductivity of hydrous olivine were performed on samples with both different iron and water content, this small iron content effect is related to their model of the dominant effect of water content on proton conduction, which has been recently debated by Gardés et al. (2014).

Electrical conductivity of minerals depends also on oxygen fugacity. As the oxidation state of the Martian mantle is very close to the experimental conditions at which conductivity measurements are performed (e.g. (Vacher and Verhoeven, 2007)), the effect of oxygen fugacity on the electrical conductivity of the Martian mantle is negligible compared to the effect of temperature and iron content.

### 2.2. Effect of iron content on small polaron conduction

For most minerals or high pressure phases, iron content affects both the pre-exponential factor and the activation enthalpy. This