Water content of the upper mantle inferred from electrical conductivity of mantle minerals

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Water in the earth's mantle plays important roles in the mantle dynamics. Although knowledge of storage capacity of mantle minerals has been obtained by many studies, water content in the mantle cannot be directly estimated from these studies. Electrical conductivity profiles of the Earth's mantle obtained from the electromagnetic studies can provide constraints on the thermal and chemical state of the mantle. Especially, electrical conductivity is very sensitive to small amount of hydrogen contents in minerals. Accurate knowledge of electrical conductivity of mantle minerals is needed to constrain water contents in the mantle as a function of depth. The mantle transition zone would be a large water storage because wadsleyite and ringwoodite can store significant amounts of water in their crystal structure. Water content in the transition zone could be quantified using electrical conductivities of hydrous wadsleyite and ringwoodite. Although the correct interpretation of water content depends on accurate knowledge of two conduction mechanisms (small polaron and proton conductions) in these minerals, early studies failed to distinguish them. In the present study, electrical conductivities of olivine, wadsleyite and ringwoodite were measured as functions of water content and temperature, rendering it possible to separate contributions of small polaron and proton conduction mechanisms.

The starting materials were olivine (Fo91) for olivine, wadsleyite and ringwoodite. The electrical conductivities of the samples were measured at various pressures from 3 and 20 GPa and temperatures up to 2000K at low frequencies ranging from 0.01 to 0.1 Hz. For all the dry samples, electrical conductivity displays Arrhenian behavior over the entire investigated temperature range. In the high temperature range above 1700K, activation energies (more than 1.5 eV) tend to be higher than those in the lower temperature range (less than 1.5 eV). The absolute values of electrical conductivity (S/m) for each mineral are very similar to each other. From these measurements we noted that the electrical conductivities of dry wadsleyite and ringwoodite (less than 100 wt. ppm of water) are much lower than those previously reported. While conductivities of samples with certain amounts of hydrogen are comparable to that of the dry one, conductivity increases with increasing hydrogen concentrations. Activation energies of hydrogen-doped minerals decreases with increasing hydrogen concentration from nearly 1 to 0.5 eV. The contributions of proton conduction are small at temperatures corresponding to the upper mantle.

The oceanic asthenosphere has very high electrical conductivity with high anisotropy in some locations. In the directions of parallel and normal to the plate motion, respectively, the conductivity is orders of 0.1 and 0.01 S/m, which cannot be explained by conductivity of anhydrous olivine. Because hydrogen can be incorporated in olivine at mantle pressures, the observation has been usually interpreted by the olivine hydration, which would cause anisotropically high conductivity by proton migration. Extrapolation of the experimental results suggests that conductivity of hydrous olivine at the top of the asthenosphere should be nearly isotropic and only of the order of 0.01 S/m. Therefore, the hydration of olivine cannot account for the geophysical observations, which instead may be explained by the presence of partial melt elongated in the direction of plate motion.

For the mantle transition zone, conductivity jumps in association with the olivine-wadsleyite and wadsleyite-ringwoodite transitions have similar magnitude (~0.7 log unit). The dry mantle model well explains the current semi-global conductivity-depth profiles obtained from the recent geoelectromagnetic studies. There is no necessity to introduce water in the transition zone.