Electrical Conductivity and Water in the Mantle

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Why mantle electrical conductivity?

- Highly sensitive to phase transitions
- Sensitive to mantle temperature
- Influenced by volatiles and trace materials

Water has a big effect on electrical conductivity. Electrical conductivity studies can be used to directly infer water content in the mantle

... but it’s a risky business.
A lot of things have to be done correctly to get useful mantle properties:

- Measurements of Electric/Magnetic Fields
- Response Functions of Frequency
- Laboratory Data
- Electrical Conductivity Model
- Time Series Analysis
- Geophysical Inversion

Estimates of Mantle Temperature, Water Content, etc.
Surface conductivity is dominated by the oceans and water in crustal rocks:
Mantle Conductivity Dominated by Semiconduction

\[ \sigma = \sigma_0 e^{-A/kT} \]

Conductivity and Water in the Mantle
Electrical Conduction in Dry Olivine

Point defects in olivine:

\[ V''_{Mg} \quad \text{Magnesium vacancies} \]

\[ Fe_{Mg}^\bullet \quad \text{Small polaron} \]

\[ e' \quad \text{Electrons} \]

\[ V''''_{Si} \quad \text{Silicon vacancies} \]
$8Fe_{Mg}^\times + 2O_2 \rightleftharpoons 2V_{Mg}'' + V_{Si}''' + 4O_O^\times + 8Fe_{Mg}^\bullet$

San Quintin Dunite

Conductivity and Water in the Mantle
Thermoelectric Power $Q$:

$$Q = - \lim_{\Delta T \to 0} \frac{\Delta V}{\Delta T}$$

![Diagram of a thermoelectric setup with a sample between two electrodes, showing temperature differences and thermopower values at 1000°C, 1100°C, and 1200°C.](image)
Conductivity equations:

$$\sigma_{\text{total}} = \sigma_{\text{Fe}} + \sigma_{\text{e}} + \sigma_{\text{Mg}} = [Fe_{Mg}^\bullet] \mu_{\text{Fe}} e + n_e \mu_e e + 2[V_{Mg}''] \mu_{\text{Mg}} e$$

Thermopower equations:

$$Q_{\text{total}} = Q_{\text{Fe}} \frac{\sigma h}{\sigma} + Q_{\text{e}} \frac{\sigma e}{\sigma} + Q_{\text{Mg}} \frac{\sigma_{\text{Mg}}}{\sigma}$$

$$Q_{\text{Mg}} = \frac{k}{e} \ln \left( \frac{1 - [V_{Mg}''][Mg_{Mg}^\times]}{[V_{Mg}'''][Mg_{Mg}^\times]} \right)$$

$$Q_{\text{e}} = \frac{k}{e} \left\{ \ln \left[ \frac{n_e}{2} \left( \frac{h^2}{2\pi m^* kT} \right)^{3/2} \right] - \frac{3}{2} \right\}$$

$$Q_{\text{Fe}} = \frac{k}{e} \ln 2 \left( \frac{1 - [Fe_{Mg}^\bullet][Fe_{Mg}^\times]}{[Fe_{Mg}^\bullet][Fe_{Mg}^\times]} \right)$$

Solve using non-linear parameter estimation:

$$\mu_x = c_x e^{-A_x/kT} \quad [X] = b_x + a_x f_{O_2}^{1/6}$$
Fits to data:
(no electrons needed)

$$\mu_{Fe} = 12.2 \times 10^{-6} e^{-1.05} eV/kT$$

$$\mu_{Mg} = 2.72 \times 10^{-6} e^{-1.09} eV/kT$$

(m$^2$V$^{-1}$s$^{-1}$)

$$[Fe^\bullet_{Mg}] \approx [V''_{Mg}] \approx 10^{24} \text{ m}^{-3}$$
**SEO3: Conductivity σ is given by**

\[
\sigma = [Fe^*_Mg] \mu_{Fe} e + 2[V'_Mg] \mu_{Mg} e
\]

**for mobilities**

\[
\mu_{Fe} = 12.2 \times 10^{-6} e^{-1.05 eV/kT}
\]

\[
\mu_{Mg} = 2.72 \times 10^{-6} e^{-1.09 eV/kT}
\]

**and concentrations**

\[
[Fe^*_Mg] = b_{Fe}(T) + 3.33 \times 10^{24} e^{-0.02 eV/kT} f_{O_2}^{1/6}
\]

\[
[V'_Mg] = b_{Mg}(T) + 6.21 \times 10^{30} e^{-1.83 eV/kT} f_{O_2}^{1/6}
\]

derived from fitting conductivity and thermopower data in silica-buffered polycrystal at lower T.
Using induction to measure Earth conductivity:

- Magnetotelluric (MT) method
  Measure electric and magnetic fields
- Geomagnetic depth sounding (GDS)
  Measure horizontal and vertical magnetic fields
- Controlled-Source EM:
  Measure E and/or B generated by man-made transmitter
A time-varying magnetic field:

Faraday’s Law: \[ \oint_C \mathbf{E} \cdot d\mathbf{l} = -\frac{d\Phi}{dt} \]

Ohm’s Law: \( \mathbf{J} = \sigma \mathbf{E} \)

Ampere’s Law: \[ \oint_C \mathbf{B} \cdot d\mathbf{l} = \mu I \]
Magnetotelluric Method:

\[ \rho(\omega) = \frac{T}{2\pi \mu} \left| \frac{E_y(\omega)}{H_x(\omega)} \right|^2 \]
Magnetotelluric Method:

\[ \rho(\omega) = \frac{T}{2\pi \mu} \left| \frac{d \ast E_y(\omega)}{H_x(\omega)} \right|^2 \]
Geomagnetic Depth Sounding:

Exploits the geometry associated with the geomagnetic ring current.

\[ \sigma(\omega) = \frac{\text{internal}(\omega)}{\text{external}(\omega)} \]
Geomagnetic Depth Sounding:

Can use either magnetic observatory network, or satellite measurements.
Globally Averaged Response Functions:

General agreement but still some scatter.
Selected observatory data set (Medin et al.):
Inverse theory at play:

Good agreement with laboratory studies.

But what about water ..... ?
It all started in 1990...
Karato ignored many things, including the anisotropy of hydrogen diffusion...
... and that high conductivities came from distorted marine MT measurements:

![Graph showing current streamlines near bathmetry](image)

To this day, measurements from marine MT, and possibly distorted land MT, drive the discussion.

Laboratory measurements of hydrogen in olivine are notoriously hard – 18 years post-Karato we are still in the dark about hydrogen’s effect on olivine conductivity...
The effect of water on the electrical conductivity of olivine

Duojun Wang\textsuperscript{1,2,3}, Mainak Mookherjee\textsuperscript{3}, Yousheng Xu\textsuperscript{3,4} & Shun-ichiro Karato\textsuperscript{3}

Activation energy low

Two orders of magnitude more conductive than dry olivine

![Graph showing the effect of water on the electrical conductivity of olivine.](image-url)
LETTERS

Hydrous olivine unable to account for conductivity anomaly at the top of the asthenosphere

Takashi Yoshino¹, Takuya Matsuzaki¹, Shigeru Yamashita¹ & Tomoo Katsura¹

Little anisotropy

Same conductivity and activation energy as dry olivine for expected concentrations

[Graph showing conductivity and water in the mantle]
Dry transition zone minerals:

Figure 8. Laboratory-based conductivity-depth profile compared with geophysical models. Shaded areas illustrate the effect of a ±100 °C temperature variation. The laboratory-based profile is similar to BD if it is considered as a three-layer mantle and similar to Olsen99 if it is smoothed.

Geophysical models shown near AGLHS99 [Alexandrescu et al., 1999], SKC93 [Schultz et al., 1993], BD [Bahr and Duba, 1999], and Olsen99 [Olsen, 1999].

Yousheng Xu, Thomas J. Shankland, and Brent T. Poe
A wet mantle conductor?


The suggestion that the transition zone of Earth's mantle (410–670 km in depth) is about four orders of magnitude more oxidizing than their experiments. Accordingly, grain size or secondary phases. Consequently, some uncertainty remains in relating labora-

Hirschmann argues that effects of $f_{O_2}$ not properly considered.

Huanget al. reply


Inference of the spatial distribution of water content in the mantle is critical to our understanding of the dynamics of Earth's interior. A model$^1$ has been described that indicates there may be a jump in water content at the 410-km discontinuity in the Earth's mantle. From the electrical conductivity, we have inferred$^1$ the water content in the transition zone and con-

olivine$^4$ and wadsleyite are compared with geophysical measurements of the electrical-conductivity jump at 410 km depth (ref. 5). Using the model of Huang et al.$^4$, a jump in electrical conductivity at 410 km can be expressed in terms of a jump in oxygen fugacity and water content as

Figure 1 | Electrical conductivity versus depth in
Whole-mantle convection and the transition-zone water filter

David Bercovici & Shun-ichiro Karato
Department of Geology and Geophysics, Yale University, PO Box 208109, New Haven, Connecticut 06520-8109, USA

Argue that water in the transition zone will cause melting at the base of the upper mantle.

Surely something we can test with EM ...
... by adding a 10 km, 0.1 S/m layer to our model:

In fact, the biggest conductor you can hide is 10 times smaller, and has to be balanced by an unreasonably resistive upper mantle.
Mantle water undoubtedly exists, and will lower melting point:
Also can cause serpentinization of olivine in the uppermost mantle:
Anisotropy is between the Moho and the max. depth of serpentine stability:
Some Conclusions:

• Dry olivine conductivity is thoroughly understood - probably the only major mantle mineral for which we can say this

• GDS measurements are compatible with a dry upper mantle

• MT data cited in support of a mantle conductivity enhanced by water are almost certainly highly distorted

• Laboratory conductivity studies on the effect of water are extremely difficult, and yet to be conclusive

• A ubiquitous transition zone melt layer does not exist

• The biggest effect of water on mantle conductivity is through depression of the melting point
Future Directions:

- Subduction zones are an excellent place to study the effects of water on the mantle—we intend to do this.

- Improved GDS estimates from satellites will constrain radial conductivity structure even more tightly and illuminate any 3D effects.

- More laboratory work on conductivity is needed, particularly under controlled $f_{O_2}$ conditions.