Electrical Conductivity and Water in the Mantle

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With thanks to: Jim Behrens, Cathy Constable, Al Duba, Kerry Key, Ashley Medin, Bob Parker, Jeff Roberts

Why mantle electrical conductivity?

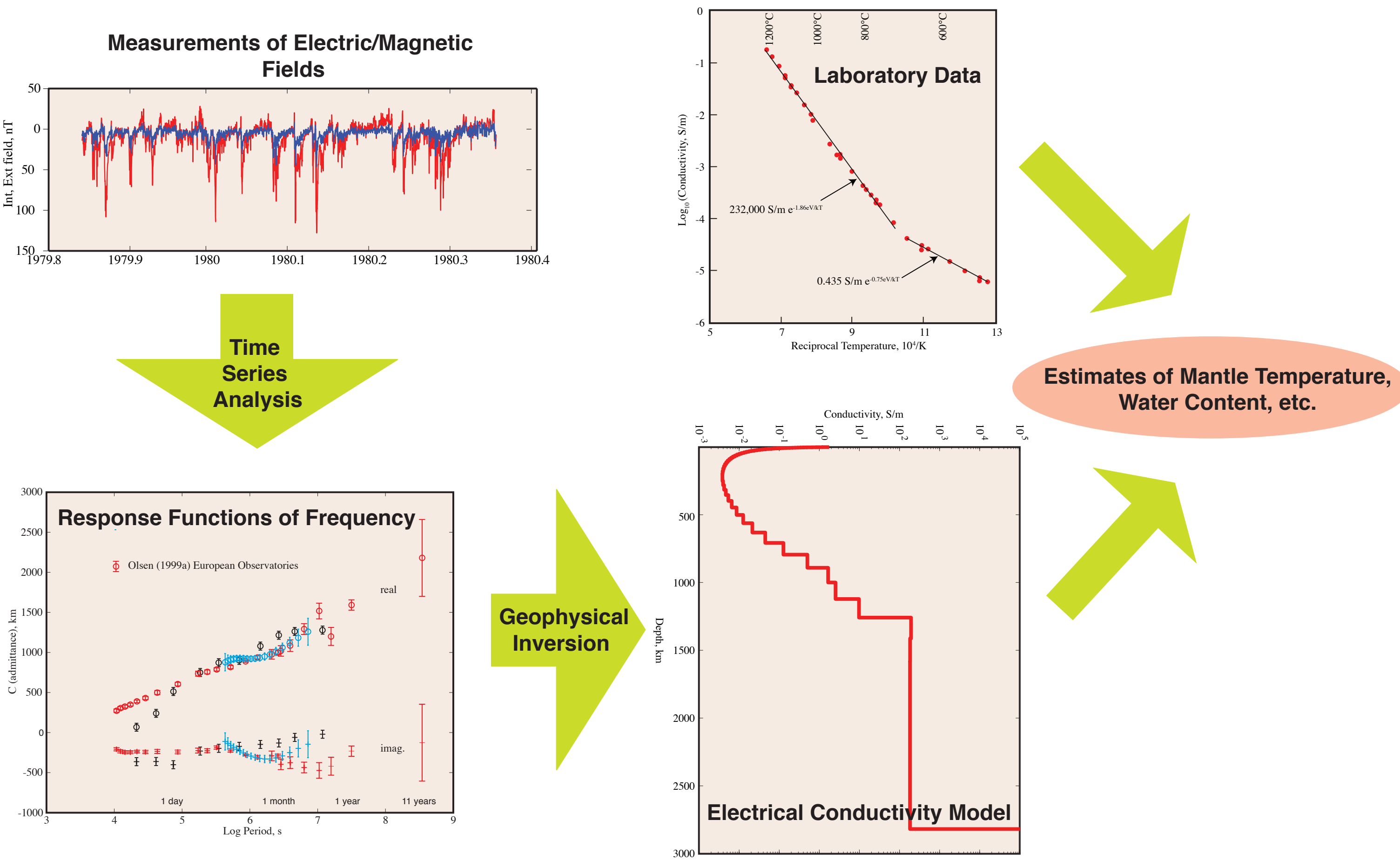
- Highly senstitive to phase transitions
- Sensitive to mantle temperature
- Influenced by volatiles and trace materials

Water has a big effect on electrical conductivity.

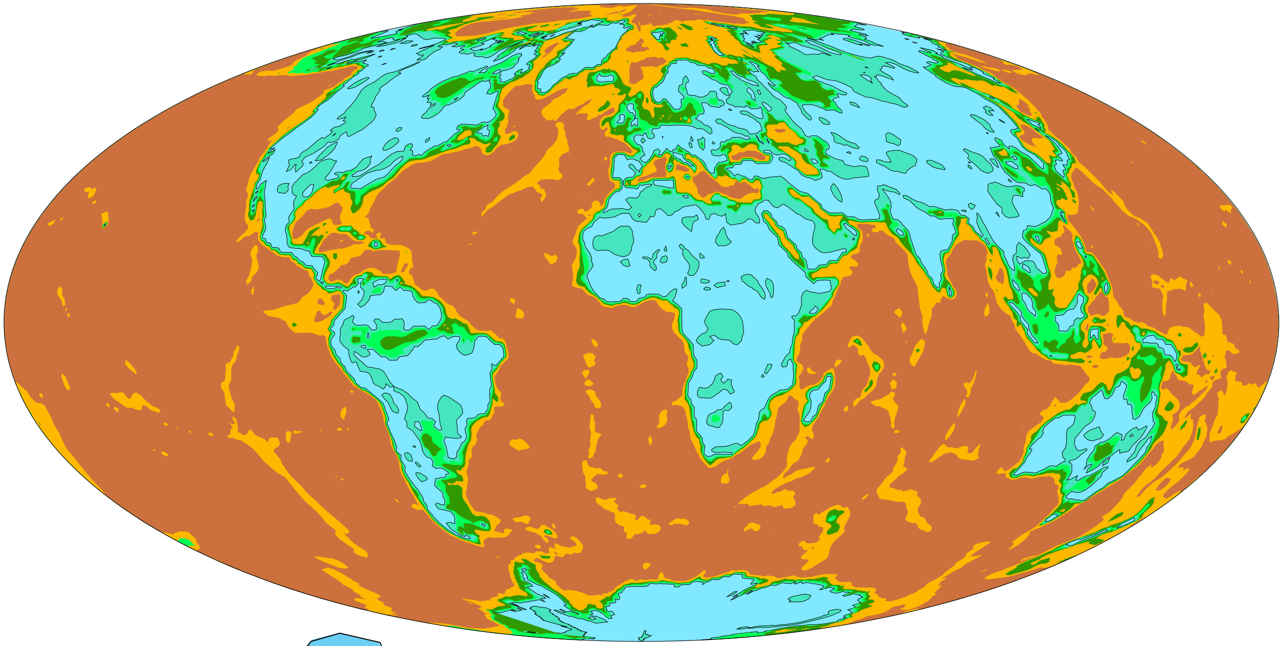
Electrical conductivity studies can be used to directly infer water content in the mantle

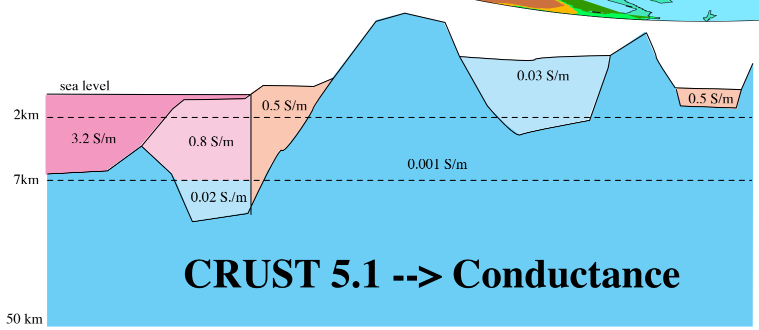
... but it's a risky business.

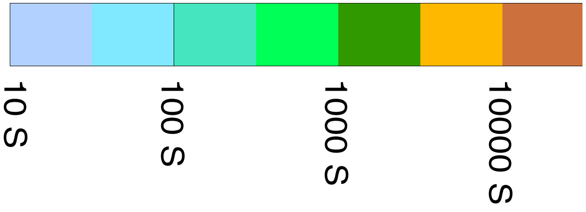
A lot of things have to be done correctly to get useful mantle properties:



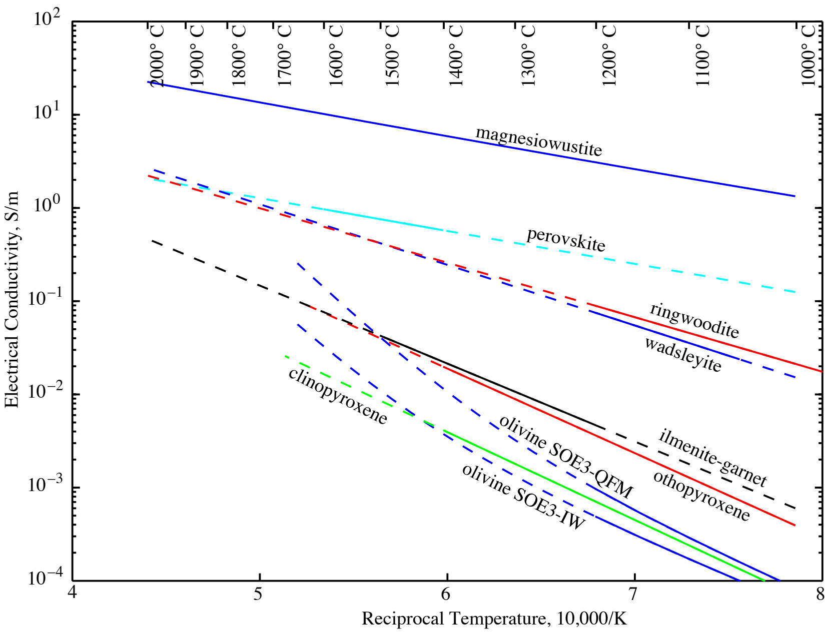
Surface conductivity is dominated by the oceans and water in crustal rocks:



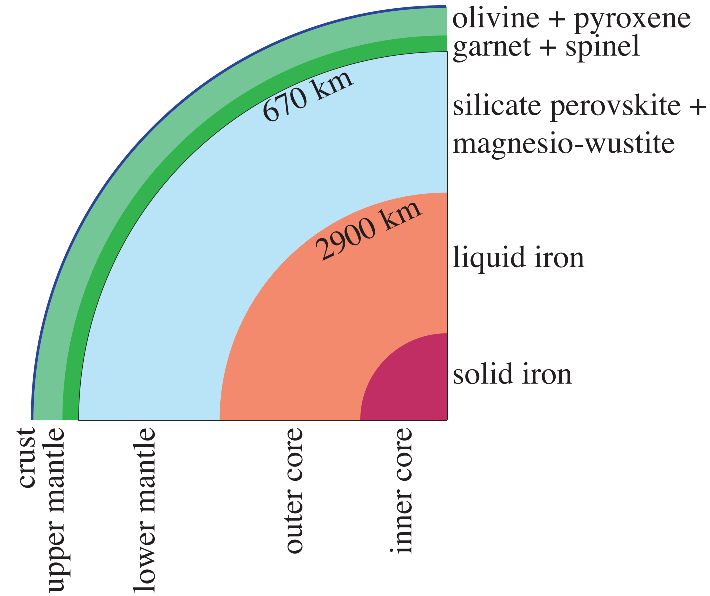




Mantle Conductivity Dominated by Semiconduction



$$\sigma = \sigma_o e^{-\frac{A}{kT}}$$

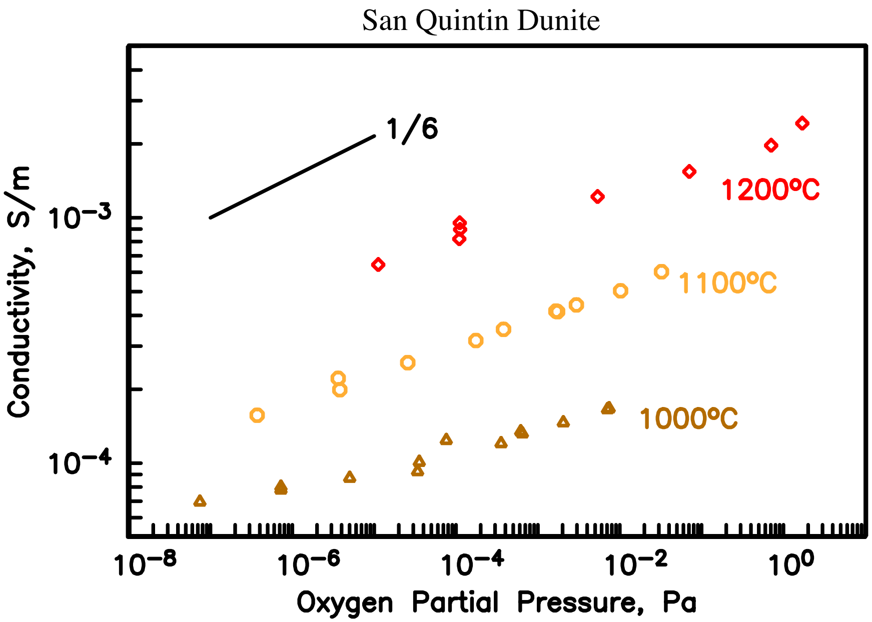


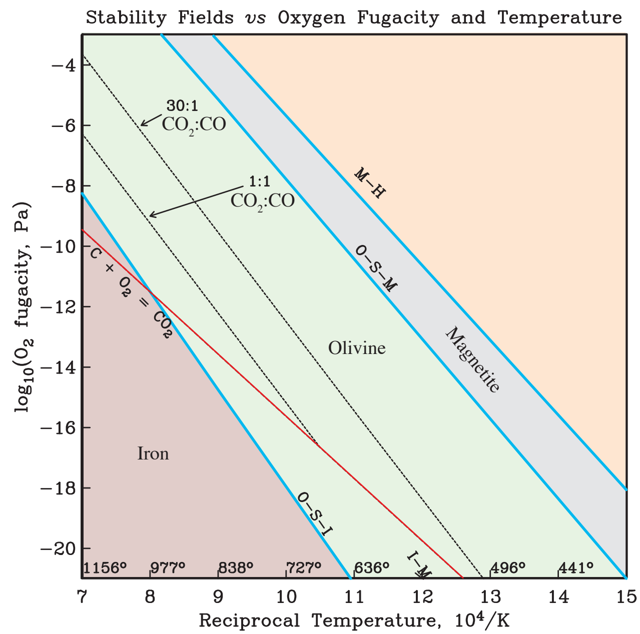
Electrical Conduction in Dry Olivine

Point defects in olivine:

V_{Mg}''	Magnesium vacancies
$Fe_{Mg}^{\bullet}$	Small polaron
e'	Electrons
V_{Si}''''	Silicon vacancies

$$8Fe^{\times}_{Mg} + 2O_2 \rightleftharpoons 2V''_{Mg} + V''''_{Si} + 4O^{\times}_{O} + 8Fe^{\bullet}_{Mg}$$

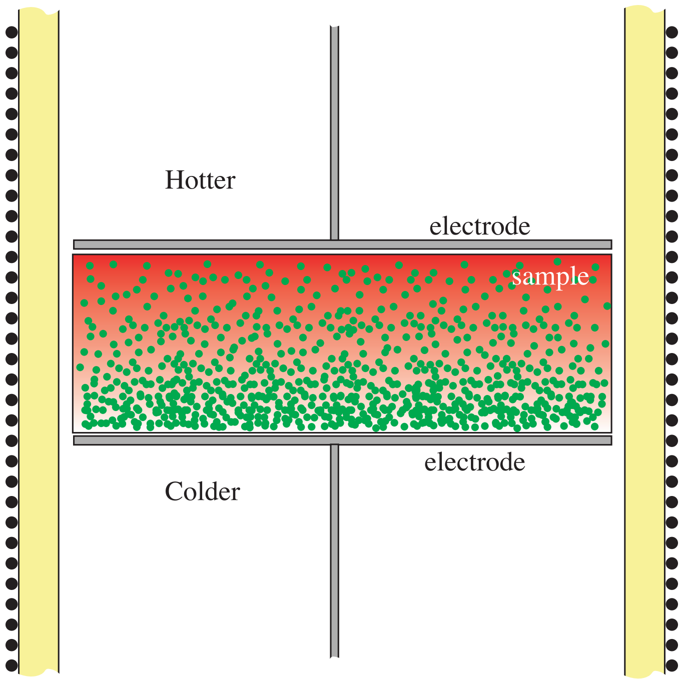


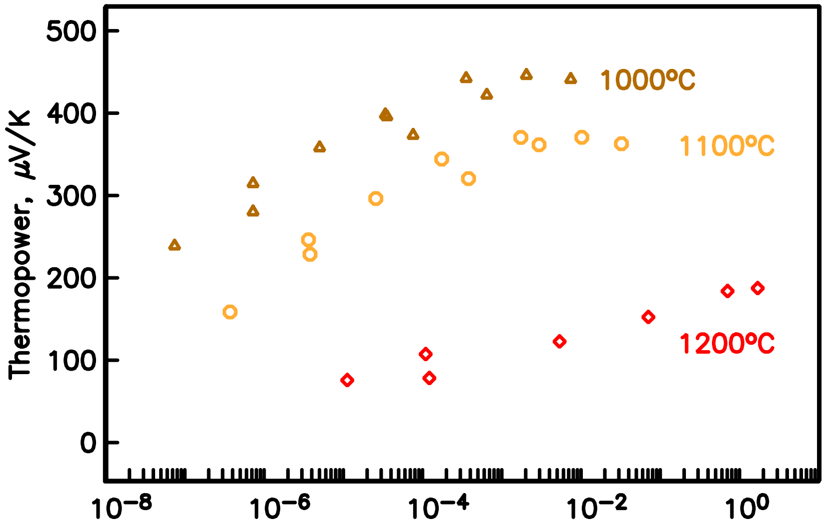


CONDUCTIVITY AND WATER IN THE MANTLE

Thermoelectric Power Q:

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





Conductivity equations:

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

Thermopower equations:

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

$$Q_{\text{Mg}} = \frac{k}{e}\ln\ \frac{(1-[V''_{Mg}]/[Mg^{\times}_{Mg}])}{[V''_{Mg}]/[Mg^{\times}_{Mg}]}$$

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

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

Solve using non-linear parameter estimation:

$$\mu_{\text{x}} = c_{\text{x}}e^{-A_{\text{x}}/kT} \qquad [\text{X}] = \text{b}_{\text{x}} + \text{a}_{\text{x}}\text{f}_{\text{O}_2}^{1/6}$$

Fits to data:

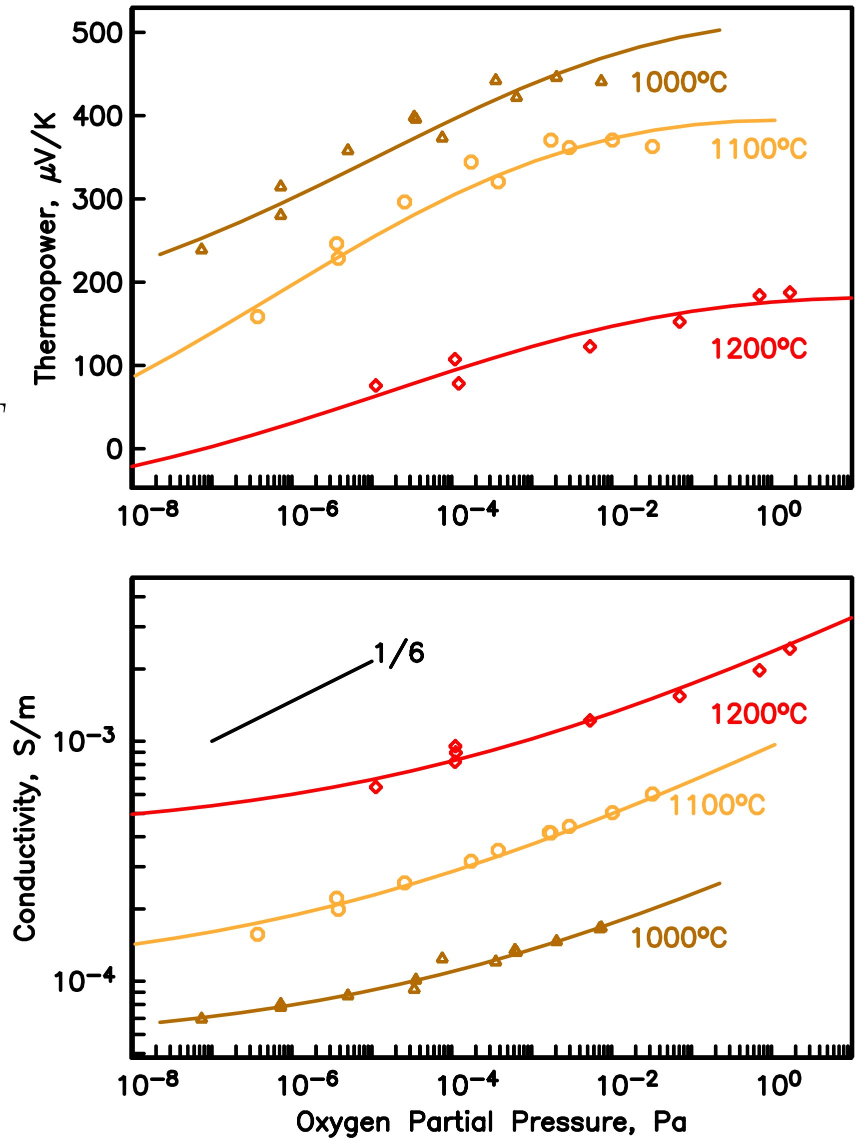
(no electrons needed)

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

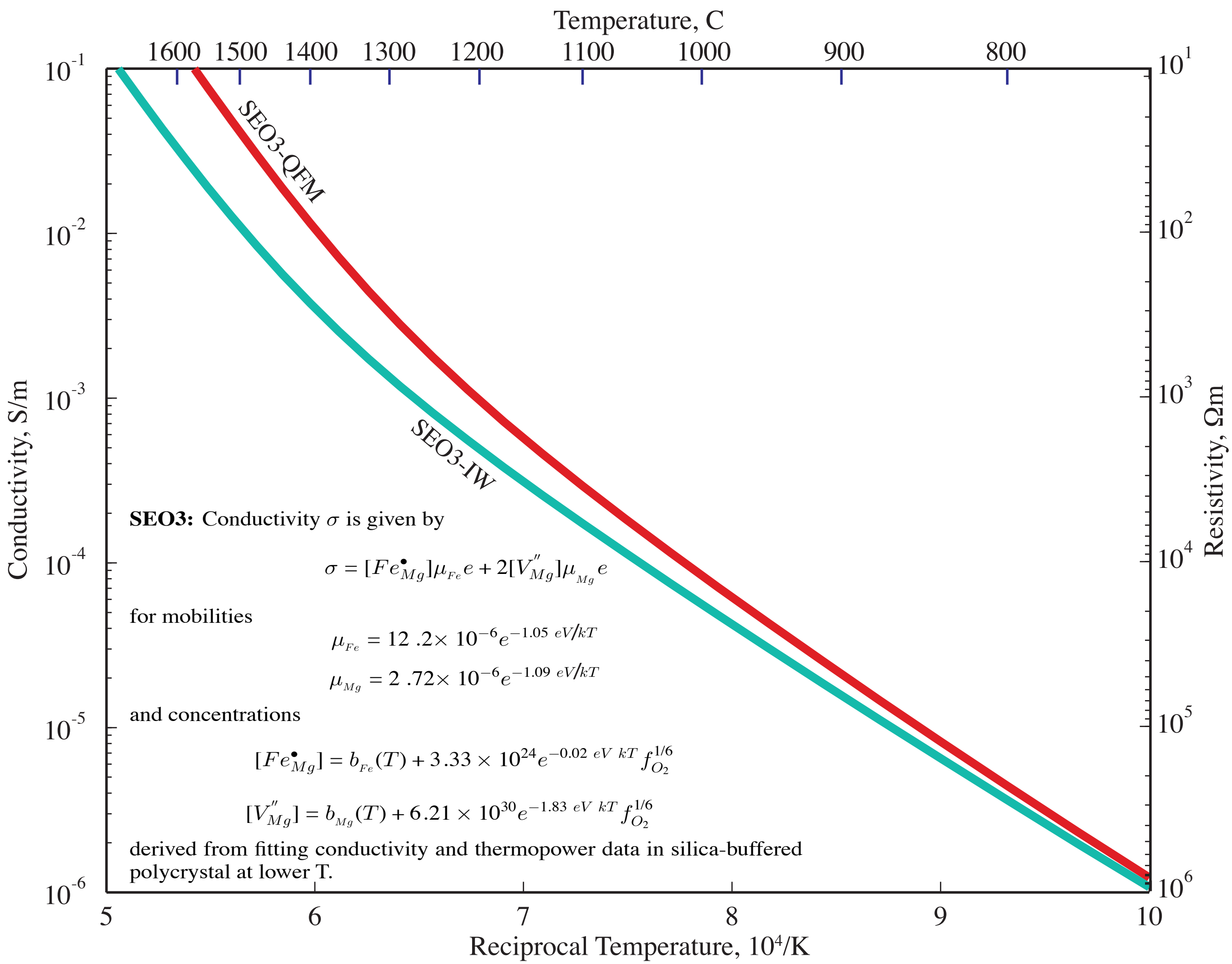
$$\mu_{Mg} = 2.72 \times 10^{-6} e^{-1.09\ eV/kT}$$

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

$$[Fe^{\bullet}_{Mg}] \approx [V''_{Mg}] \approx 10^{24}\ \mathrm{m^{-3}}$$



Standard Electrical Olivine model 3



Using induction to measure Earth conductivity:

- Magnetotelluric (MT) method

  Measure electric and magnetic fields

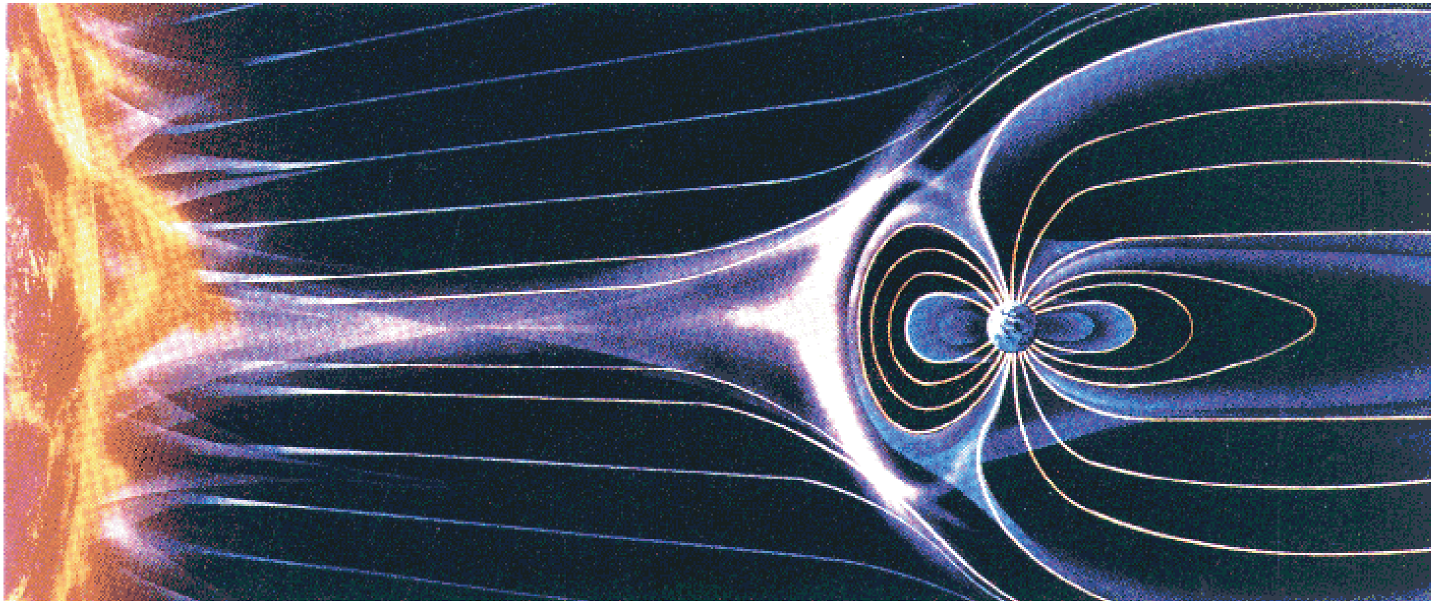
- Geomagnetic depth sounding (GDS)

  Measure horizontal and vertical magnetic fields

- Controlled-Source EM:

  Measure E and/or B generated by man-made transmitter

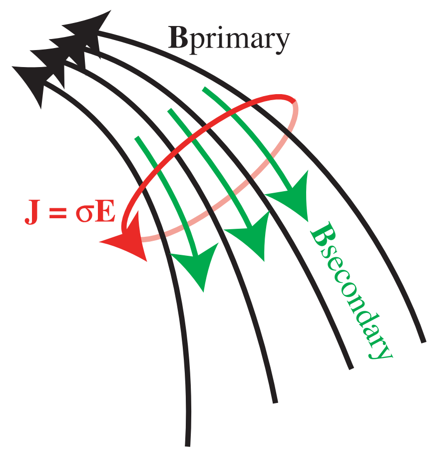
A time-varying magnetic field:



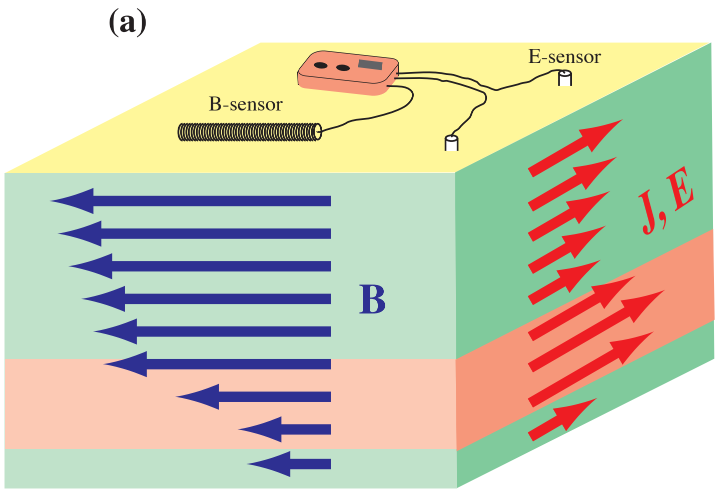
Faraday's Law: $$\oint_C \mathbf{E} \cdot d\mathbf{l} = -\frac{d\Phi}{dt}$$

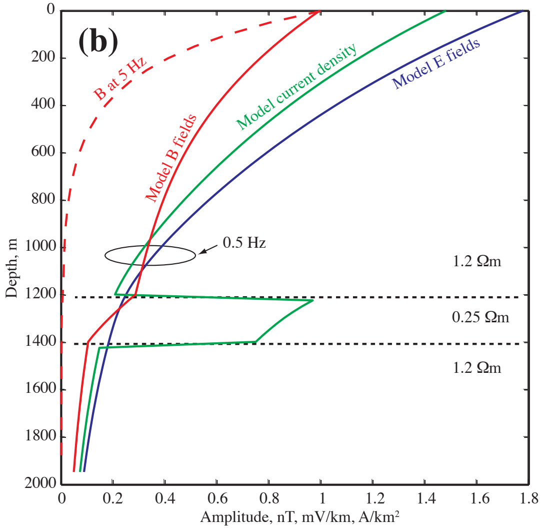
Ohm's Law: $$\mathbf{J} = \sigma\mathbf{E}$$

Ampere's Law: $$\oint_C \mathbf{B} \cdot d\mathbf{l} = \mu I$$



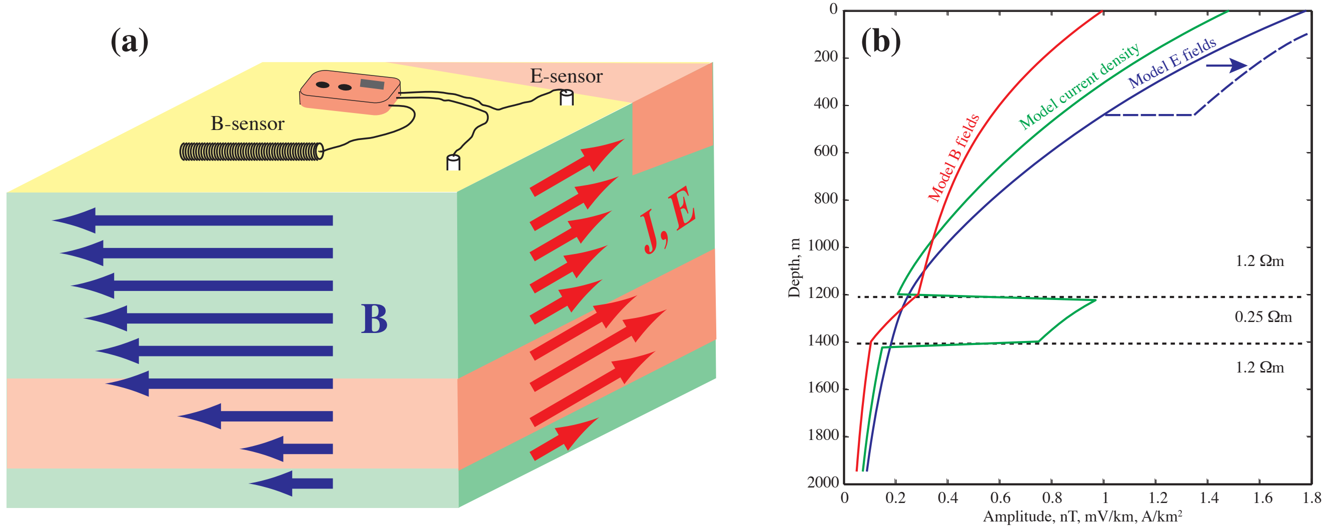
Magnetotelluric Method:





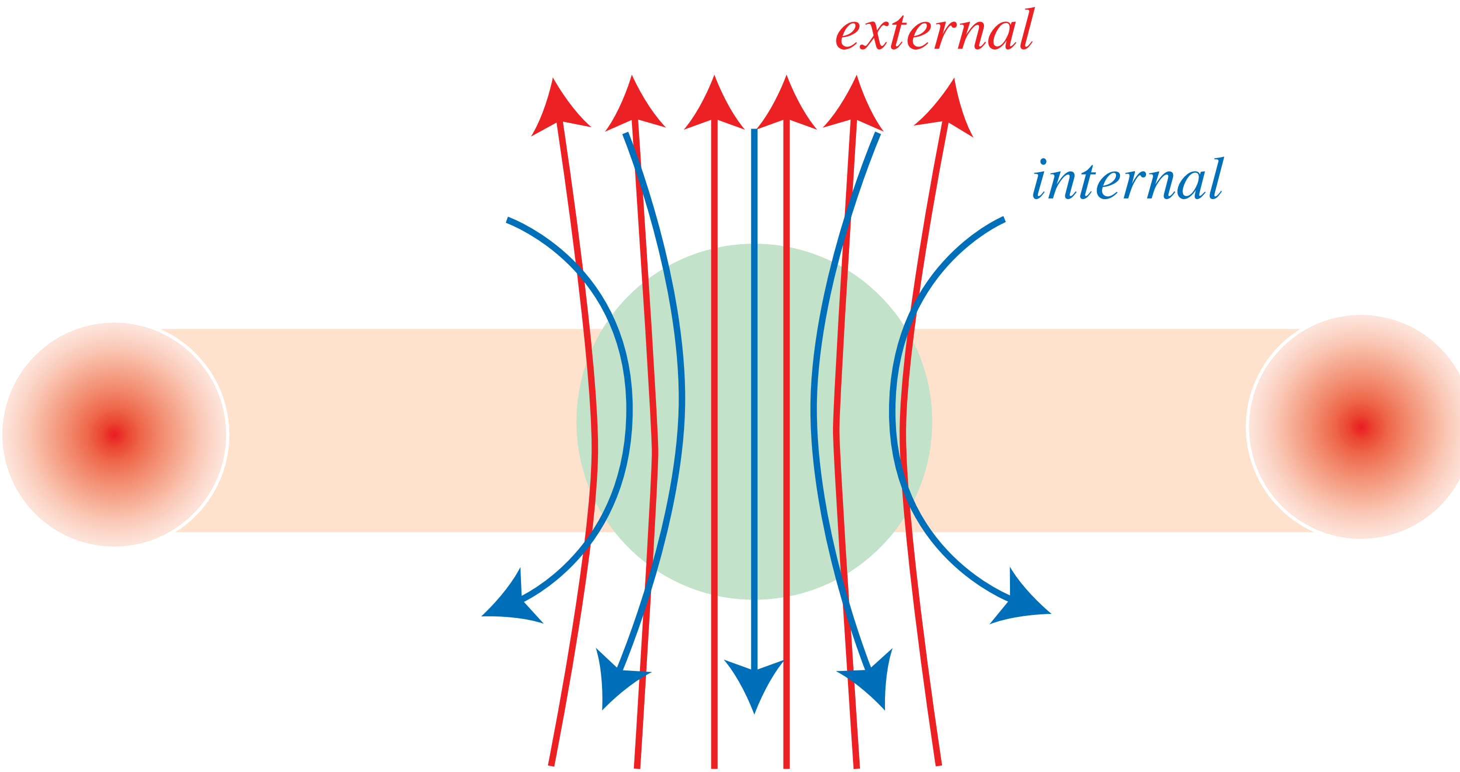
$$\rho(\omega) = \frac{T}{2\pi\mu}\left|\frac{E_y(\omega)}{H_x(\omega)}\right|^2$$

Magnetotelluric Method:



$$\rho(\omega) = \frac{T}{2\pi\mu}\left|\frac{d * E_y(\omega)}{H_x(\omega)}\right|^2$$

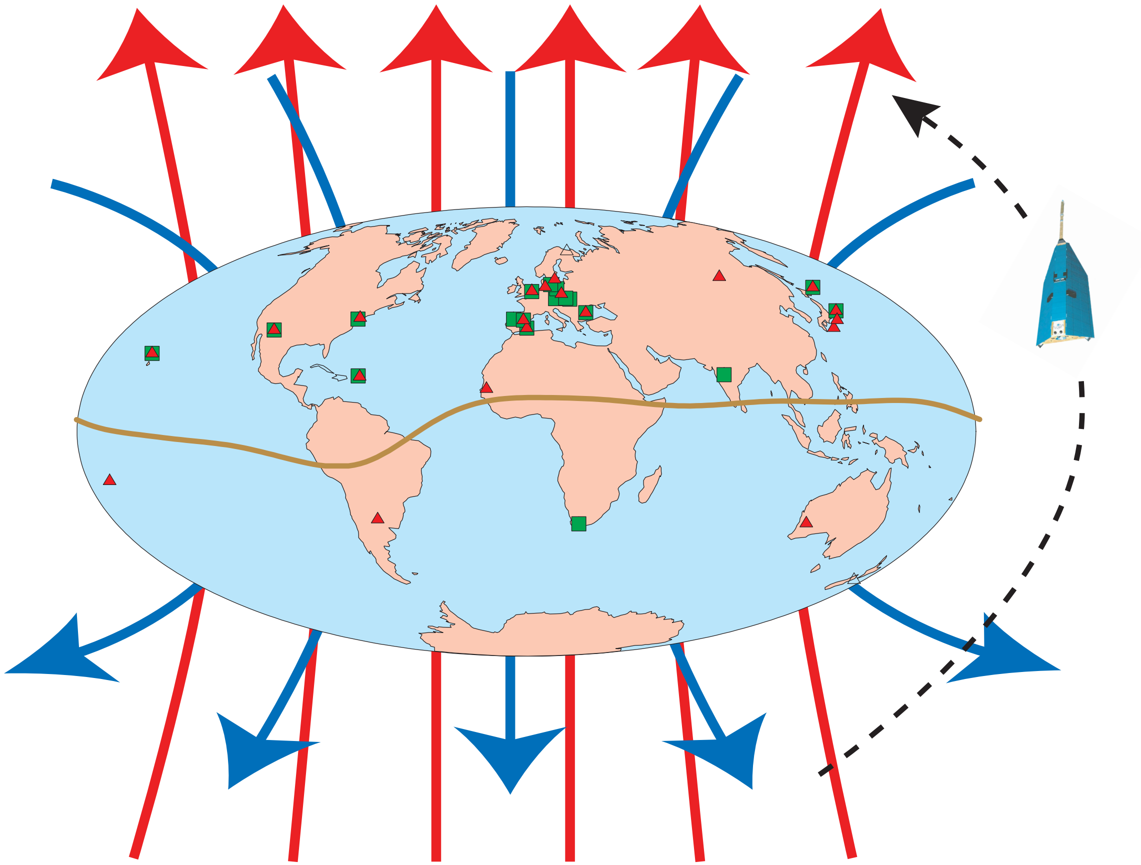
Geomagnetic Depth Sounding:



Exploits the geometry associated with the geomagnetic ring current.

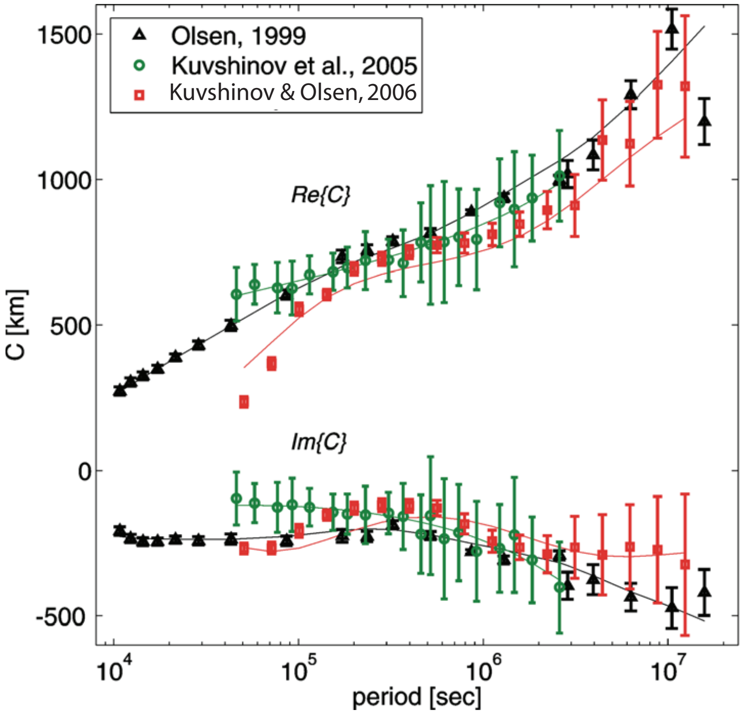
$$\sigma(\omega) = \frac{internal(\omega)}{external(\omega)}$$

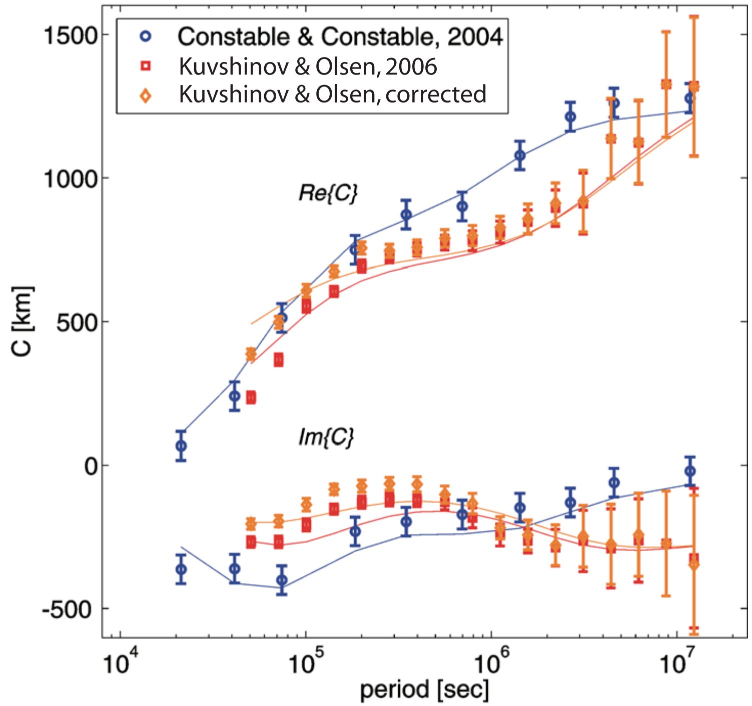
Geomagnetic Depth Sounding:



Can use either magnetic observatory network, or satellite measurements.

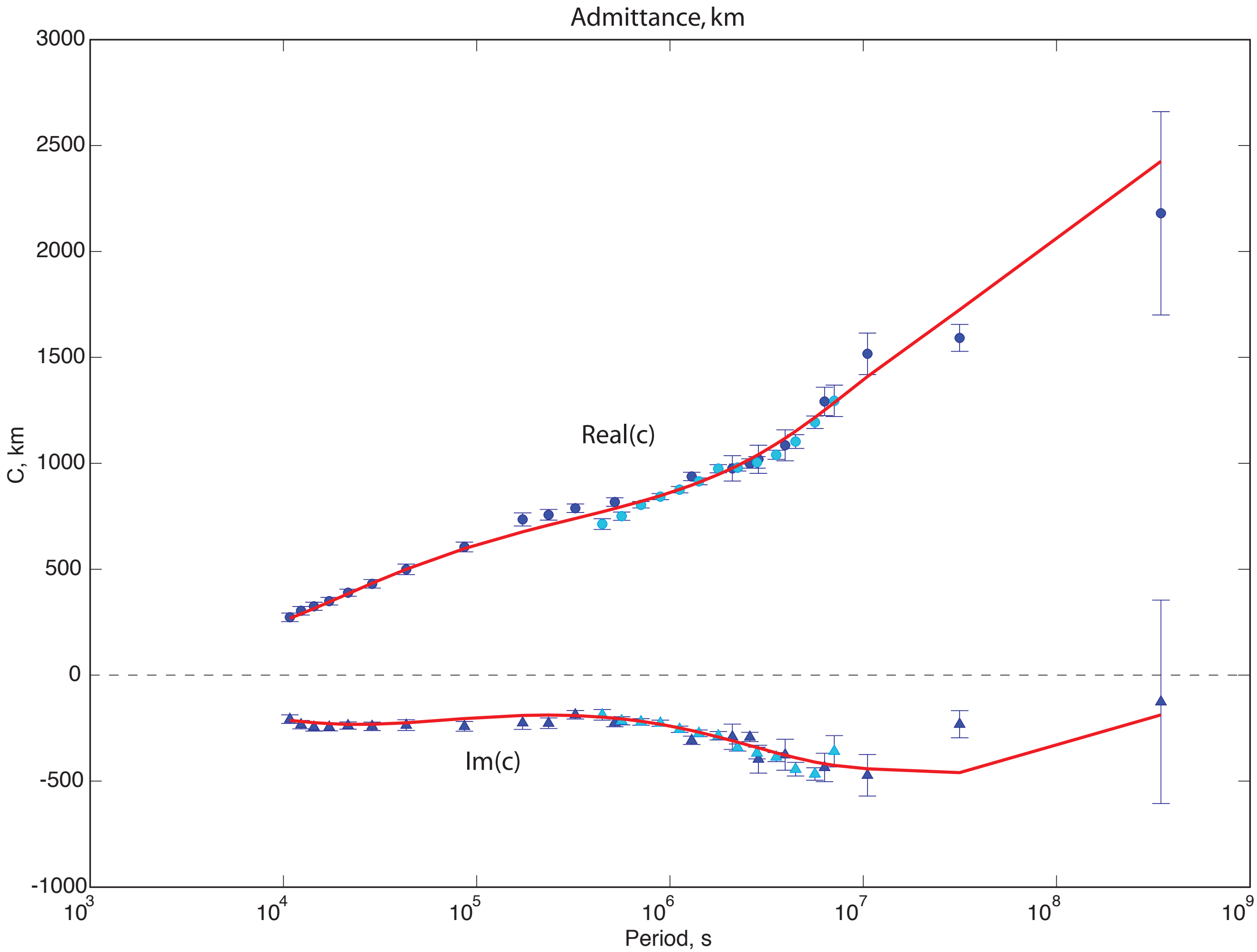
Globally Averaged Response Functions:



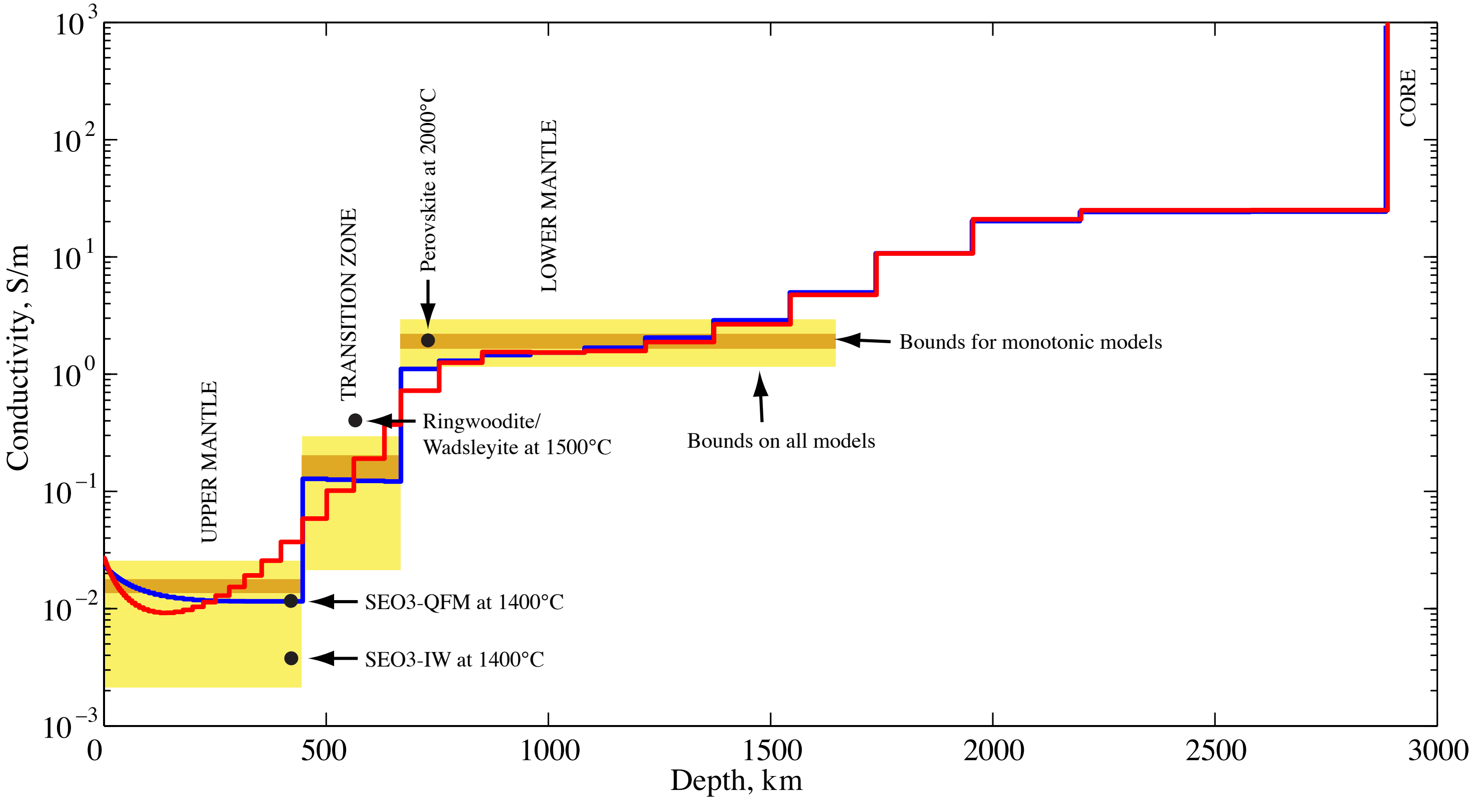


General agreement but still some scatter.

Selected observatory data set (Medin et al.):



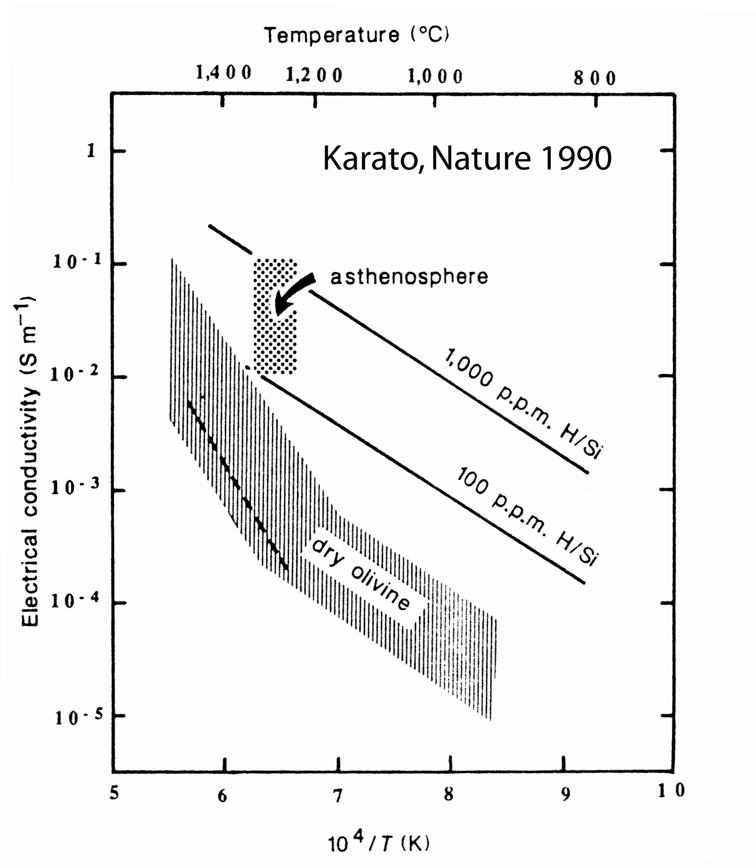
Inverse theory at play:



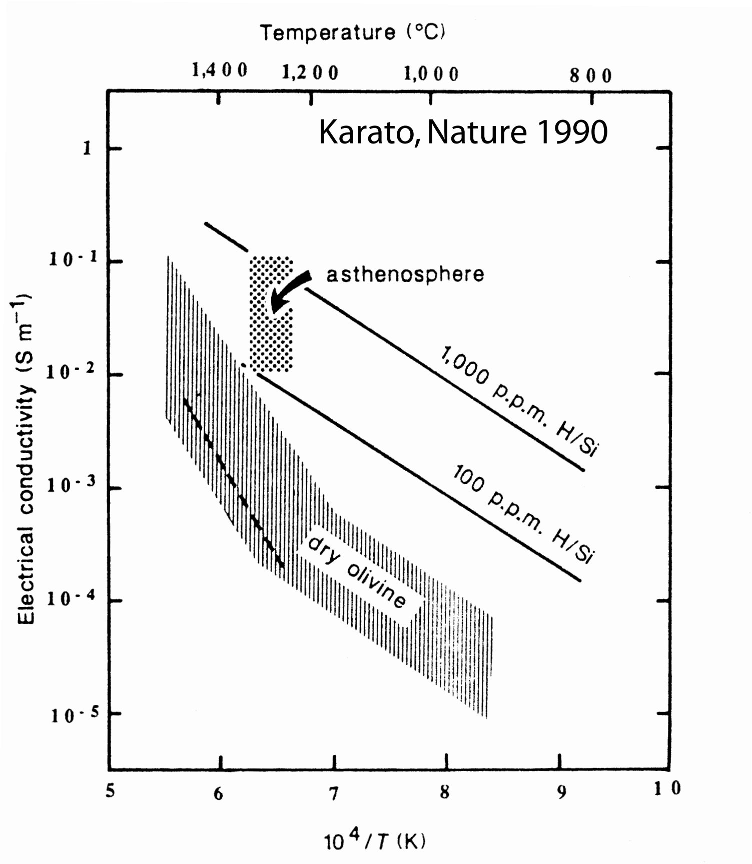
Good agreement with laboratory studies.

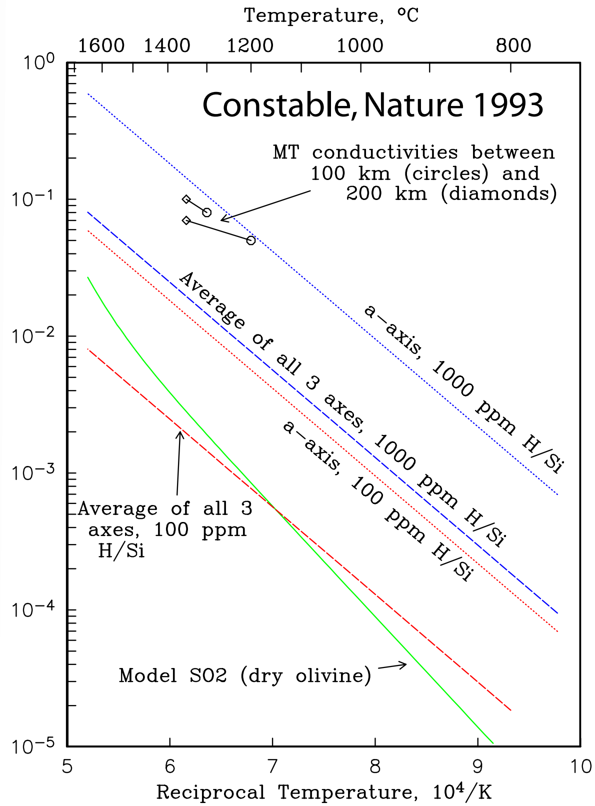
But what about water ..... ?

It all started in 1990...

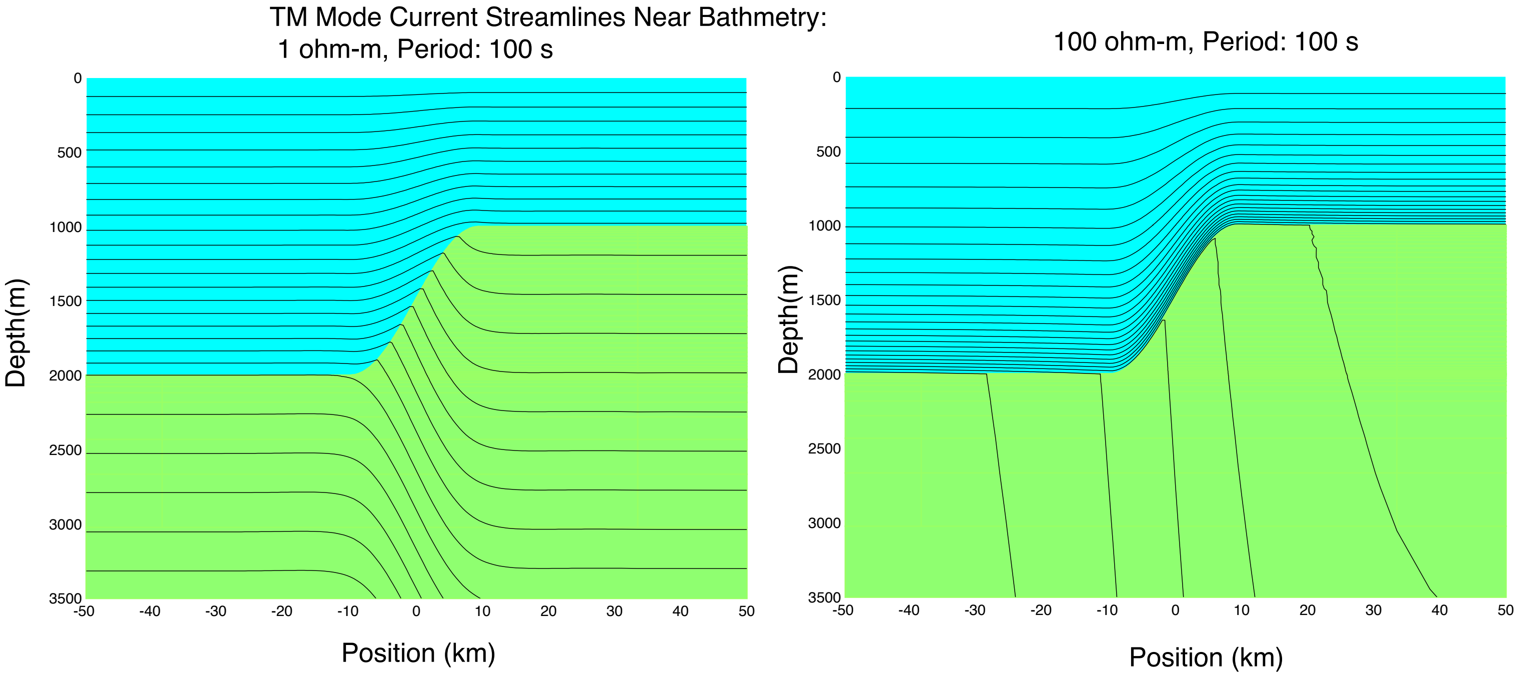


Karato ignored many things, including the anisotropy of hydrogen diffusion...





... and that high conductivities came from distorted marine MT measurements:



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...

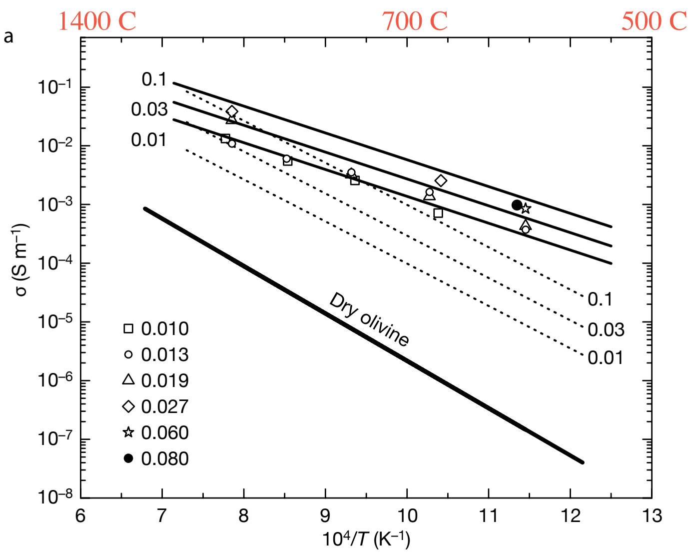
Vol 443 | 26 October 2006 | doi:10.1038/nature05256

nature

LETTERS

The effect of water on the electrical conductivity of olivine

Duojun Wang[1,2,3], Mainak Mookherjee[3], Yousheng Xu[3,4] & Shun-ichiro Karato[3]



Activation energy low

Two orders of magnitude more conductive than dry olivine

Vol 443 | 26 October 2006 | doi:10.1038/nature05223

nature

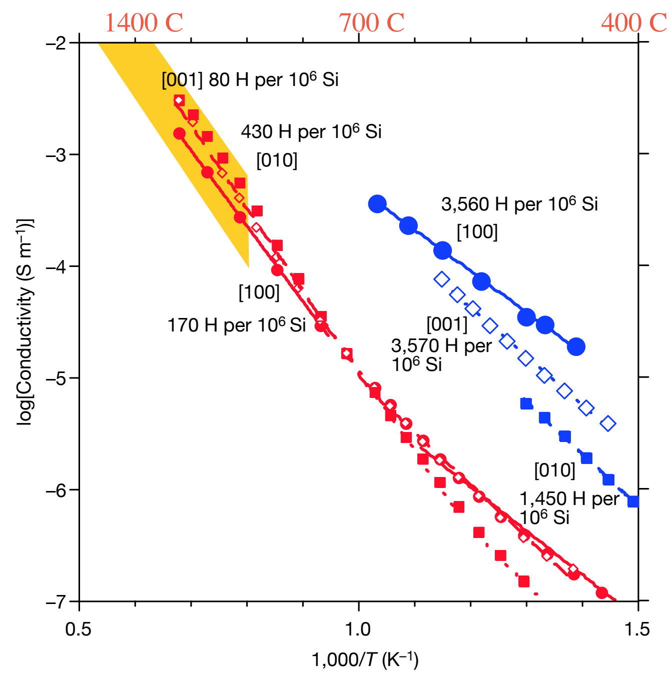
LETTERS

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

Takashi Yoshino [1], Takuya Matsuzaki [1], Shigeru Yamashita [1] & Tomoo Katsura [1]

Little anisotropy

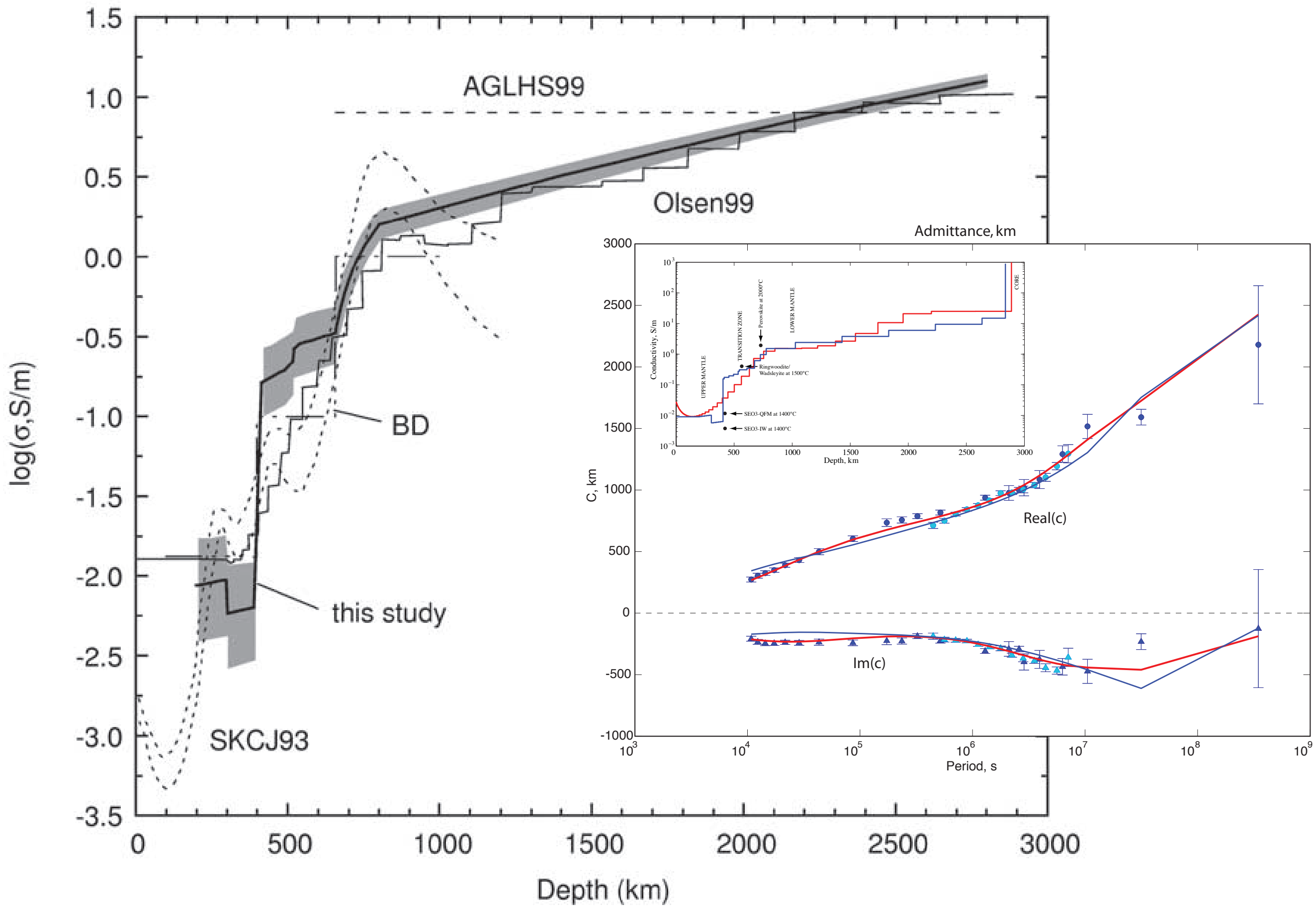
Same conductivity and activation energy as dry olivine for expected concentrations



Dry transition zone minerals:

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 108, NO. B6, 2314, doi:10.1029/2003JB002552, 2003

Yousheng Xu, Thomas J. Shankland, and Brent T. Poe



EARTH SCIENCE

A wet mantle conductor?

Arising from: X. Huang, Y. Xu & S. Karato Nature 434, 746–749 (2005)

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

⋮

ductivity of mantle minerals may be critically dependent on oxygen state and assume that the oxygen fugacity of the transition zone of the Earth is similar to conditions imposed by the coexistence of nickel metal and NiO, which

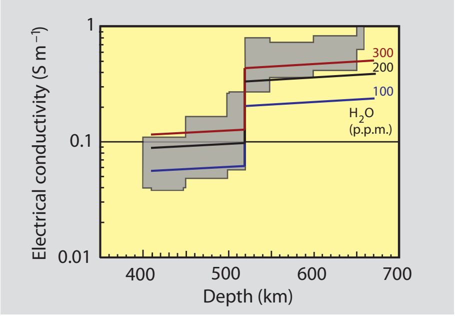


Figure 1 | Electrical conductivity versus depth in

EARTH SCIENCE

Huanget al. reply

Replying to: M. Hirschmann Nature 439, doi:10.1038/nature04528 (2005)

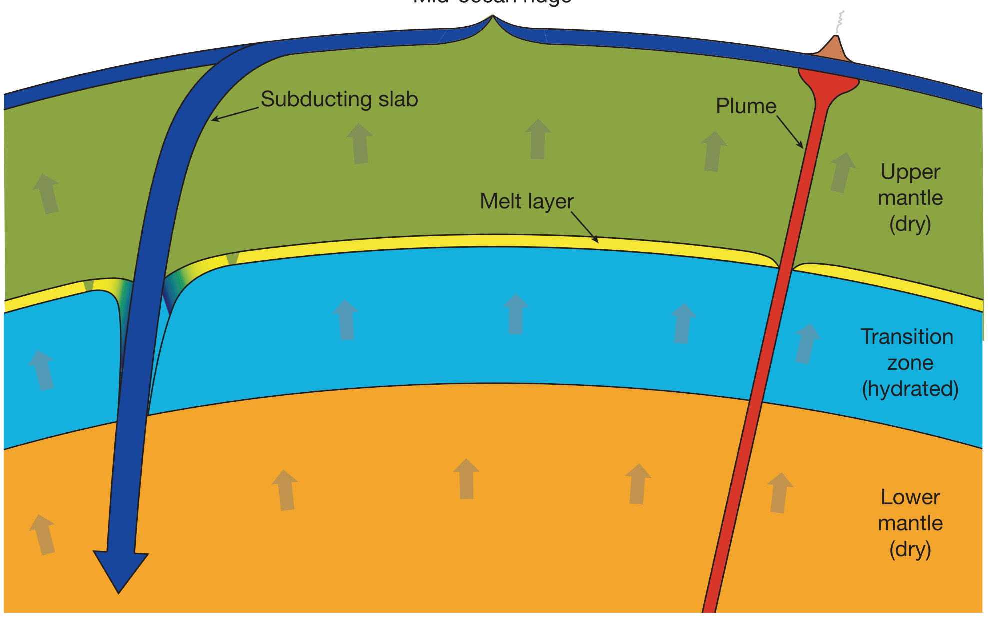
Inference of the spatial distribution of water content in the mantle is critical to our understanding of the dynamics of Earth's interior. A model[1] has been described that indicates there may be a jump in water content at the 410-km discontinuity in the Earth's mantle. From the electrical conductivity, we have inferred[2] 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.*[2], a jump in electrical conductivity at 410 km can be expressed in terms of a jump in oxygen fugacity and water content as

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

Whole-mantle convection and the transition-zone water filter

David Bercovici & Shun-ichiro Karato

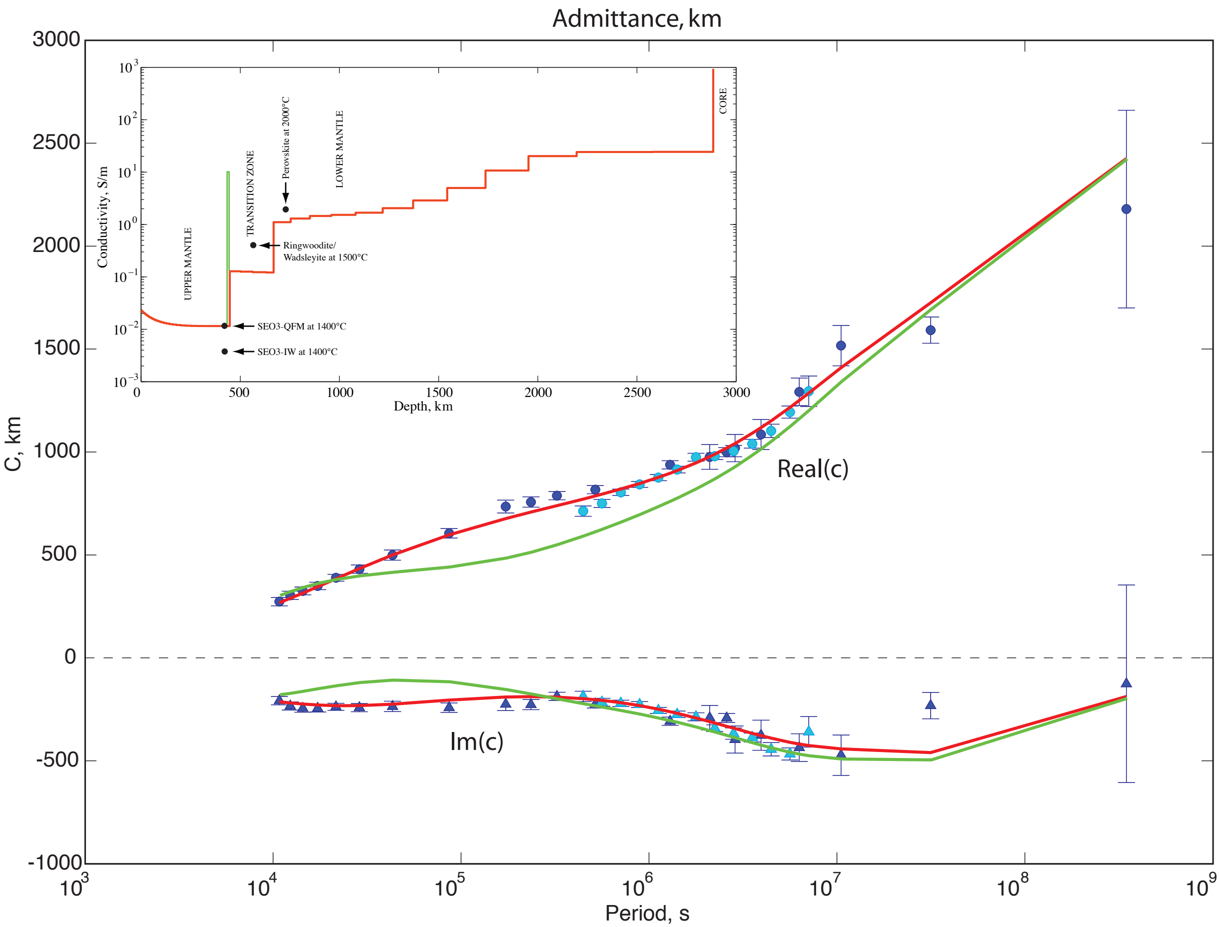
Department of Geology and Geophysics, Yale University, PO Box 208109, New Haven, Connecticut 06520-8109, USA



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

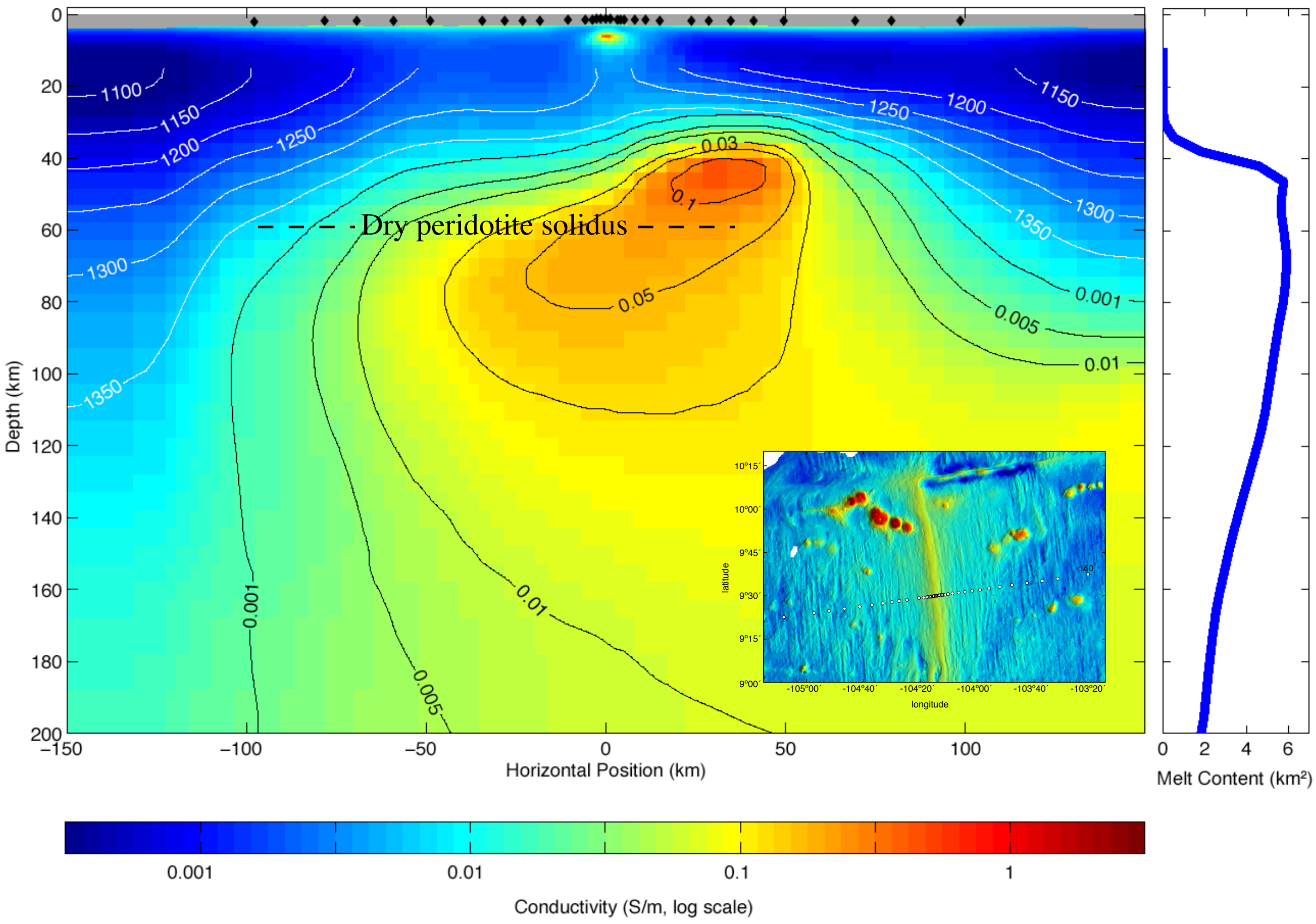
Surely something we can test with EM ...

... by adding a 10 km, 0.1 S/m layer to our model:



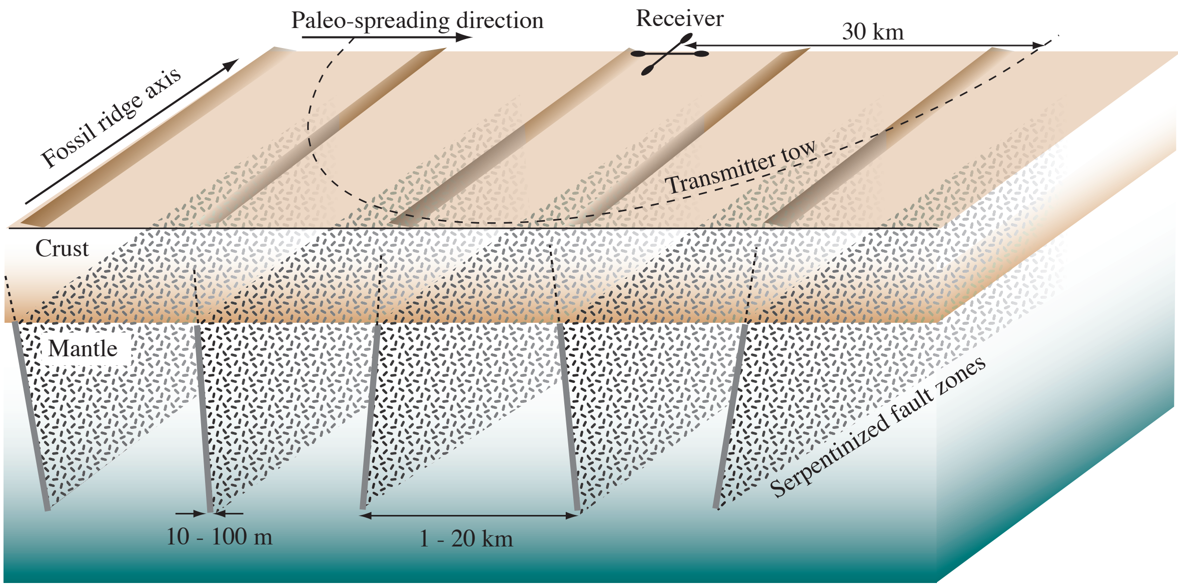
In fact, the biggest conductor you can hide is 10 times smaller, and has to be balanced by an unreasonably resistive upper mantle.

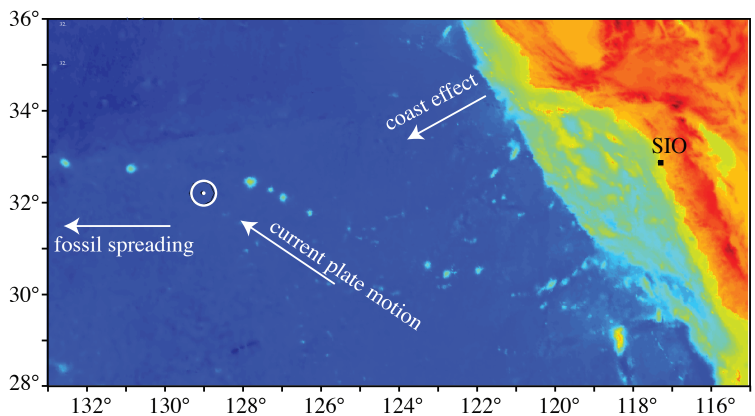
Mantle water undoubtedly exists, and will lower melting point:

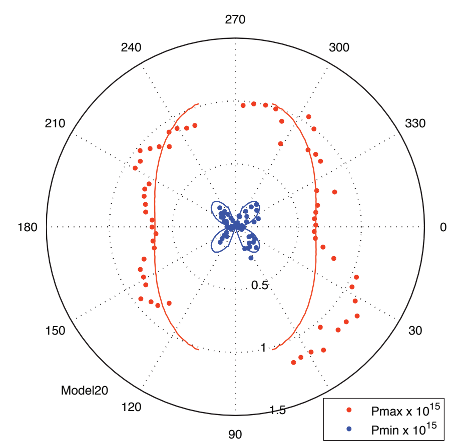


CONDUCTIVITY AND WATER IN THE MANTLE

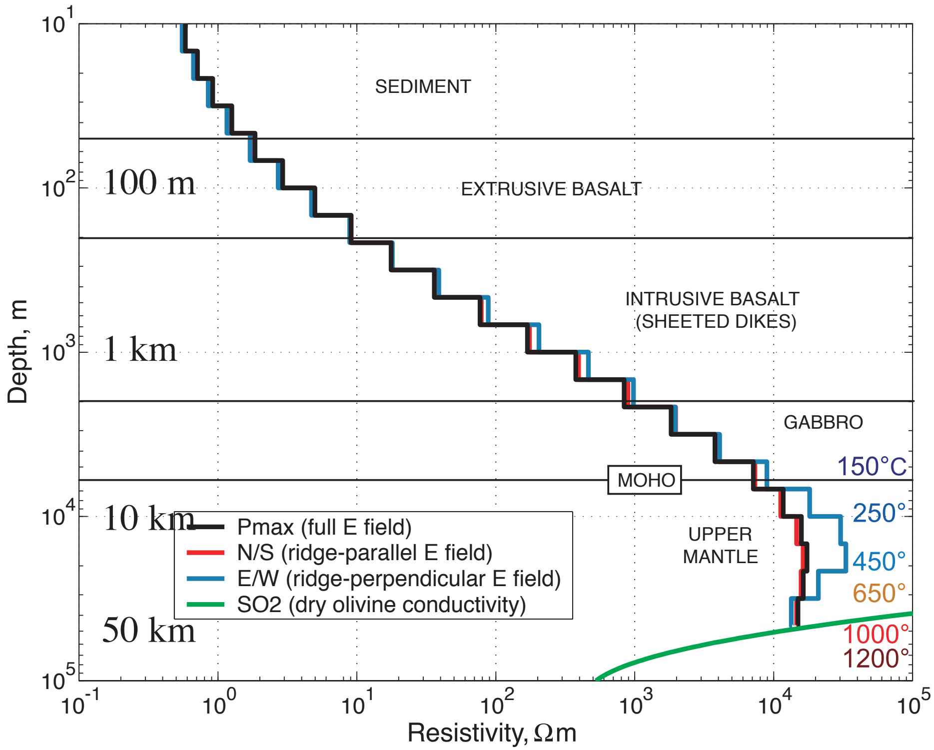
Also can cause serpentinization of olivine in the uppermost mantle:

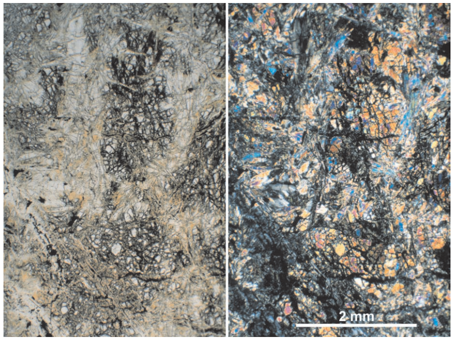


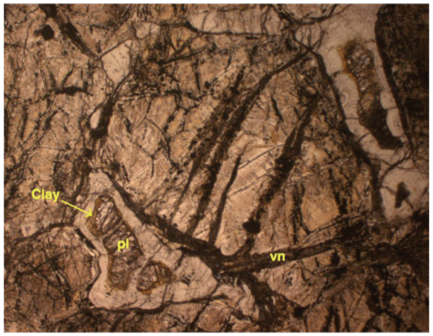




Anisotropy is between the Moho and the max. depth of serpentine stability:







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