Integrating magnetotelluric and seismic geophysical observations to improve upper mantle viscosity estimates beneath polar regions

Florence Ramirez

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Abstract

Mantle viscosity controls a variety of geodynamic processes, e.g. Glacial Isostatic Adjustment (GIA). Constraining GIA using better viscosity estimates would improve our estimates of recent ice mass loss from the Greenland and Antarctic ice sheets and the associated sea level rise. However, mantle viscosity is poorly constrained as it can rarely be measured directly, making geophysical observations that could place constraints on viscosity more essential. Empirically, viscosity is mainly controlled by temperature, water content of nominally anhydrous minerals, partial melt, grain size and stress. Of these, temperature, water content, and the presence of partial melt can be inferred from seismic and magnetotelluric (MT) measurements, which are important tools in imaging the subsurface of the Earth. In this study, we develop a method to estimate mantle viscosity in which we: (1) constrain temperature from MT, seismic, and surface heat flow observations; (2) constrain compositional structure (i.e., water content and partial melt) from MT and seismic data coupled with experimental mineral physics data; and finally, (3) convert the calculated thermal and compositional structures into a viscosity structure. In each step, we assess and quantify the involved uncertainties. In addition, we introduce a useful parameter – the viscosity ratio (a ratio between viscosities of a target region and a nearby reference region at the same stress and grain size), and quantify its amplitude and uncertainty for a range of temperatures and water contents. We find that the uncertainty in this ratio is relatively small when computed from both seismic and MT observations, compared to either constraint applied alone. We also explore how viscosity ratio uncertainties vary with grain size and stress. Information about grain size can potentially be obtained from seismic attenuation or tectonic history. Overall, we find that both seismic and MT observations can considerably improve estimates of mantle viscosity, and place useful constraints on its lateral variations in the upper mantle. Geophysically-derived mantle viscosity models can be calibrated in areas like Scandinavia, which has well-constrained GIA models, and applied to polar regions where the GIA response is poorly known.
Integrating MAGNETOTELLURIC & SEISMIC observations to improve UPPER MANTLE VISCOSITY

Florence Ramirez
Kate Selway
Clint Conrad
What are the common approaches in constraining upper mantle viscosity? What are their limitations?

<table>
<thead>
<tr>
<th>Approach</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1] From GIA (glacial isostatic adjustment) observables</td>
<td>Geographically-bounded, low depth resolution and usually provides 1D viscosity profile, restricts us from inferring lateral viscosity variations</td>
</tr>
<tr>
<td>[2] From postseismic relaxation</td>
<td>Geographically-bounded, data-limited</td>
</tr>
<tr>
<td>[3] Geophysical measurements: Seisms alone, MT alone</td>
<td>Uncertainties involved are poorly constrained</td>
</tr>
</tbody>
</table>

Why use geophysical observables (MT & seisms)?

- scan beneath the region of interest
- Probe mantle parameters that relate to mantle viscosity, and potentially detect lateral variations in these parameters
# Relationship between geophysical observations and mantle viscosity

## Parameters influencing mantle viscosity

### Olivine (for upper mantle) deformation:

Strain rate:

\[
\dot{\varepsilon} = A \sigma^n d^{-p} C_{OH}^r \exp(\alpha \varphi) \exp\left(-\frac{E^* + PV^*}{RT}\right)
\]

- **Activation energy**
- **Pressure Activation volume**

### Controlling factors:

1. Temperature
2. Water content
3. Melt fraction
4. Grain size
5. Stress

### Constrain these parameters from:

#### Seismics

- **From seismic velocity:**
  - (1) Temperature
  - (3) Melt fraction
- **From seismic attenuation:**
  - (4) Grain size

#### Magnetotellurics

- **From electrical conductivity:**
  - (1) Temperature
  - (2) Water content
  - (3) Melt fraction

  (5) Stress

Numerical models of tectonic history or loading

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Karato, 2008
Jackson et al., 2002

Gardés et al., 2014
Sifre et al., 2014
Step 1: Convert $v_{S(p)}$ to $T$, neglecting chemical effects (for now)

Step 2: Determine water content from MT derived-conductivity $\sigma_c$ using conductivity model

Step 3: Determine $\eta$ using

$$\eta_{eff} = \frac{\sigma}{\dot{\varepsilon}_{tot}}$$

where

$$\dot{\varepsilon}_{tot} = \dot{\varepsilon}_{Dis} + \dot{\varepsilon}_{Dif} + \dot{\varepsilon}_{DisGBS}$$
Use of deformation map over water content and $T$ space

[stress = 0.1 MPa, grain size = 10 mm, $P = 3.5$ GPa]

**Effective Viscosity**

**Shear wave velocity**

**Electrical conductivity**

*Seismic velocity and electrical conductivity for olivine at any $C_{OH}$ and $T$ are calculated using Hacker and Abers (2004) and Gardés et al. (2014), respectively*
Estimating viscosity for a certain region

\[ \text{stress} = 0.1 \text{ MPa}, \text{ grain size} = 10 \text{ mm}, P = 3.5 \text{ GPa} \]

\[ v_s = 4.60 \pm 0.02 \text{ km/s} \]

\[ T = (1256 \pm 51) \text{ K} \]

\[ \sigma_c = 10^{-2.5\pm0.5} \text{ S/m} \]

both MT and seismics put tighter bounds on viscosity estimate
Seismic velocity is sensitive to both 

[1] composition

[2] temperature

Tradeoff between temperature and composition in determining velocity?

Models courtesy of Prof. C. Lithgow-Bertelloni using self-consistent thermodynamic formalism (Stixrude and Lithgow-Bertelloni, 2005) and bulk composition in Xu et al. (2008)
Different viscosity estimates for upper mantle with same seismic velocity (different T and composition)

1. **dry upper mantle**: $\sim 0.6$ order magnitude difference
2. **wet upper mantle**: $\sim 0.8$ order magnitude difference
Take home message

[1] Mantle viscosity (and its lateral variations) can be better constrained by utilizing both seismic and MT geophysical constraints.

[2] We identify a trade-off between temperature and composition when converting seismic velocity to viscosity.

[3] It is necessary to account compositional variations when estimating viscosity. (FOR FURTHER INVESTIGATION)
THANK YOU!