

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

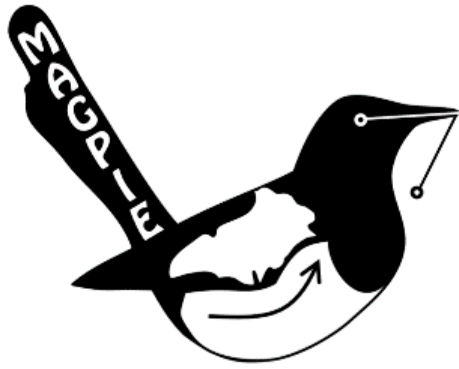
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Abstract

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.



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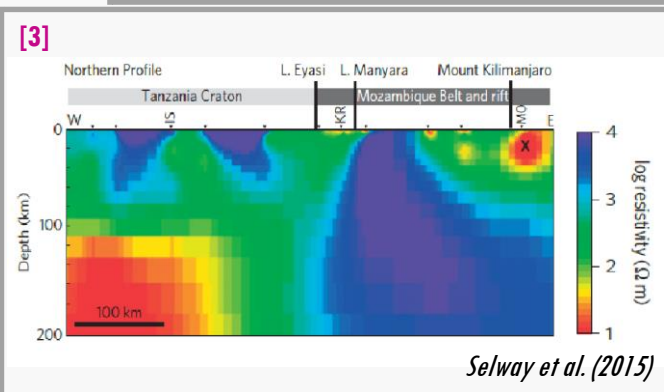
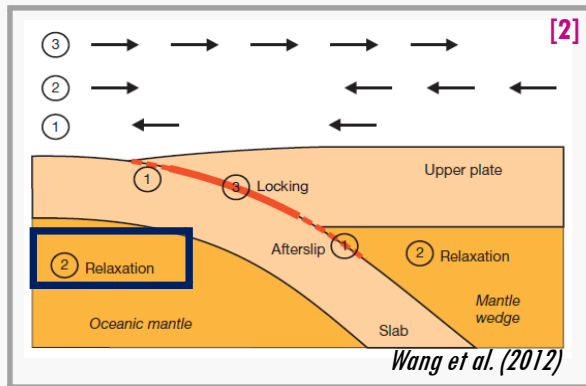
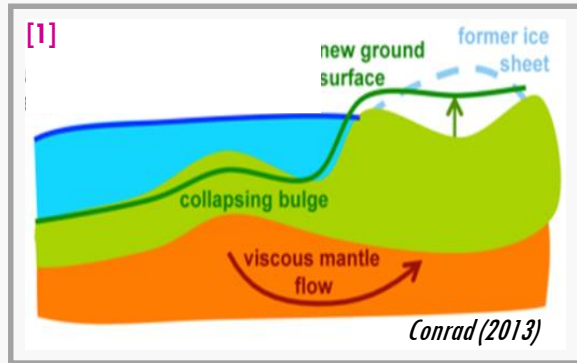
Kate Selway

Clint Conrad

Integrating MAGNETOTELLURIC & SEISMIC observations to improve UPPER MANTLE VISCOSITY



What are the common approaches in constraining upper mantle viscosity? What are their limitations?



Approach	Limitations
[1] From GIA (glacial isostatic adjustment) observables	Geographically-bounded, low depth resolution and usually provides 1D viscosity profile, restricts us from inferring lateral viscosity variations
[2] From postseismic relaxation	Geographically-bounded, data-limited
[3] Geophysical measurements: Seismics alone, MT alone	uncertainties involved are poorly constrained

Why use geophysical observables (MT & seismics)?

- 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:

$$\underset{\text{[power law creep]}}{\dot{\epsilon}} = \underset{\text{Strain rate}}{A} \underset{(5)}{\sigma}^{\underset{(4)}{n}} \underset{(2)}{d^{-p}} \underset{(2)}{C_{OH}^r} \exp(\underset{(3)}{\alpha\varphi}) \exp\left(\underset{\text{Activation energy}}{-\frac{E^*}{RT}} + \underset{\text{Pressure Activation volume}}{\frac{PV^*}{RT}}\right)$$

Hirth & Kohlstedt, 2003

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

Karato, 2008
Jackson et al., 2002

Magnetotellurics

From electrical conductivity:

- (1) Temperature
- (2) Water content
- (3) Melt fraction

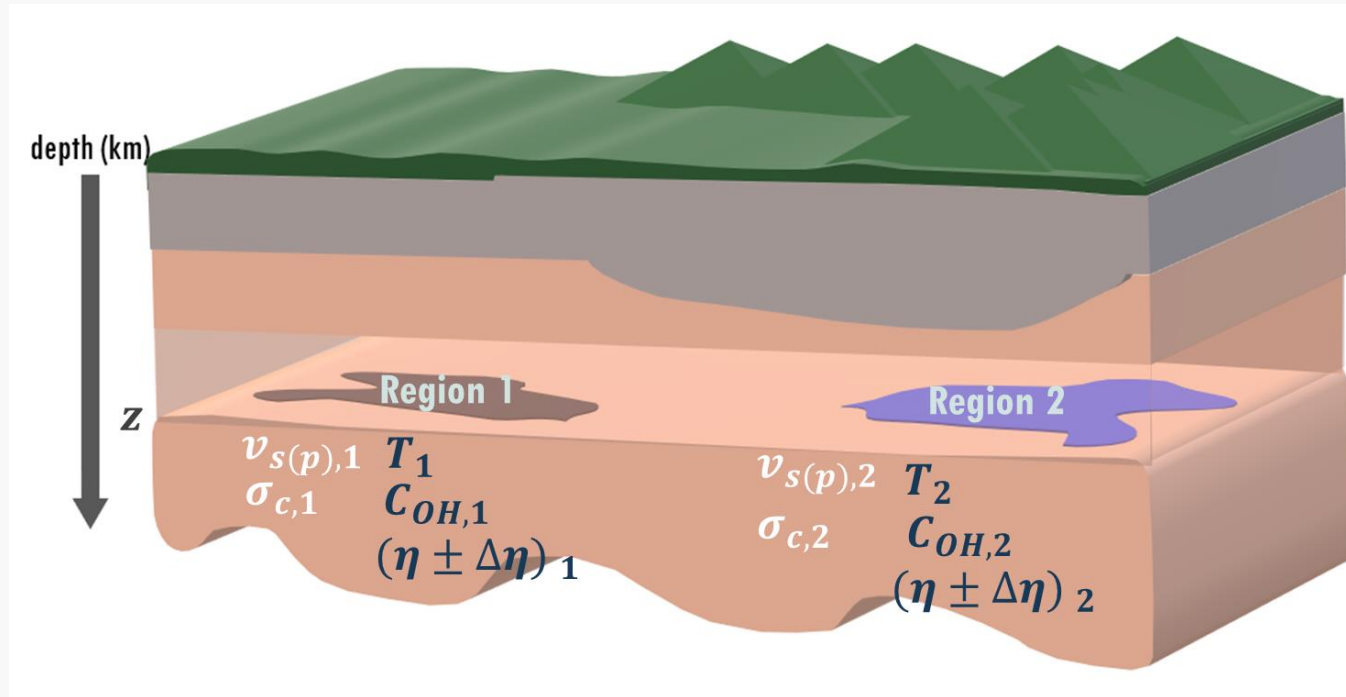
Gardés et al., 2014
Sifre et al., 2014

- (5) Stress

Numerical models of tectonic history or loading

Set-up and method

[melt-free (olivine) upper mantle]



Step 1: Convert $v_{s(p)}$ to T , neglecting chemical effects (for now)

Step 2: Determine **water content** from MT derived-conductivity σ_c using conductivity model

Step 3: Determine η using

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

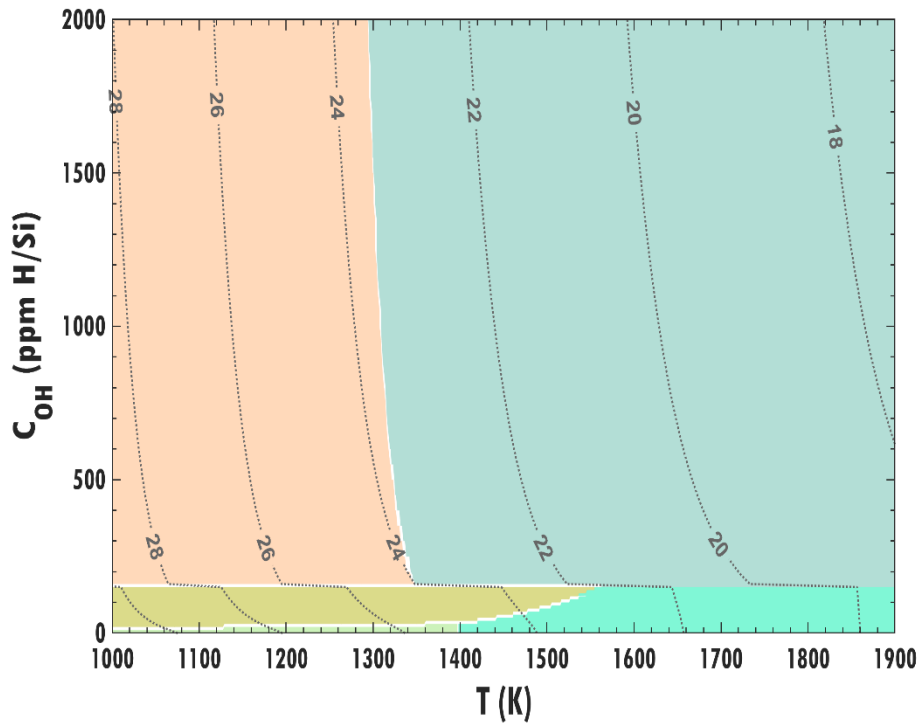
where

$$\dot{\epsilon}_{tot} = \dot{\epsilon}_{Dis} + \dot{\epsilon}_{Dif} + \dot{\epsilon}_{DisGBS}$$

Use of deformation map over water content and T space

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

Effective Viscosity



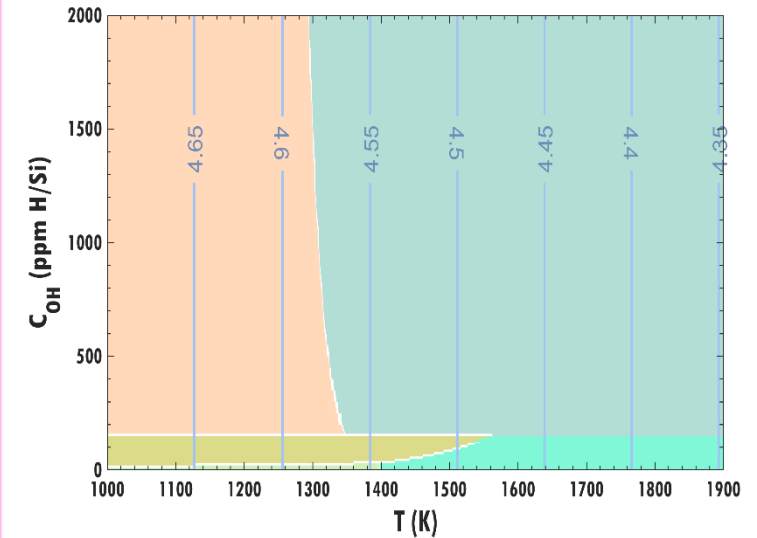
LEGEND:

- $\log \eta$ (Pa·s)
- $\log \sigma_c$ (S/m)
- v_s (km/s)
- orange wet diffusion
- teal wet dislocation
- light green dry diffusion
- cyan dry dislocation
- yellow-green (dry) DisGBS

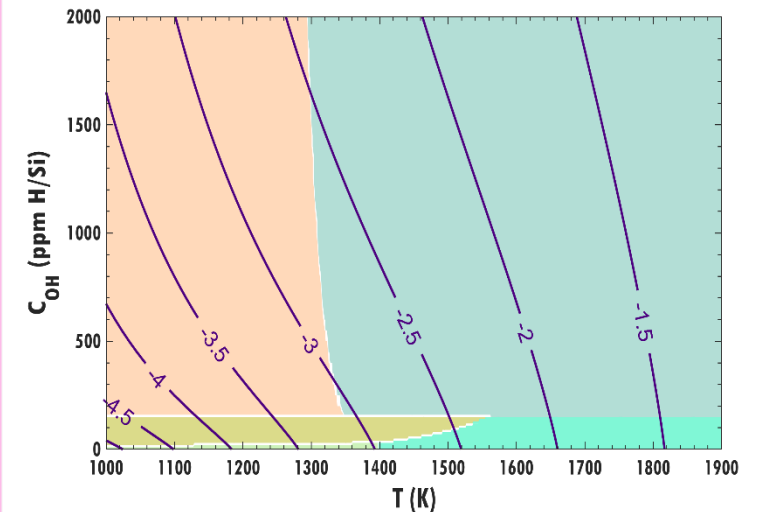
OVERLAP to
estimate VISCOSITY
for a given
geophysical
observation

*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

Shear wave velocity*

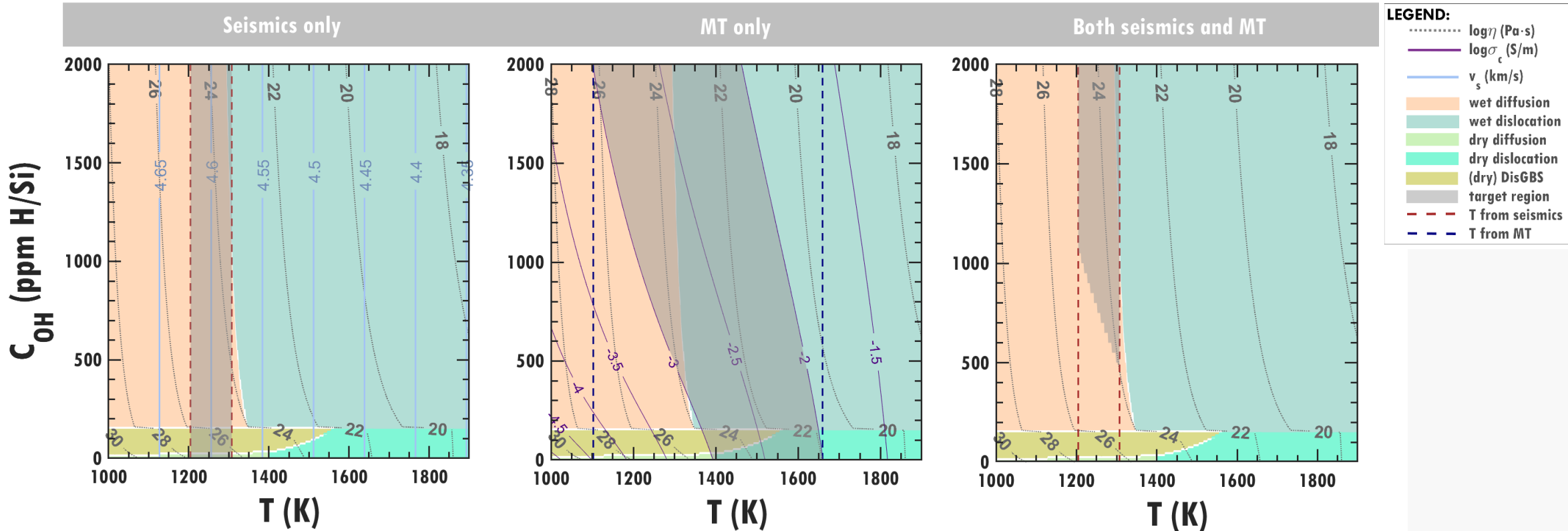


Electrical conductivity*



Estimating viscosity for a certain region

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



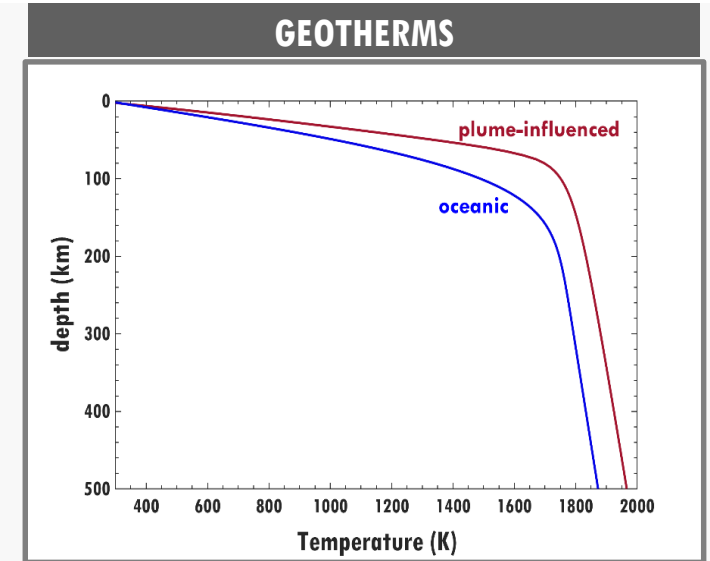
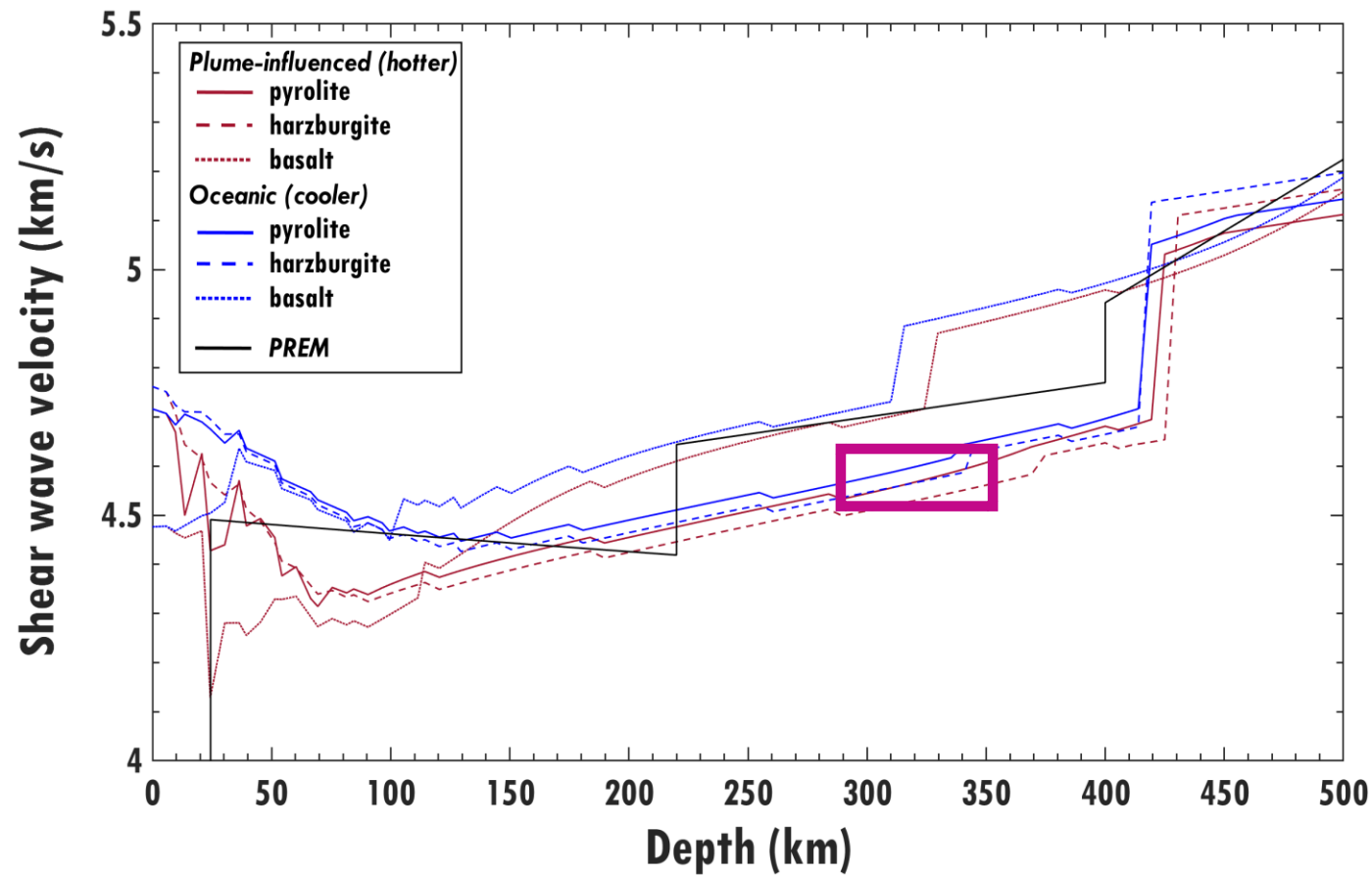
assumed $v_s = (4.60 \pm 0.02)$ km/s

$\sigma_c = 10^{-(2.5 \pm 0.5)}$ S/m

inferred $T = (1256 \pm 51)$ K

both MT and seismics put tighter bounds on viscosity estimate

Tradeoff between temperature and composition in determining velocity?



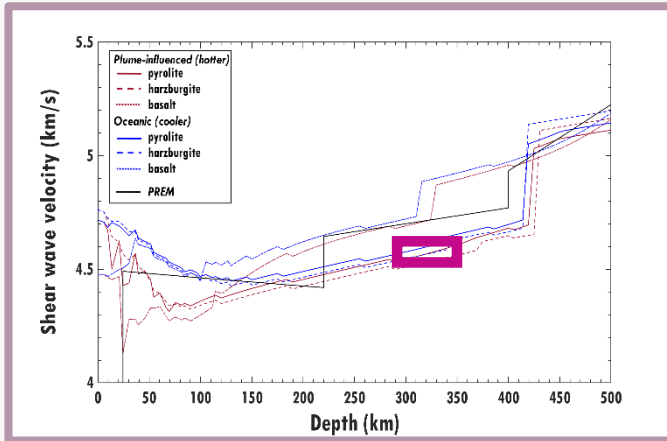
Seismic velocity is sensitive to both

[1] **composition**

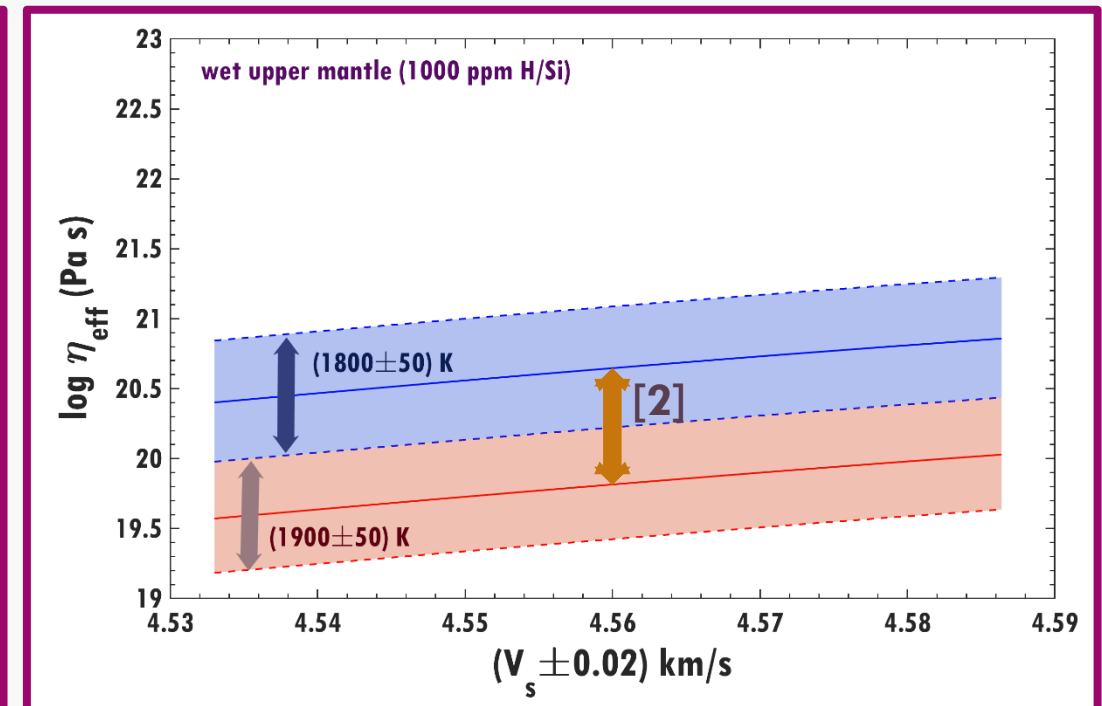
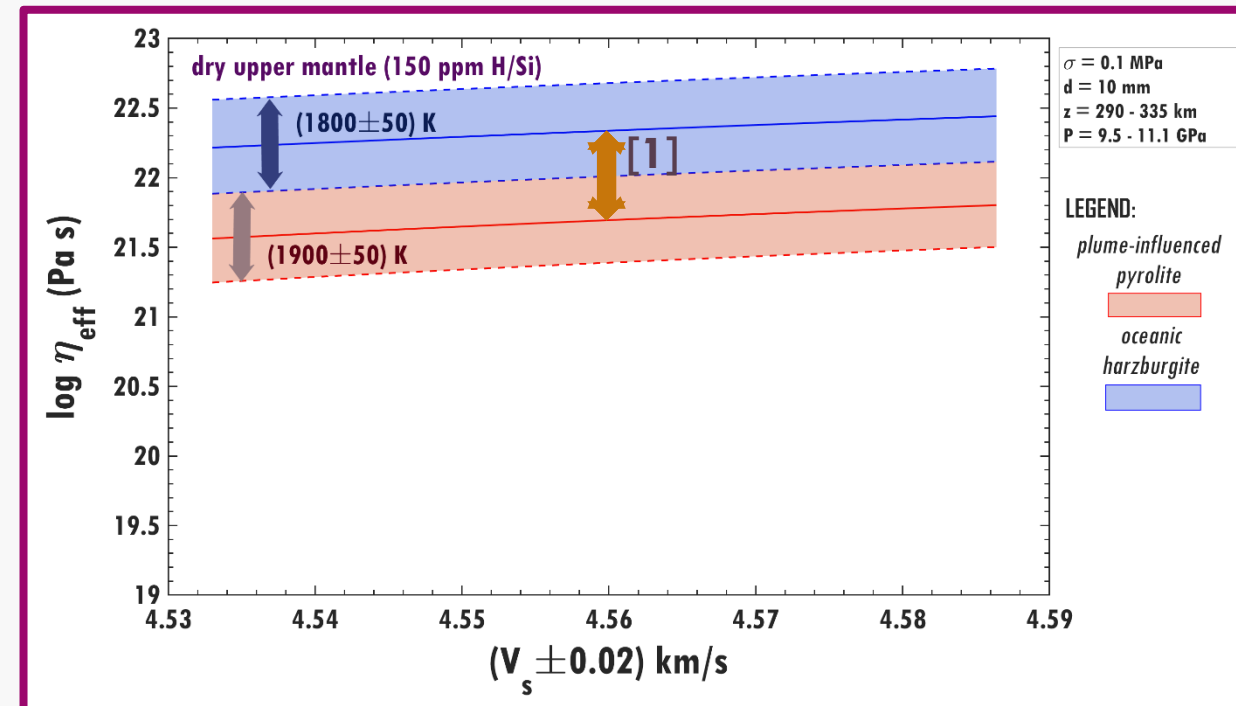
[2] **temperature**

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)

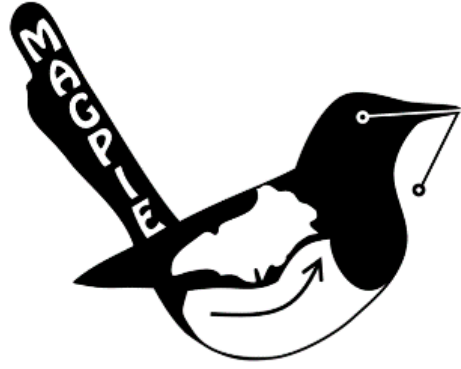


- [1] **dry upper mantle**: ~ 0.6 order magnitude difference
- [2] **wet upper mantle**: ~ 0.8 order magnitude difference



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!

