Using paleo sea level records to image Earth's internal structure and decipher drivers of sea level change

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Committee on Solid Earth Geophysics (COSEG) Fall 2020 Meeting

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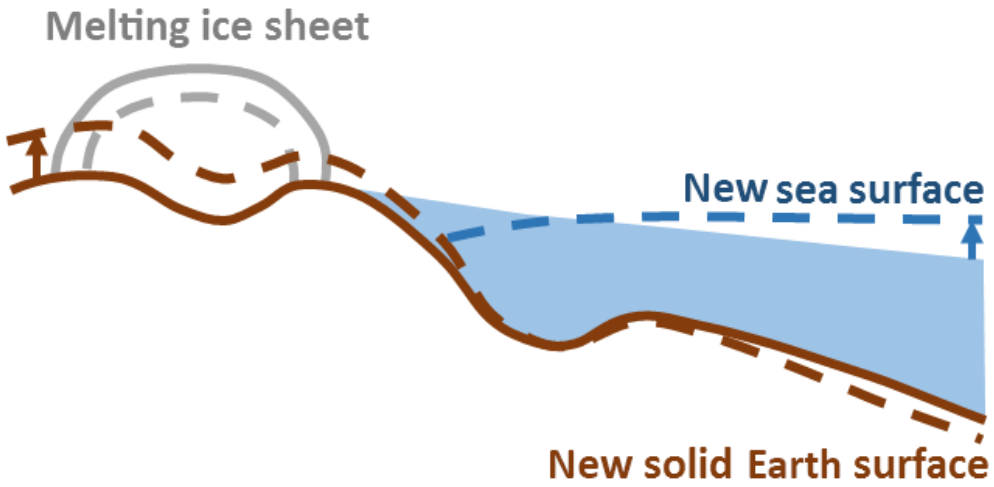
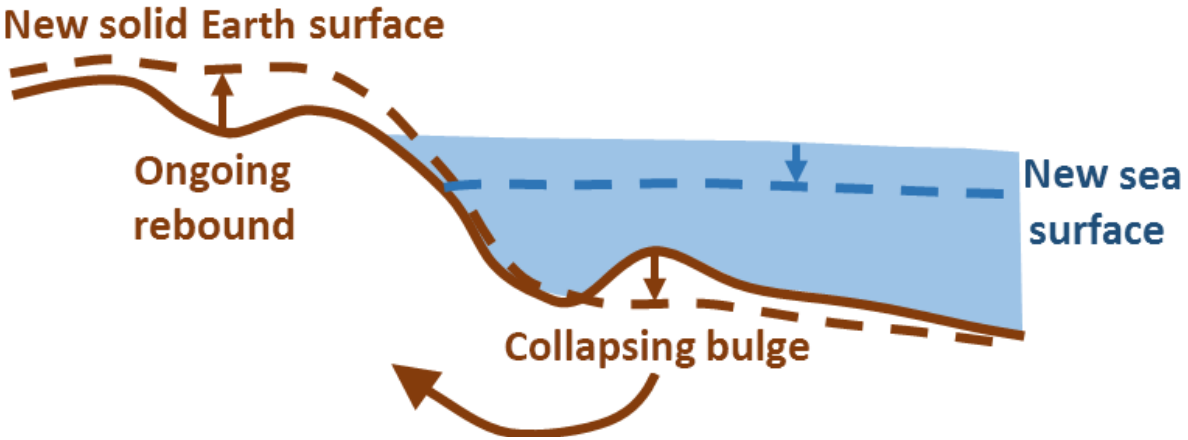
Glacial isostatic adjustment (GIA)



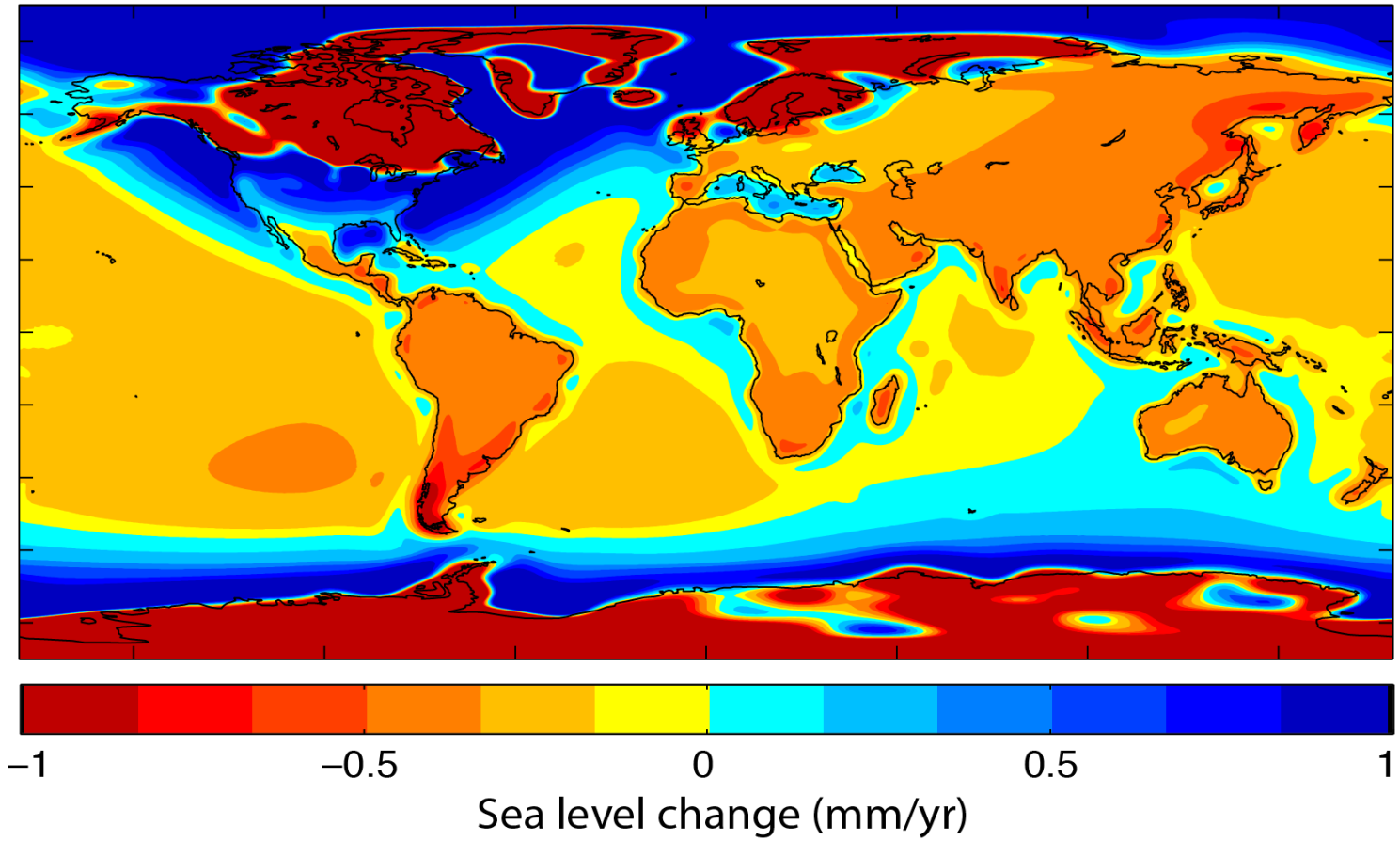


- Elastic response
  - instantaneous deformation of solid earth
  - instantaneous change in ocean volume
  - instantaneous change in shape of geoid

- Viscous response
  - time-decaying earth deformation
  - no change in ocean volume
  - Instantaneous change in shape of geoid

Whitehouse, 2018

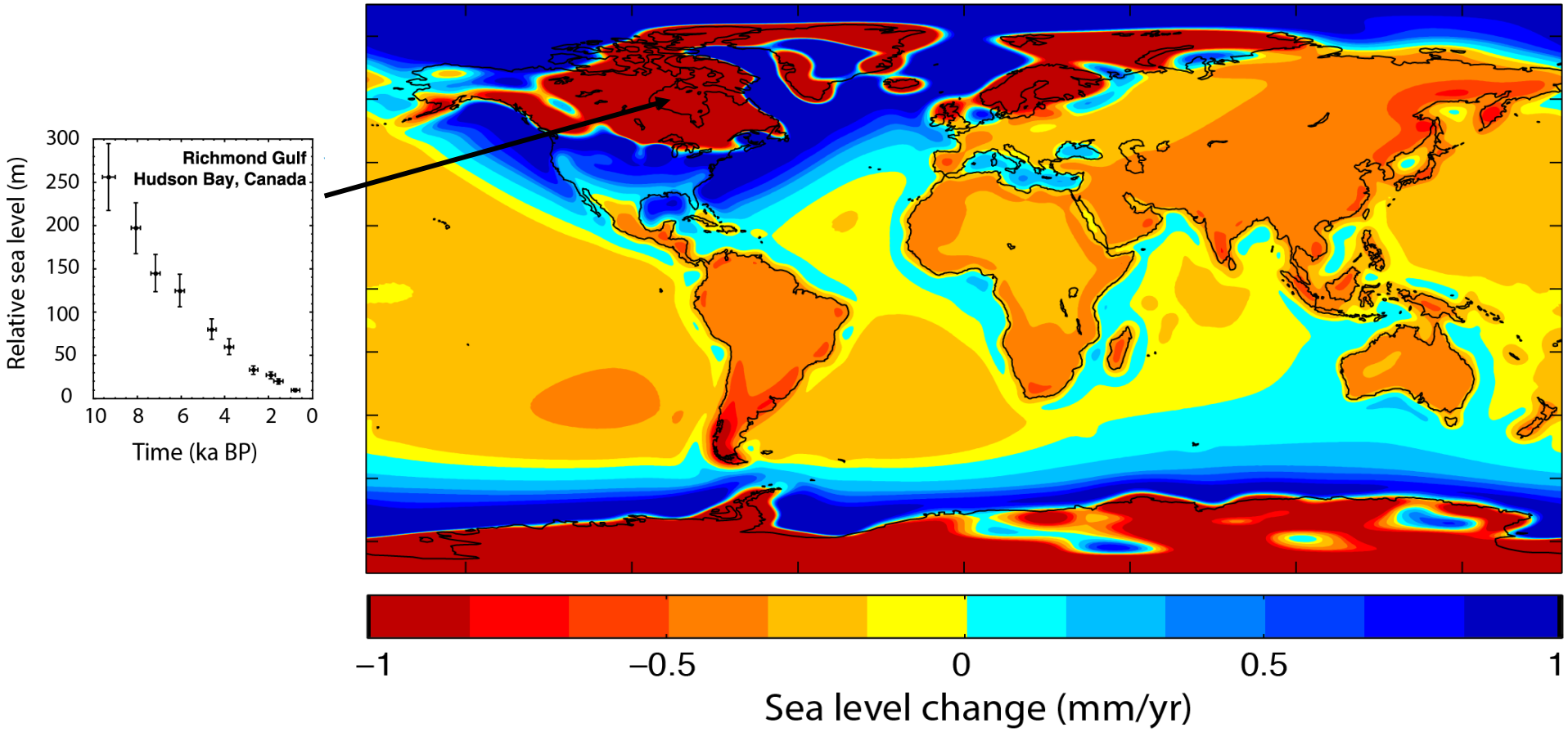
Present-day sea level change due to ‘background’ GIA



Numerical Prediction of present-day rate of global sea-level change due to ongoing glacial isostatic adjustment

ICE5G/VM2 from Peltier, 2004; after Mitrovica and Milne, 2002

Present-day sea level change due to ‘background’ GIA



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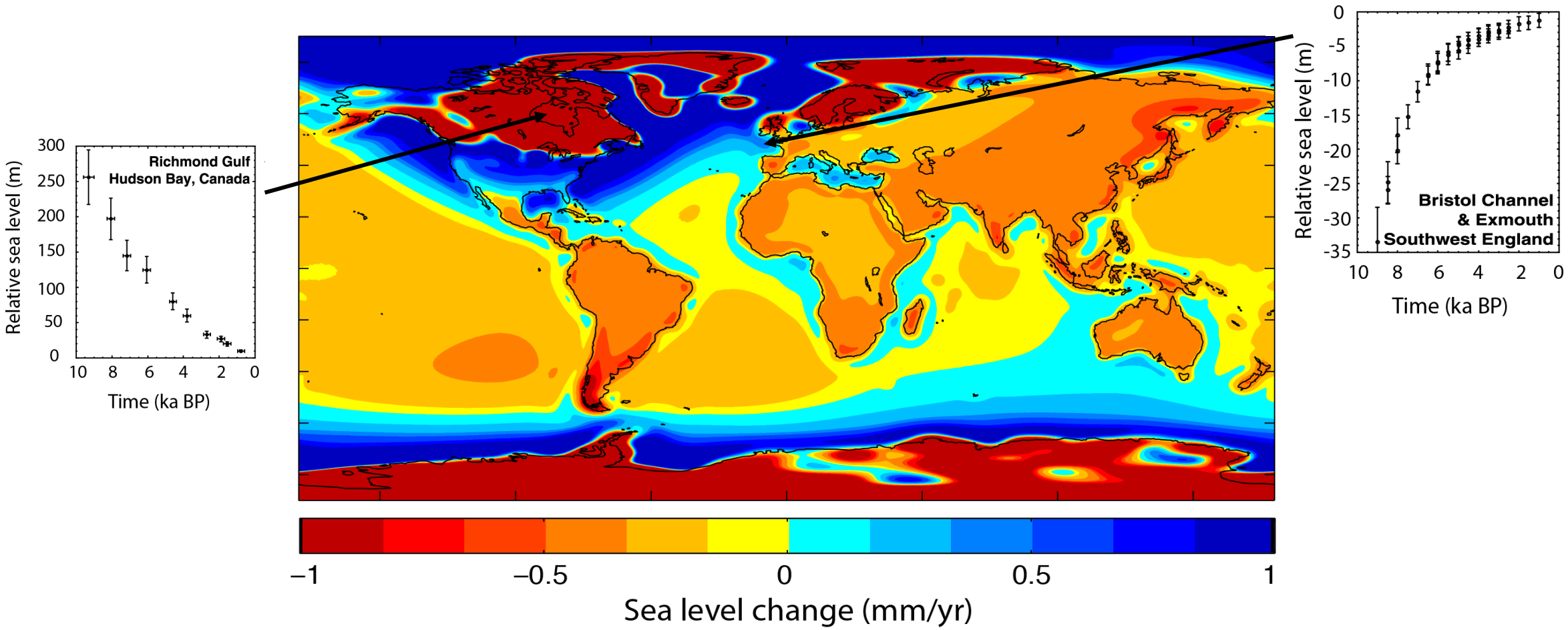

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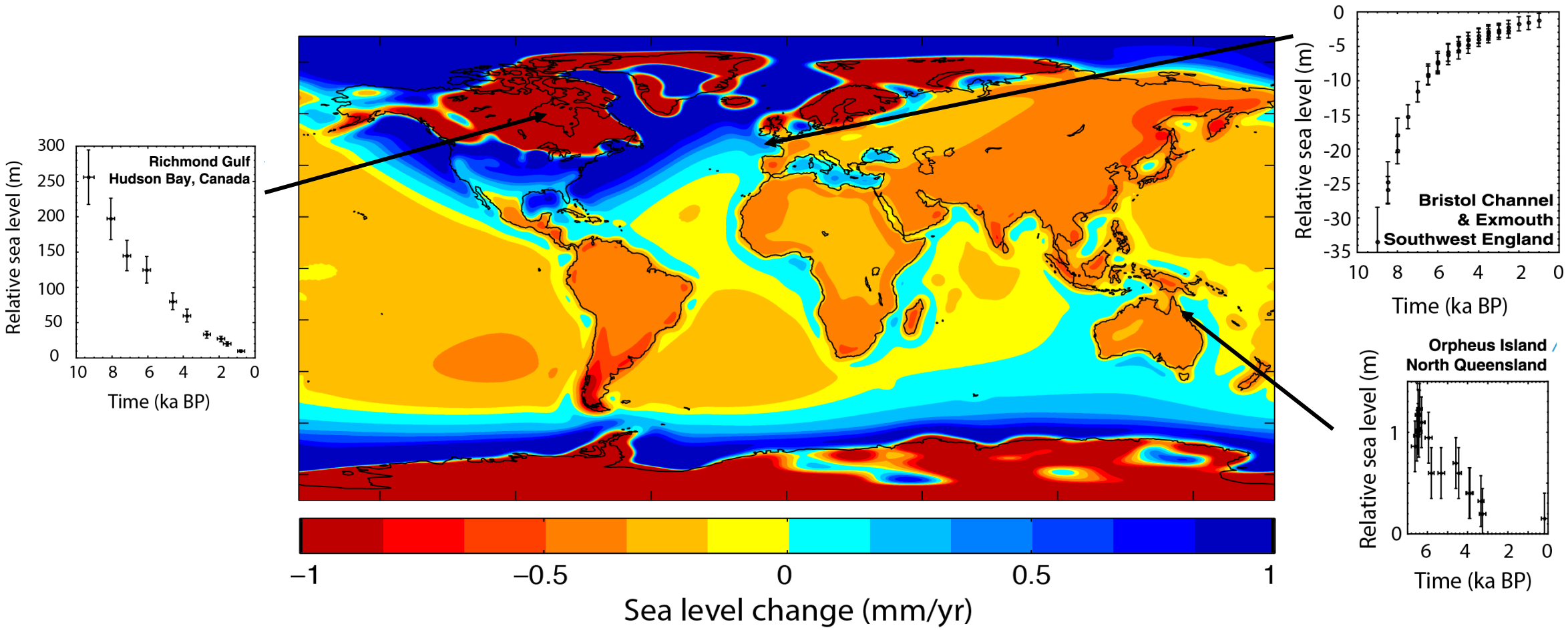


Numerical Prediction of present-day rate of global sea-level change due to ongoing glacial isostatic adjustment

ICE5G/VM2 from Peltier, 2004; after Mitrovica and Milne, 2002

Earth's viscosity

The Motion of a Viscous Fluid Under a Surface Load

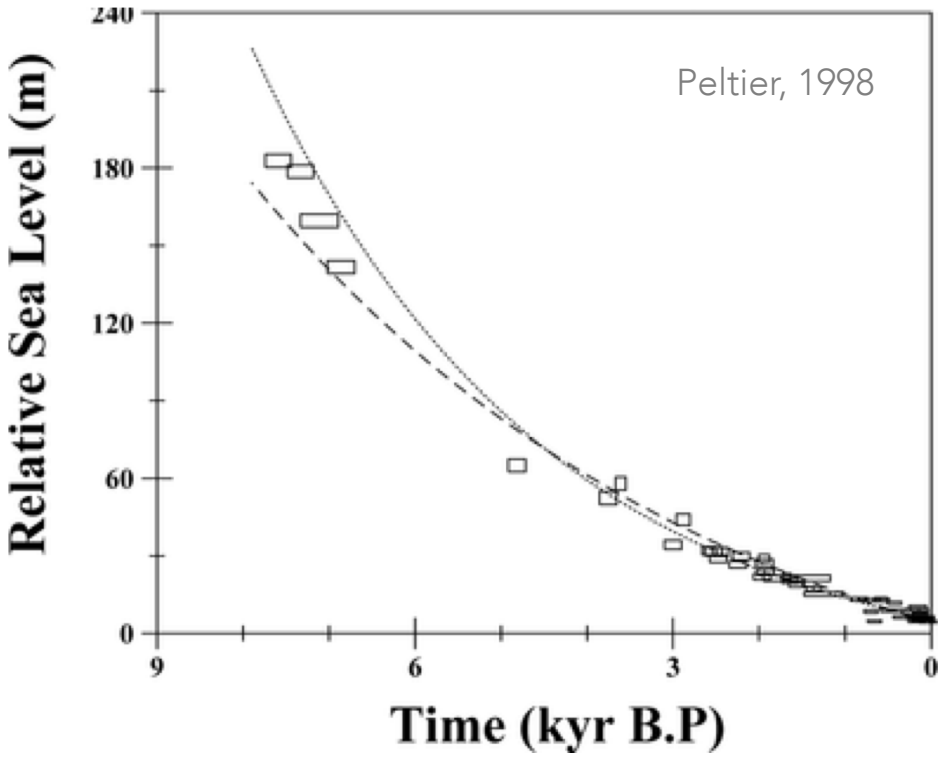
N. A. HASKELL, *Massachusetts Institute of Technology*

(Received April 25, 1935)

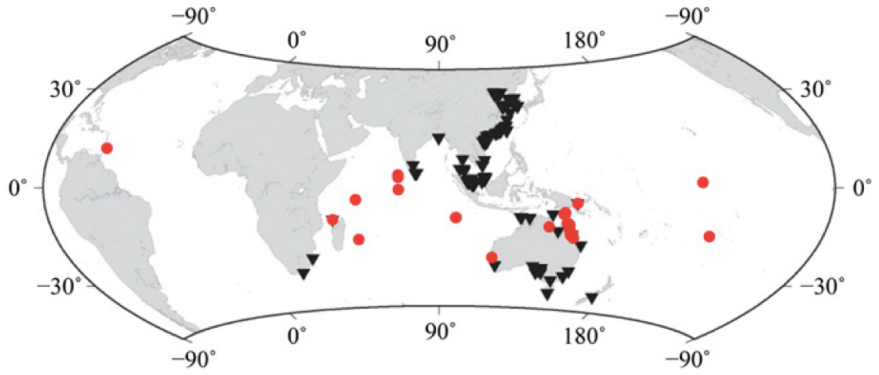
A formal solution is given for the motion of a highly viscous fluid when a symmetrical pressure is applied at the surface. This is applied to the subsidence of a cylindrical body of constant thickness and to the recovery of the fluid after removal of a load. Applying the latter case to the plastic recoil of the earth after the disappearance of the Pleistocene ice sheets, it is found that the geological data imply a kinematic viscosity of the order of 3×10^{21} c.g.s. units.

Dynamic viscosity of ~ 10^{21} Pa s

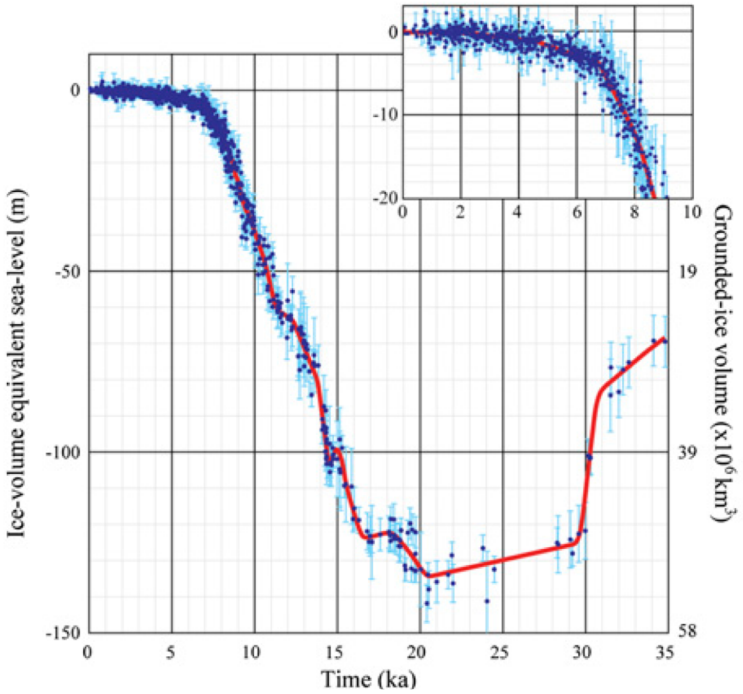
Uplifted beaches: decay time only sensitive to Earth's viscosity

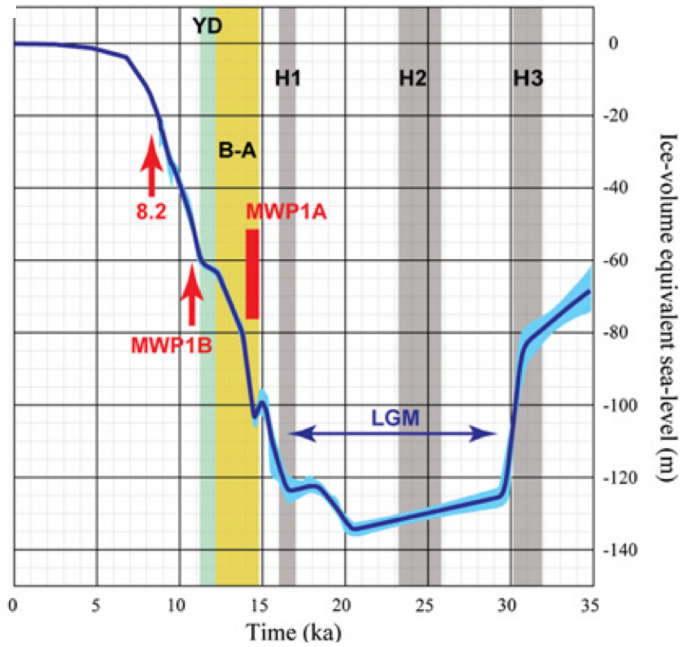


Earth's viscosity and past ice history



Higher viscosity favored

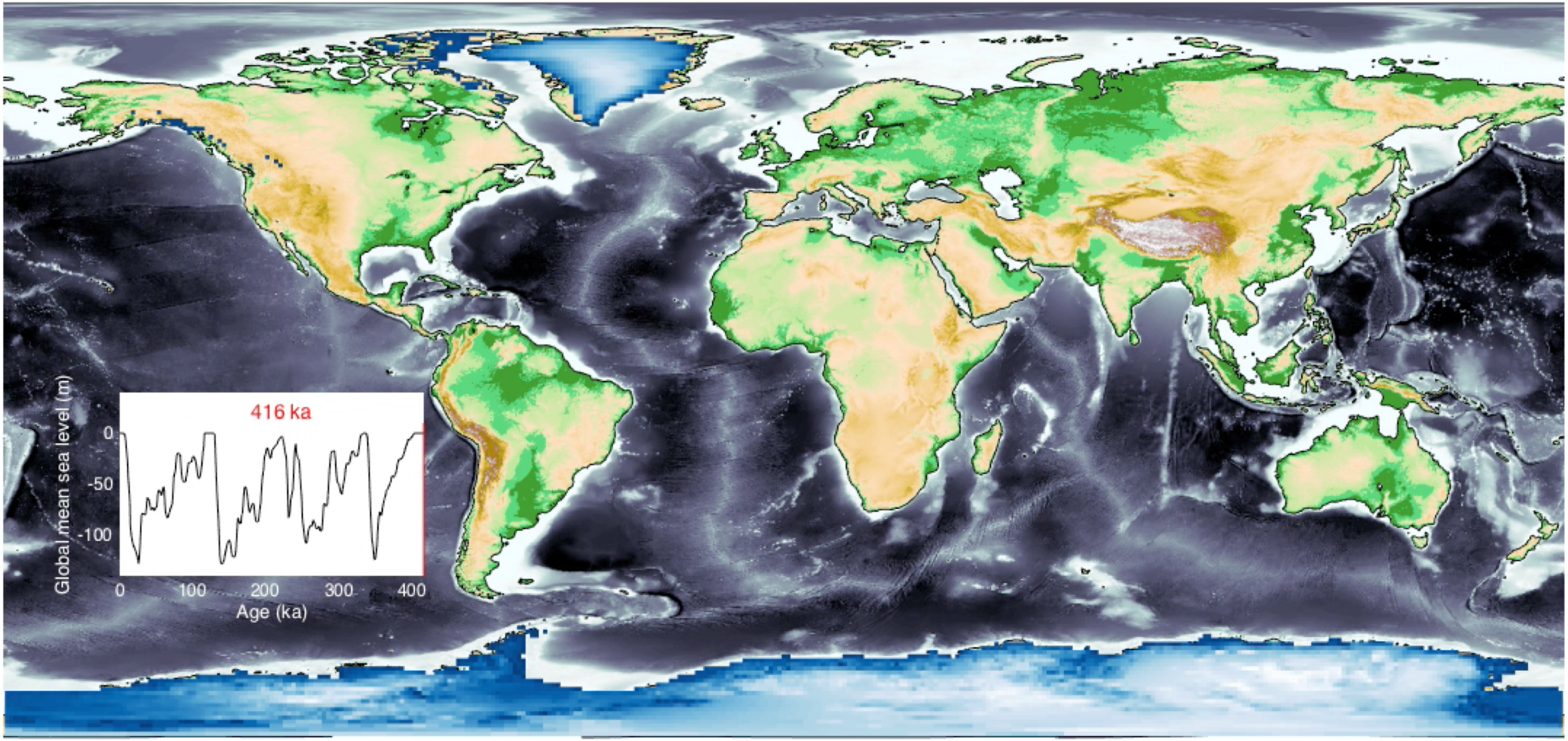




Lambeck *et al.*, 2014

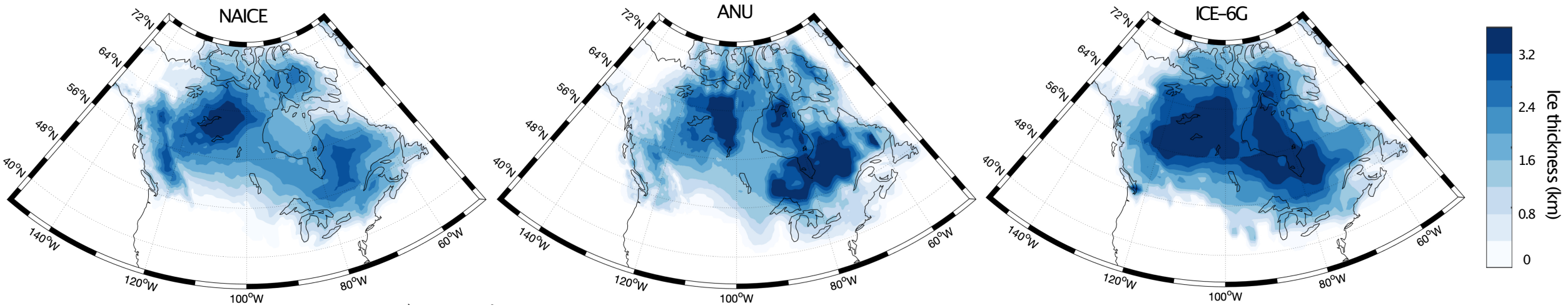
Earth's ice sheets and sea level

Video available at
https://www.ldeo.columbia.edu/~jackya/teaching.html



Ice sheet reconstructions

Laurentide ice sheet at 18 ka



Gowan *et al.*, 2016

Lambeck *et al.*, 2017

Peltier *et al.*, 2015

Outstanding questions:

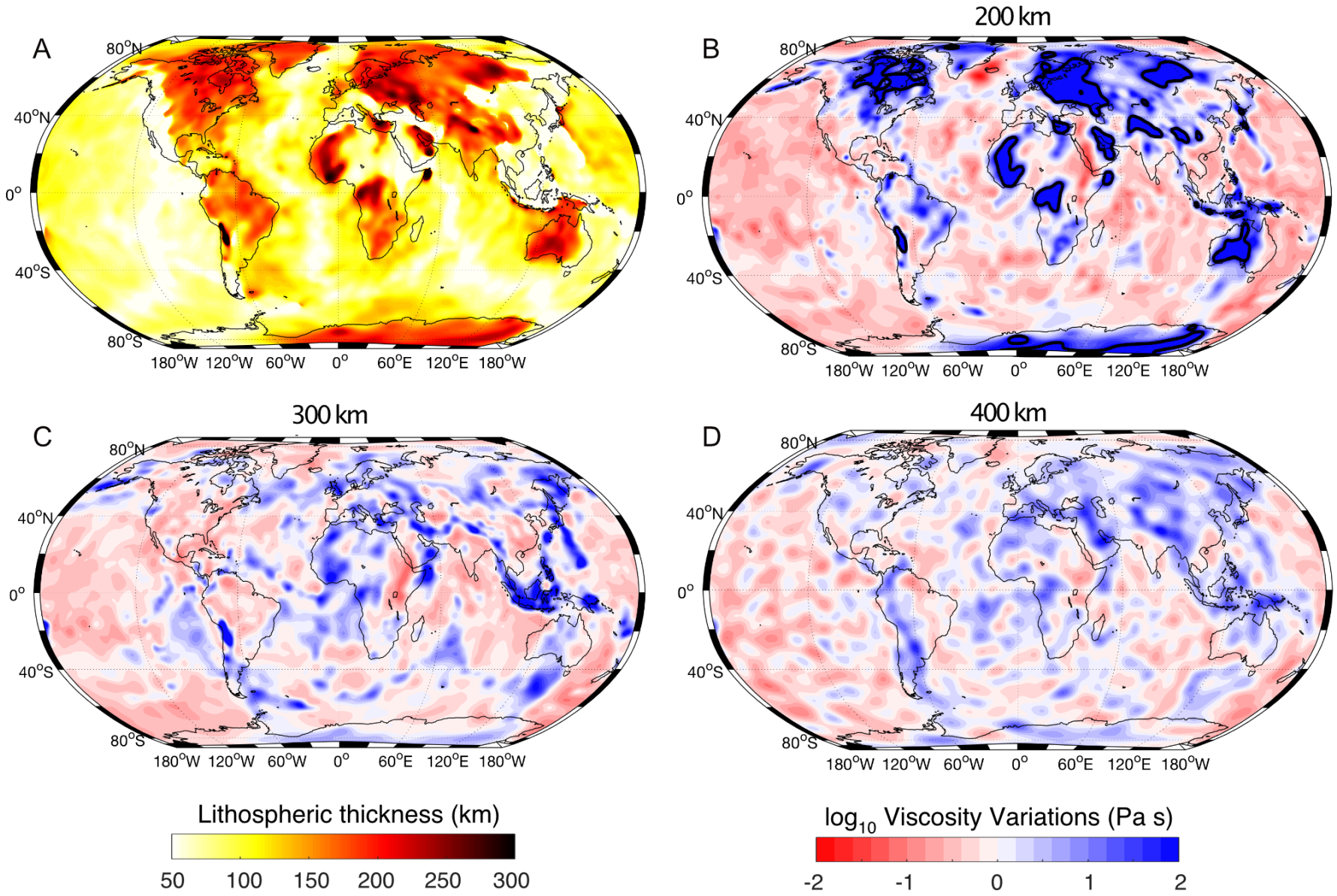
- More detailed size and evolution of all ice sheets
- “Missing ice problem” at the Last Glacial Maximum
- Contribution from different ice sheets to Meltwater Pulse 1A and other meltwater events

Earth's viscoelastic structure

Earth's internal viscosity varies laterally.

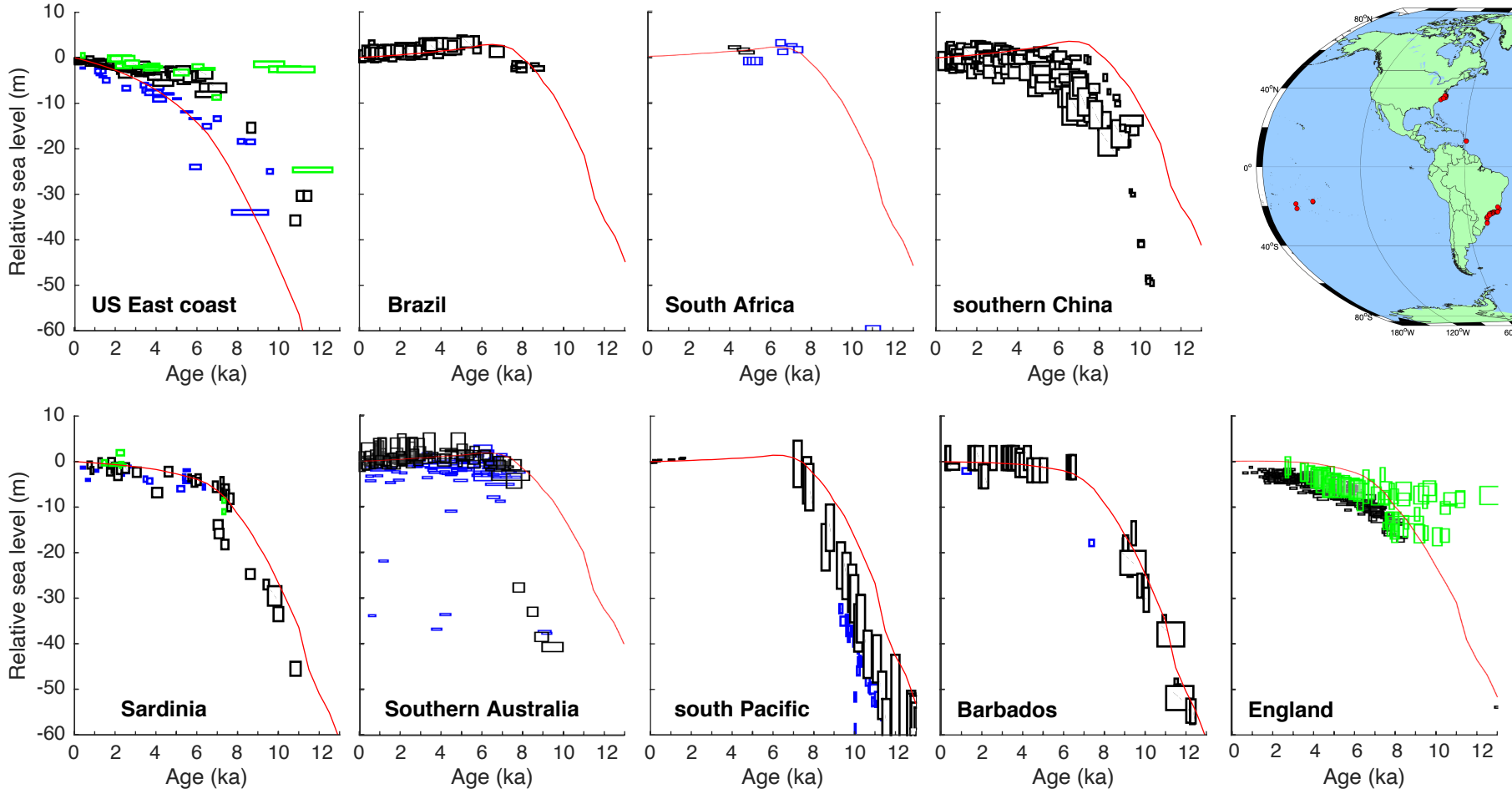
Relies on seismic tomography and rheological laws (uncertainties).

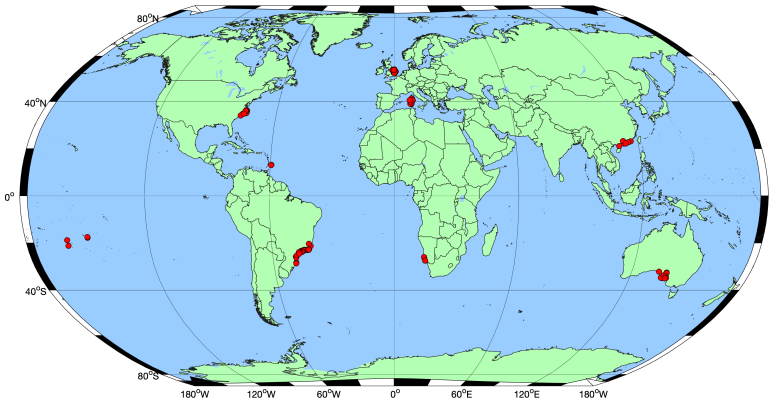
Accounting for this in GIA calculation is computationally expensive.



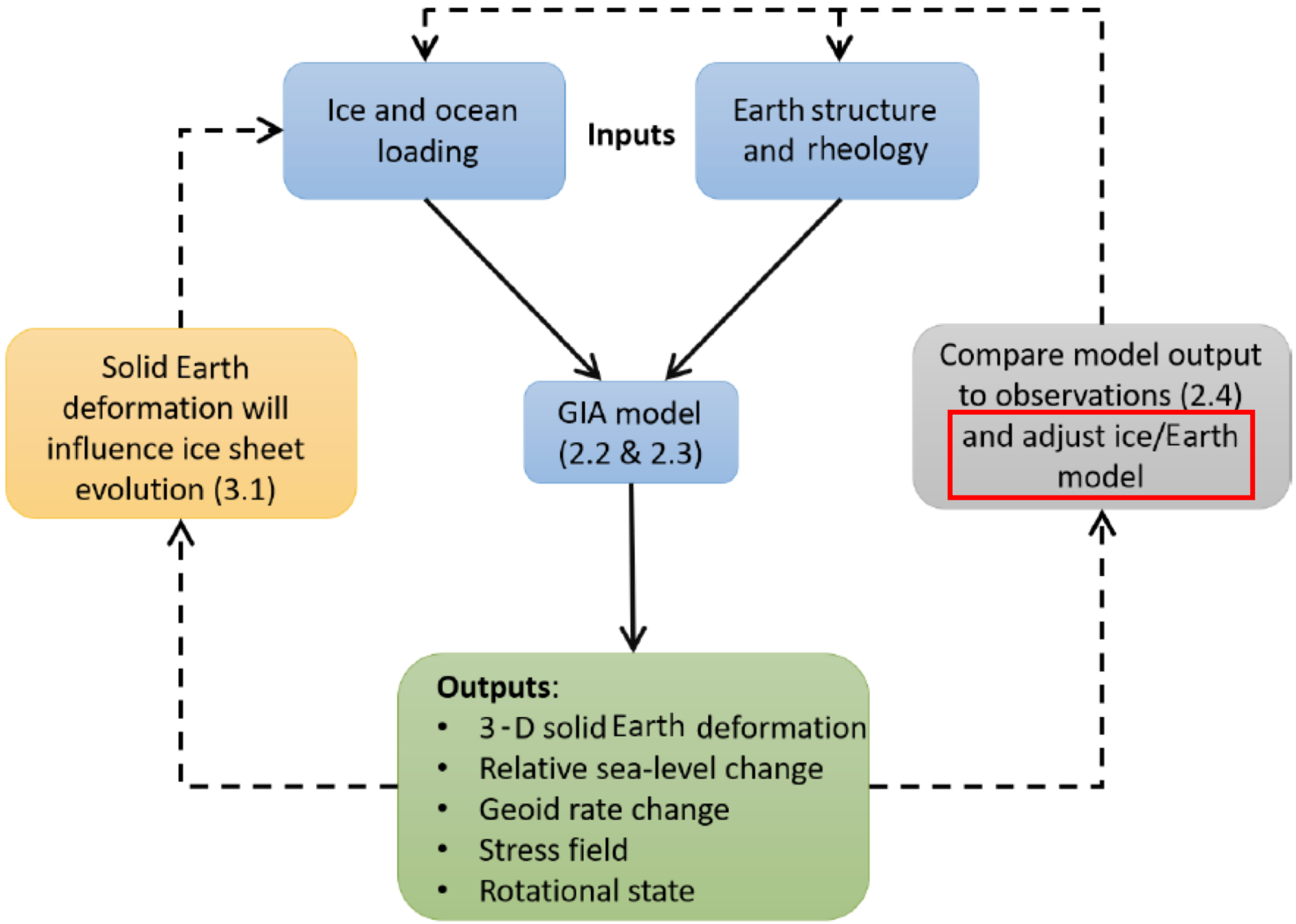
Austermann et al., *in rev.*

Remaining data – model misfit



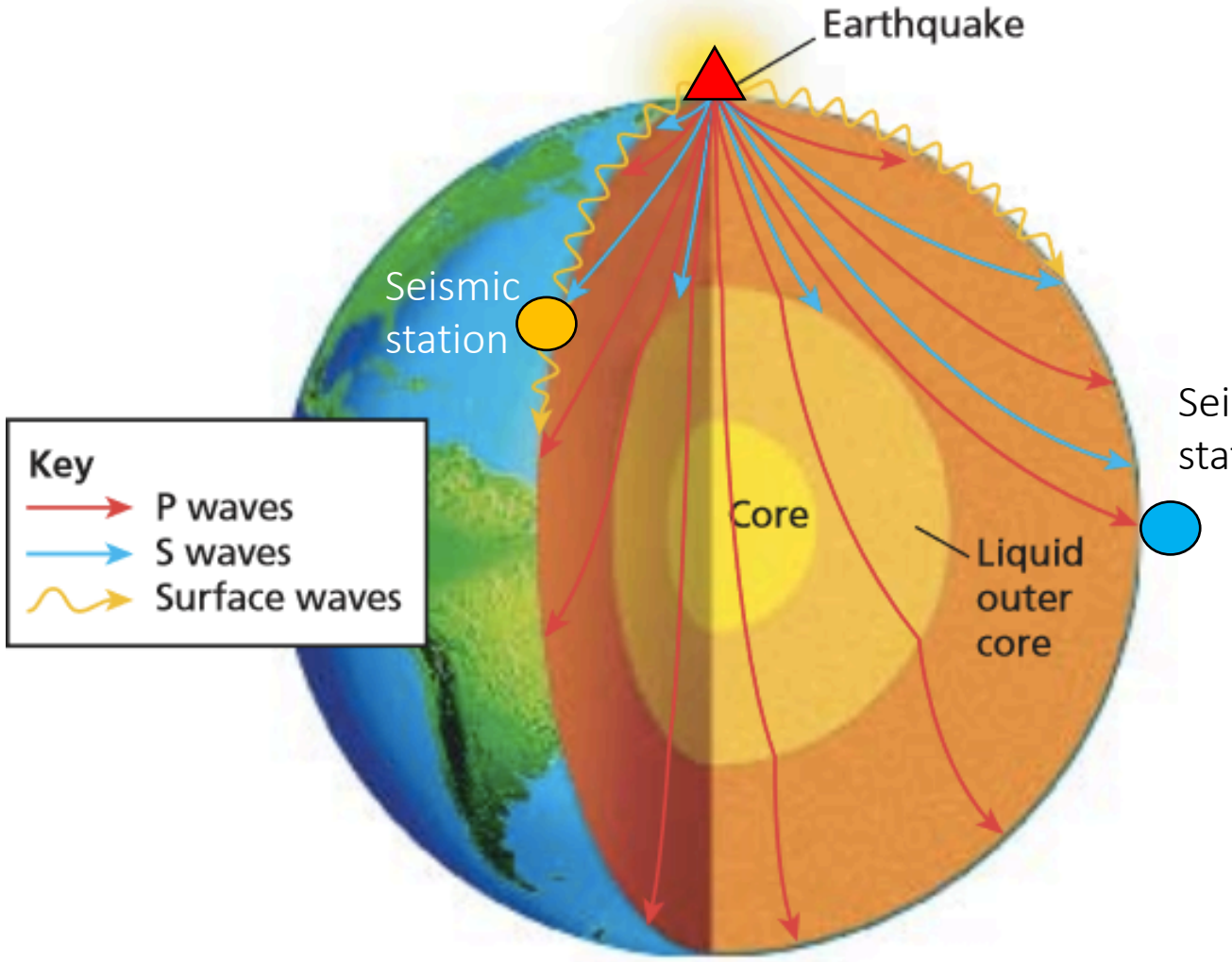


Inverting GIA models with data

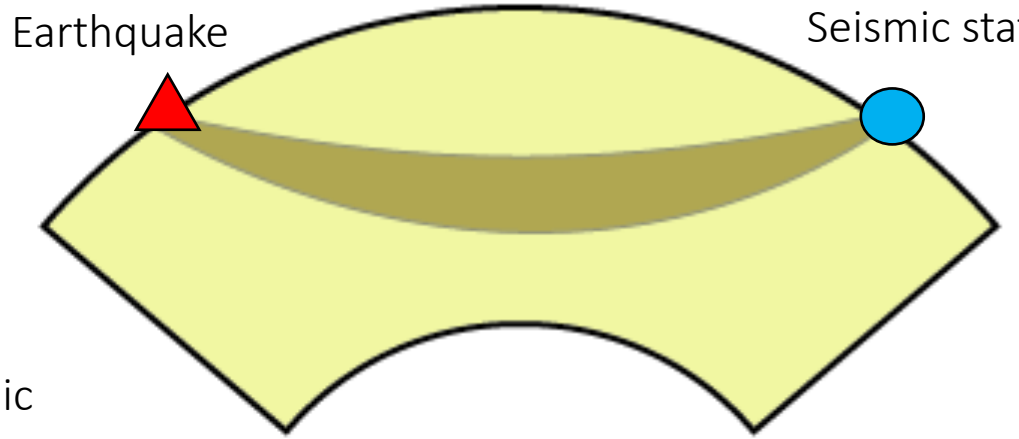


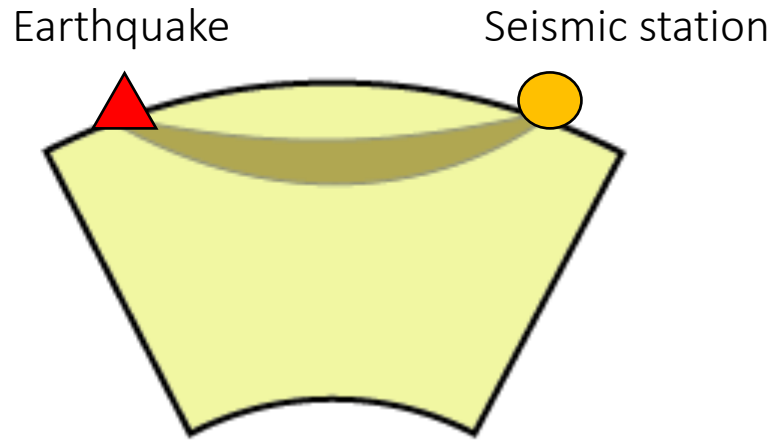
Whitehouse, 2018

Seismic tomography

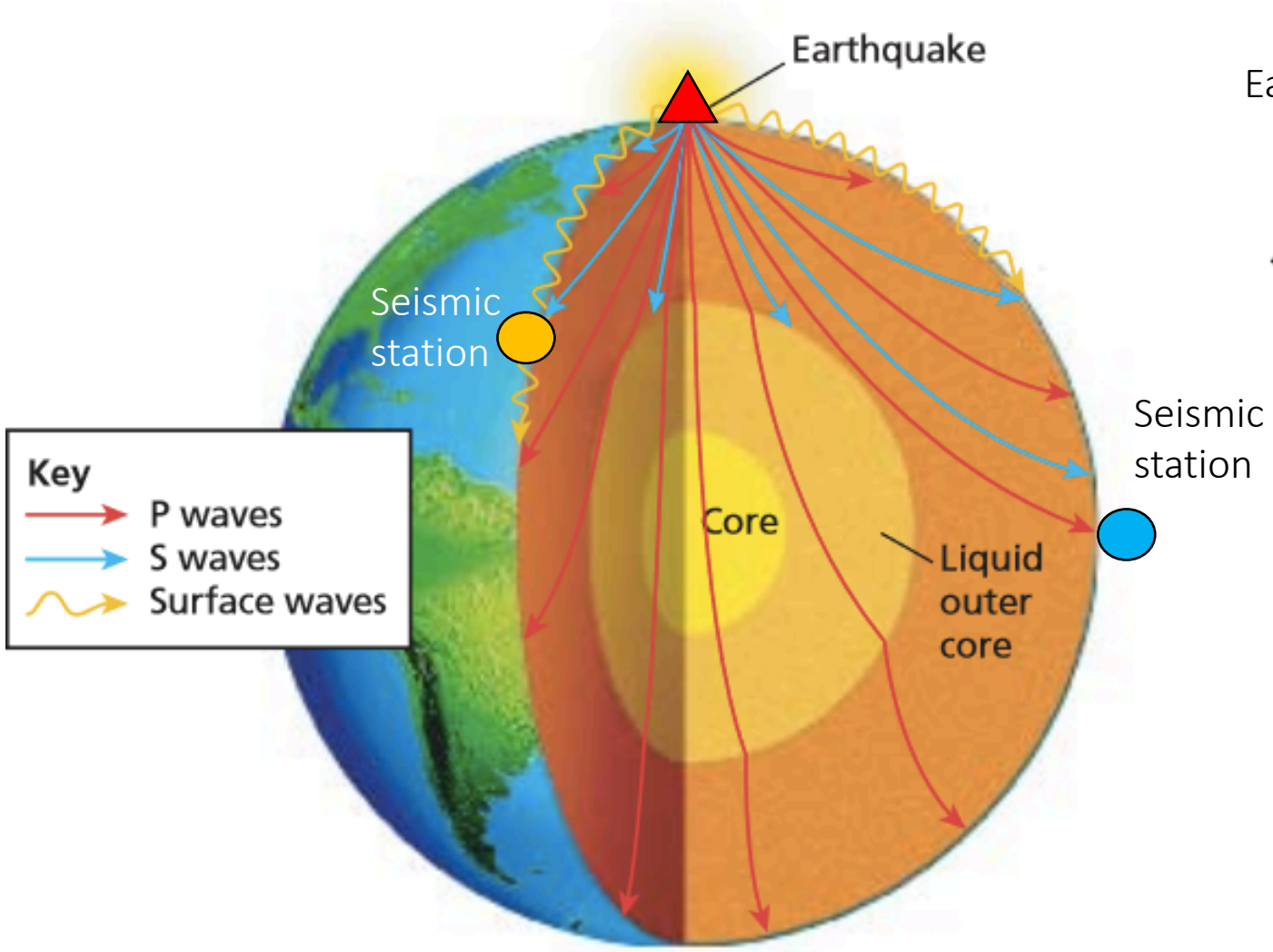


Sensitivity kernels



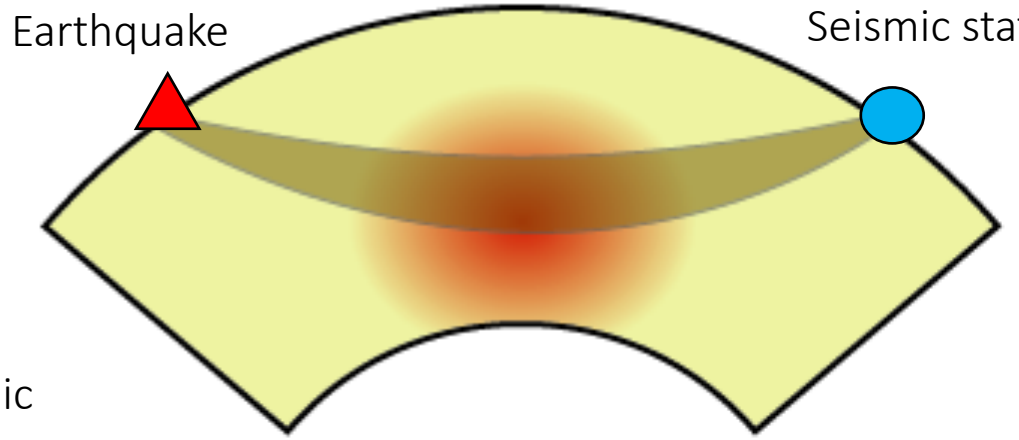


Seismic tomography

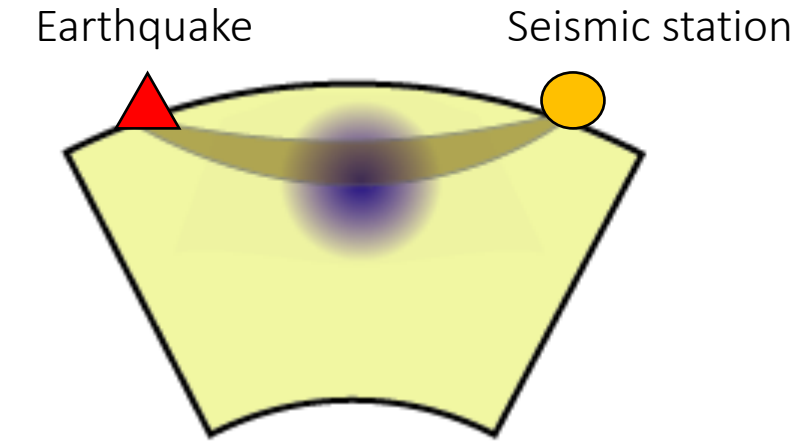


Sensitivity kernels

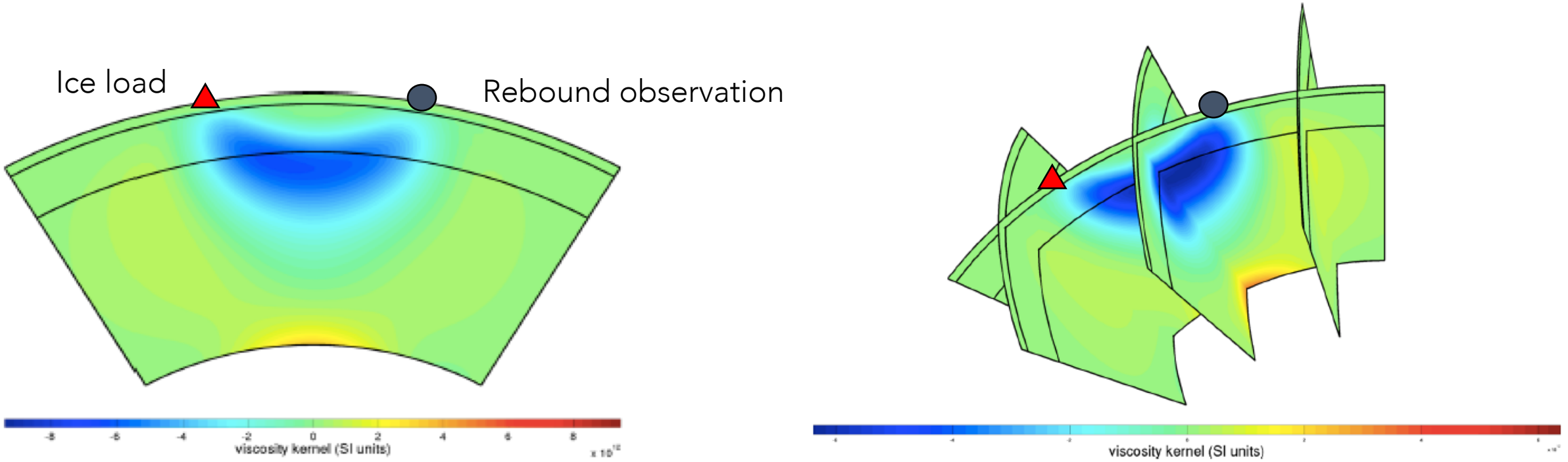
Slower than expected



Faster than expected



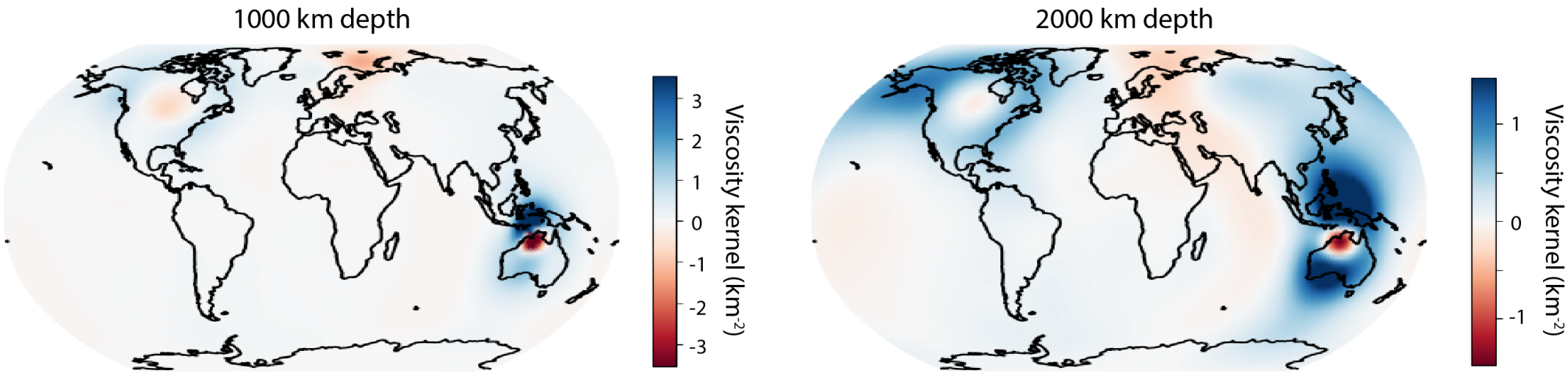
Sensitivity kernels for viscoelastic deformation



Sensitivity kernels can be calculated very cheaply by solving the adjoint equations

Al-Attar and Tromp, 2014

Sensitivity kernels for GIA (ice and ocean loading)



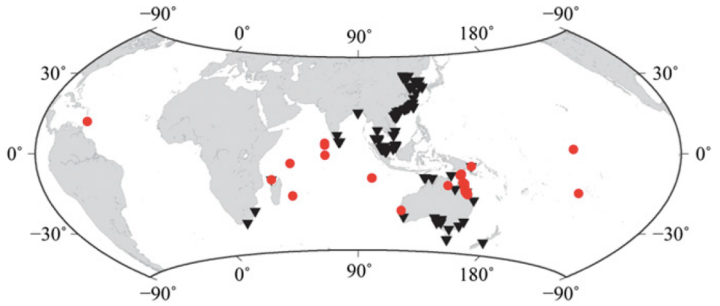
Sensitivity of a sea level observation at Bonaparte Gulf at 13 ka to Earth's internal viscoelastic structure.

<u>Positive viscosity kernel:</u>
Increasing viscosity in this region will lead to an **increase** in local sea level at Bonaparte Gulf at 13 ka

<u>Negative viscosity kernel:</u>
Increasing viscosity in this region will lead to a **decrease** in local sea level at Bonaparte Gulf at 13 ka

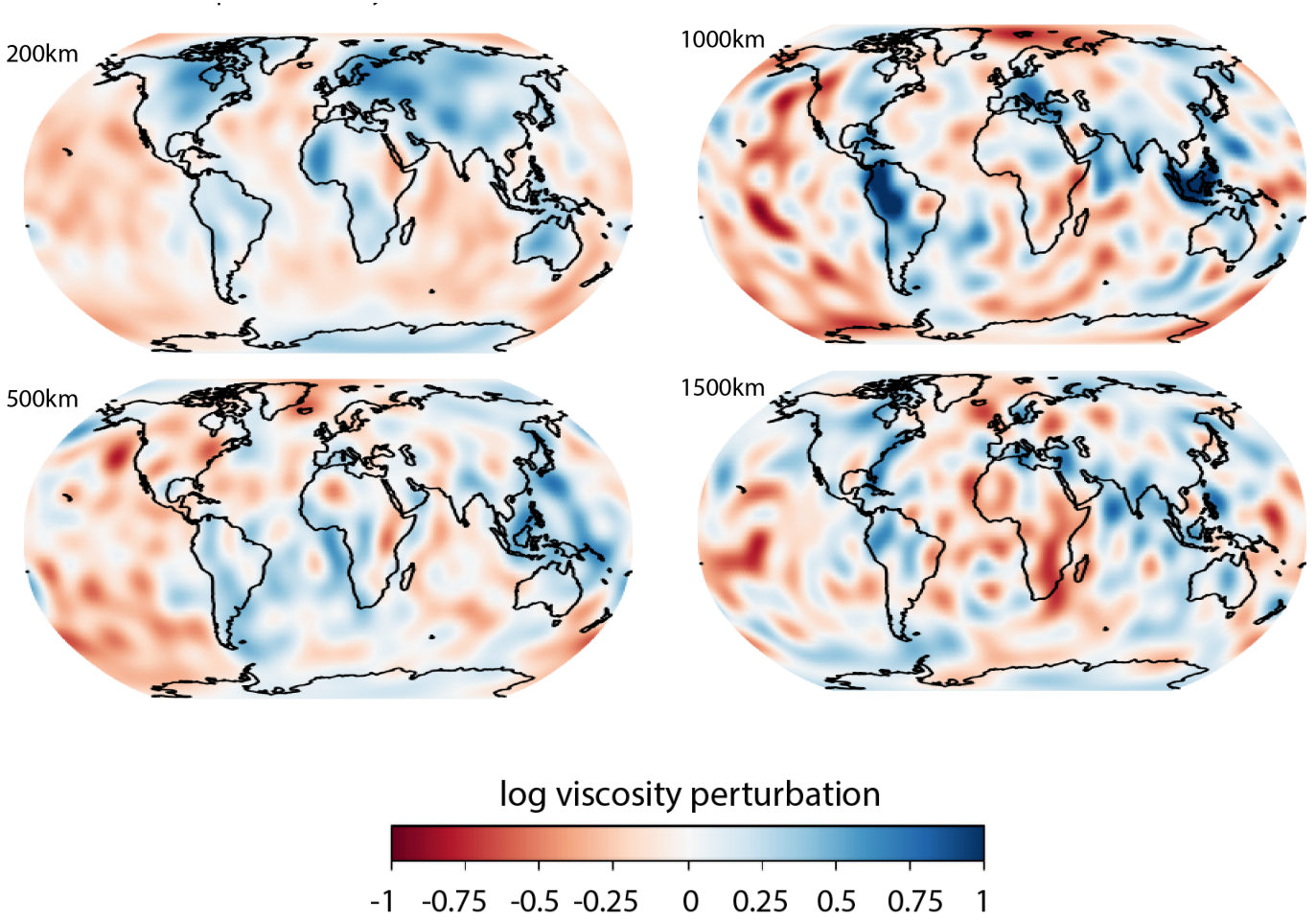
Crawford *et al.*, 2018

Synthetic test: setup

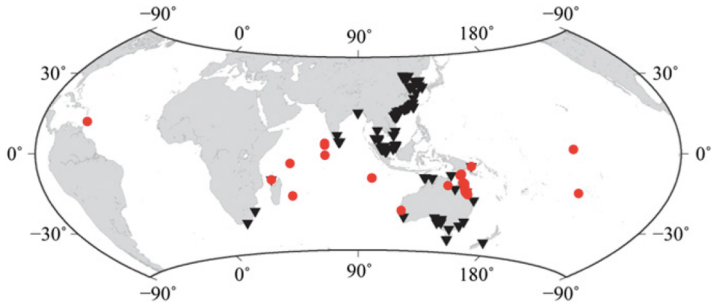


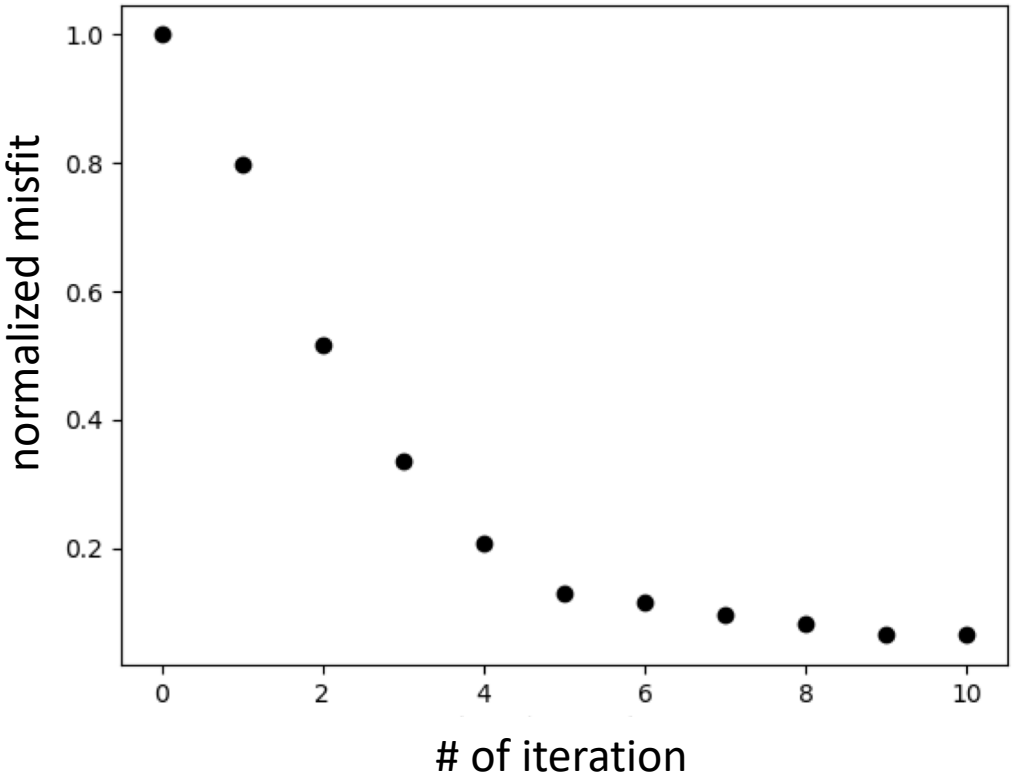
- 3D viscosity model based on S20RTS
- ICE-5G assumed as known
- Synthetic data at sites from Lambeck et al. (2014); same number of data points, random times, data have no uncertainty

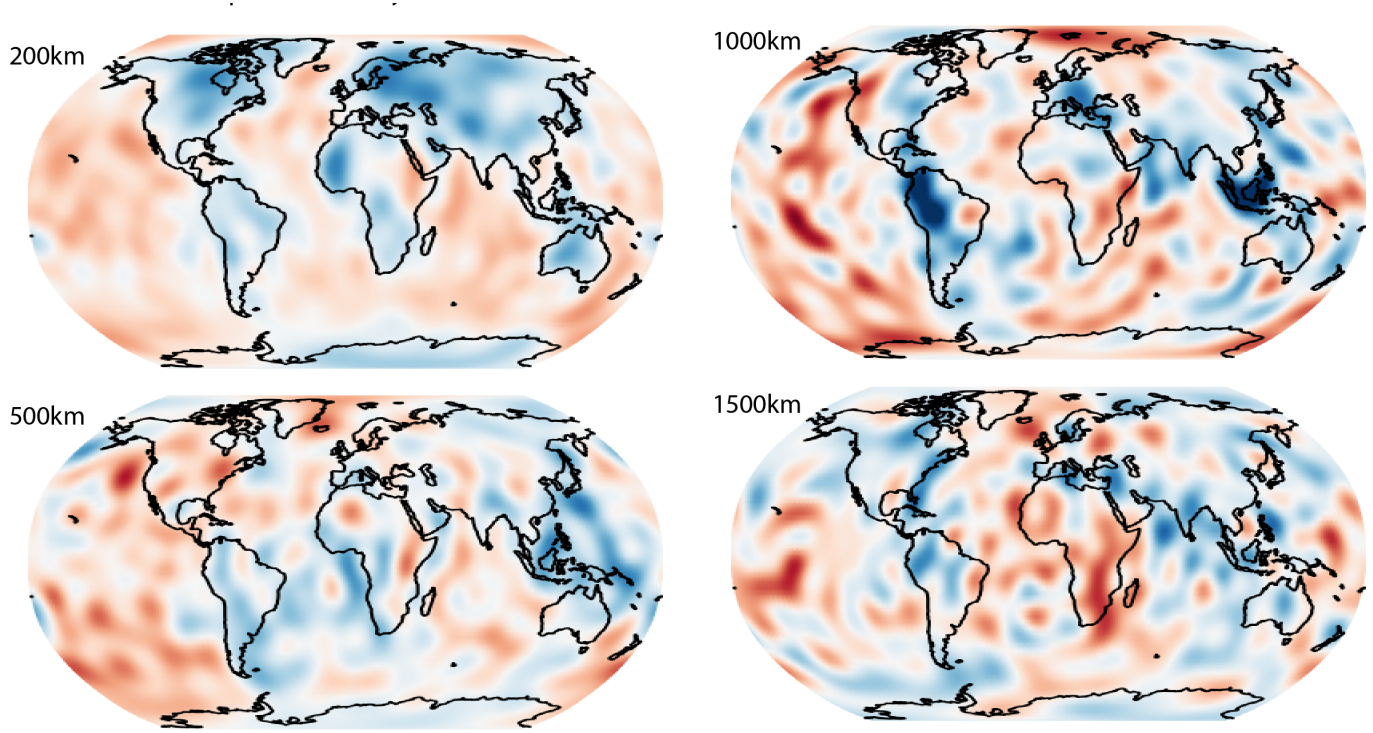
Start with no 3D viscosity perturbations and use synthetic data to invert for viscosity structure



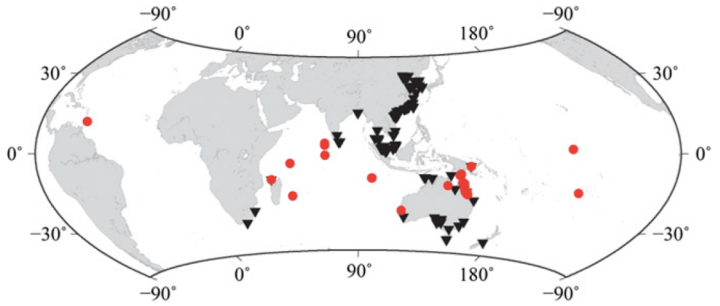
Synthetic test: misfit

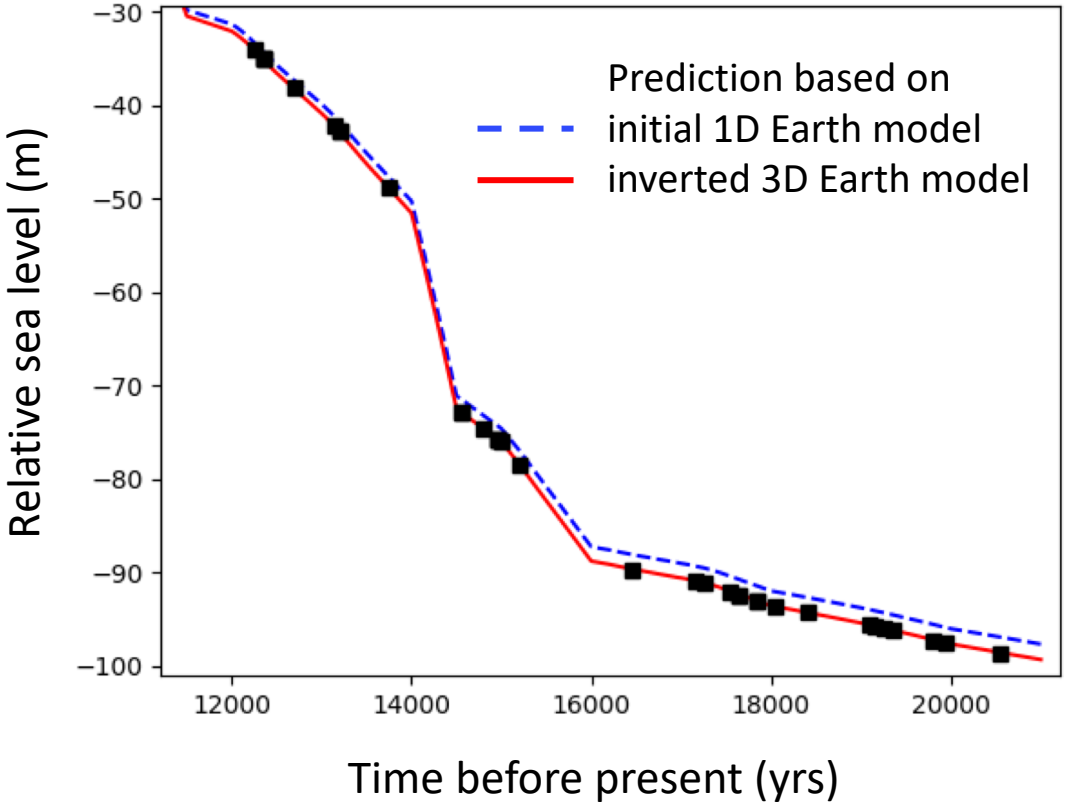


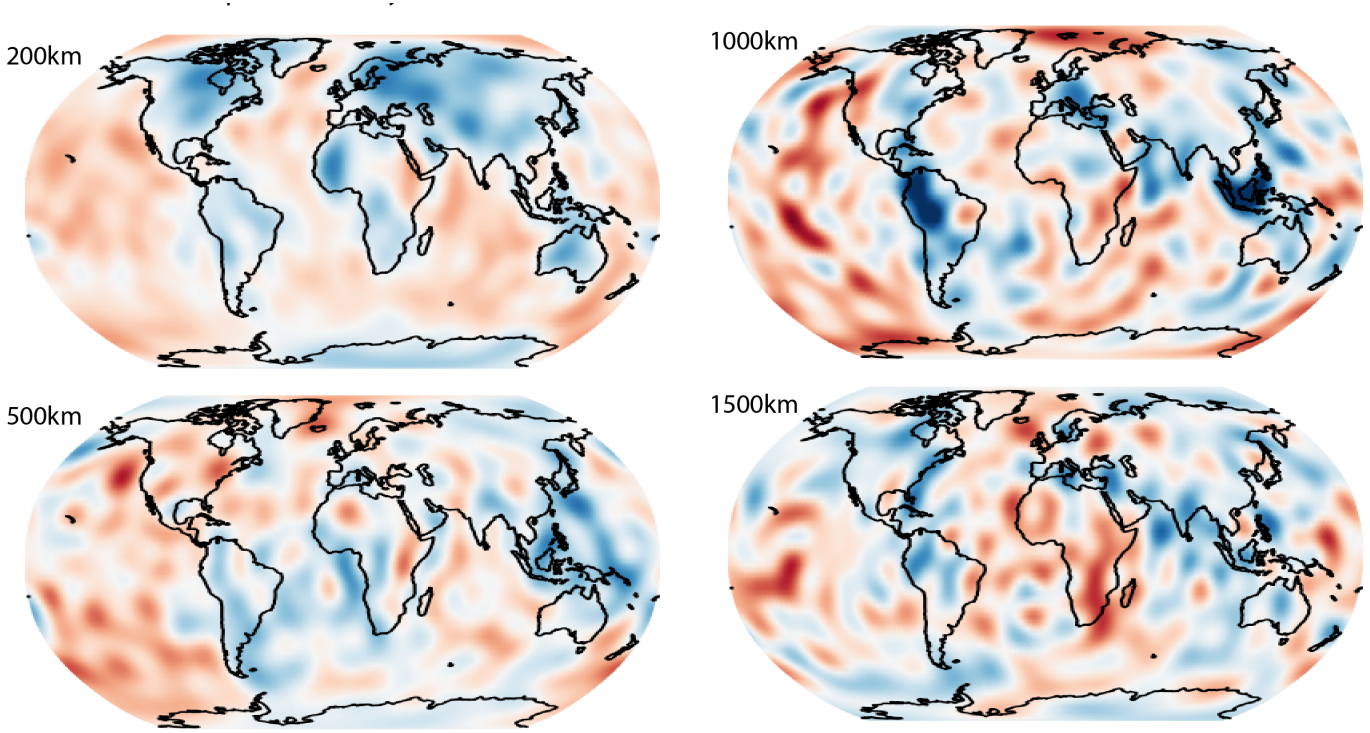




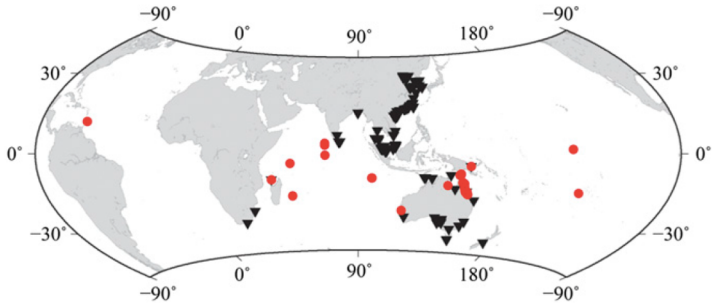
Synthetic test: RSL prediction



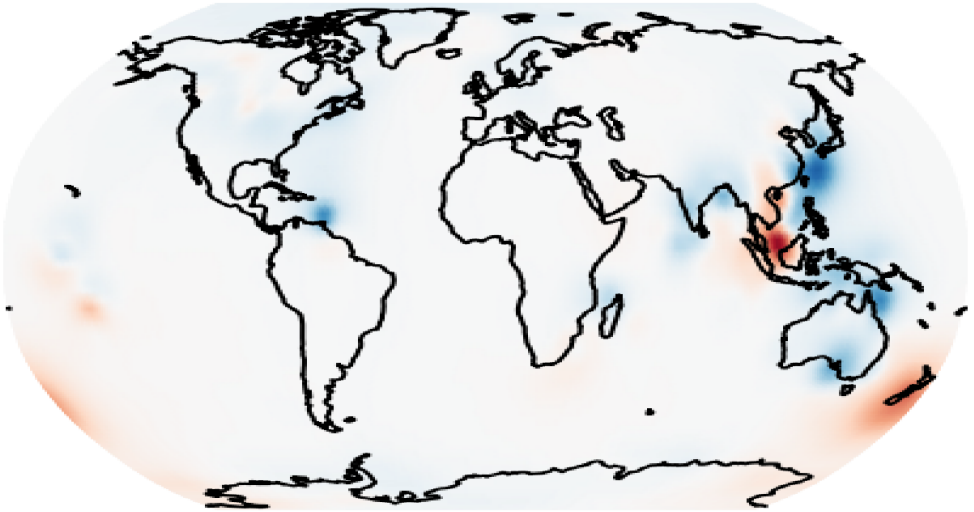




Synthetic test: resulting viscosity

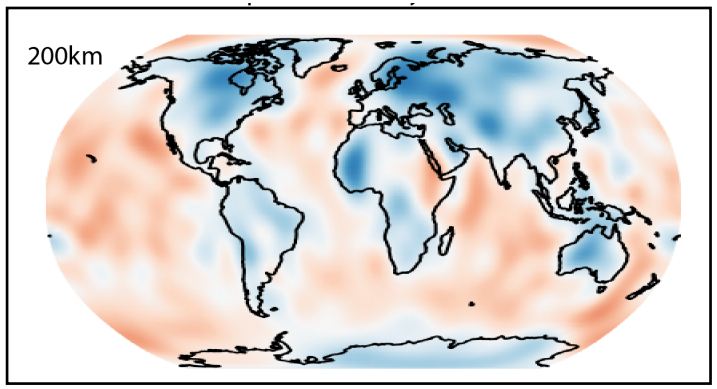


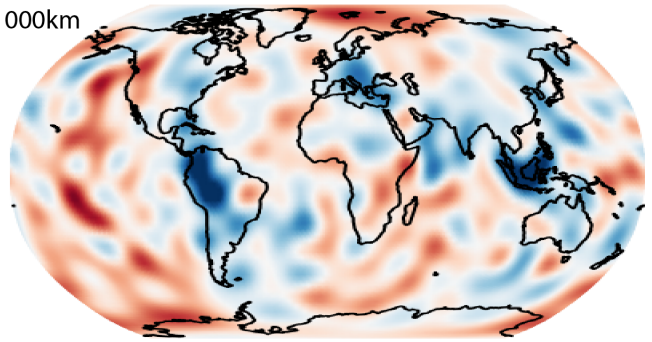
200km

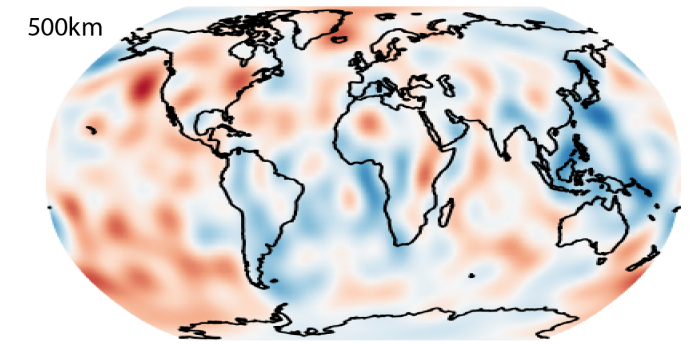


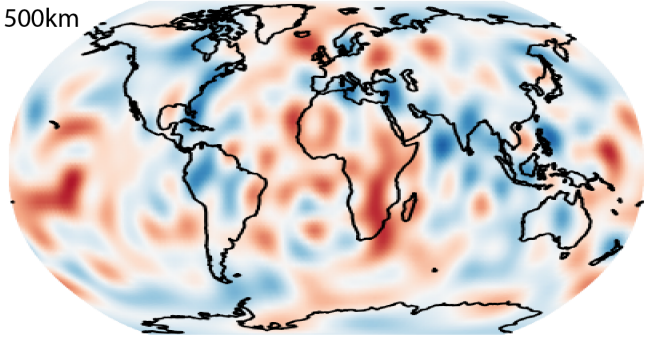
log viscosity perturbation

-0.3 -0.2 -0.1 0 0.1 0.2 0.3





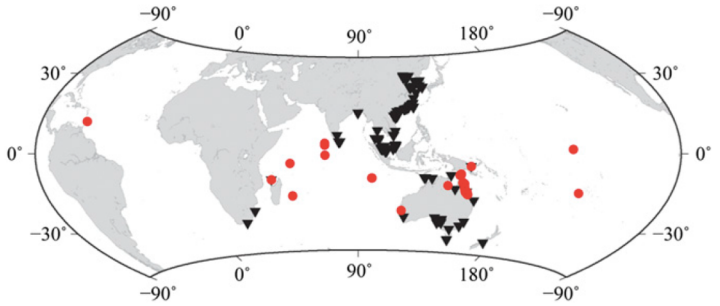




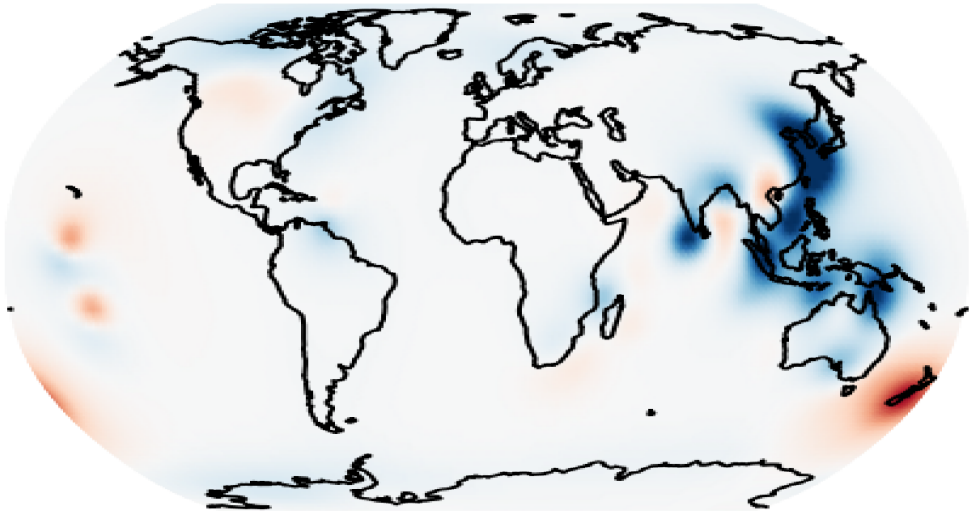
log viscosity perturbation

-1 -0.75 -0.5 -0.25 0 0.25 0.5 0.75 1

Synthetic test: resulting viscosity

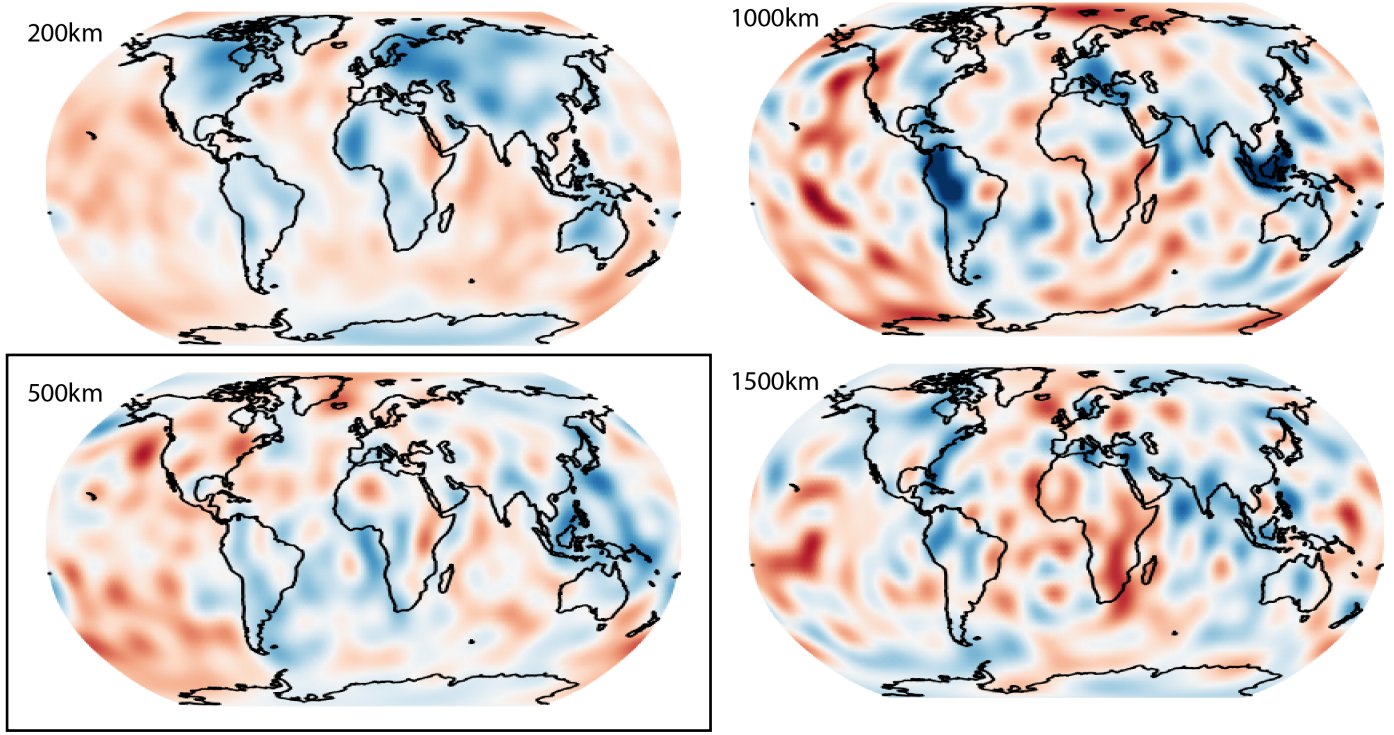


500km



log viscosity perturbation

-0.3 -0.2 -0.1 0 0.1 0.2 0.3



log viscosity perturbation

-1 -0.75 -0.5 -0.25 0 0.25 0.5 0.75 1

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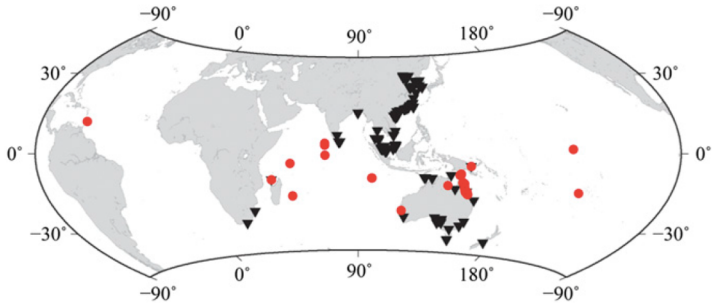
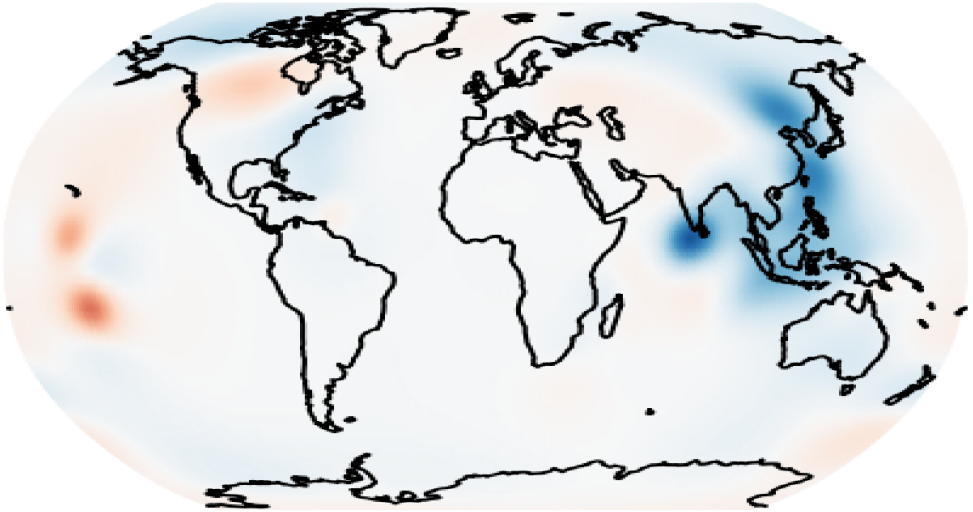
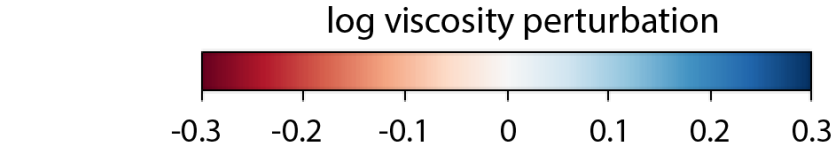
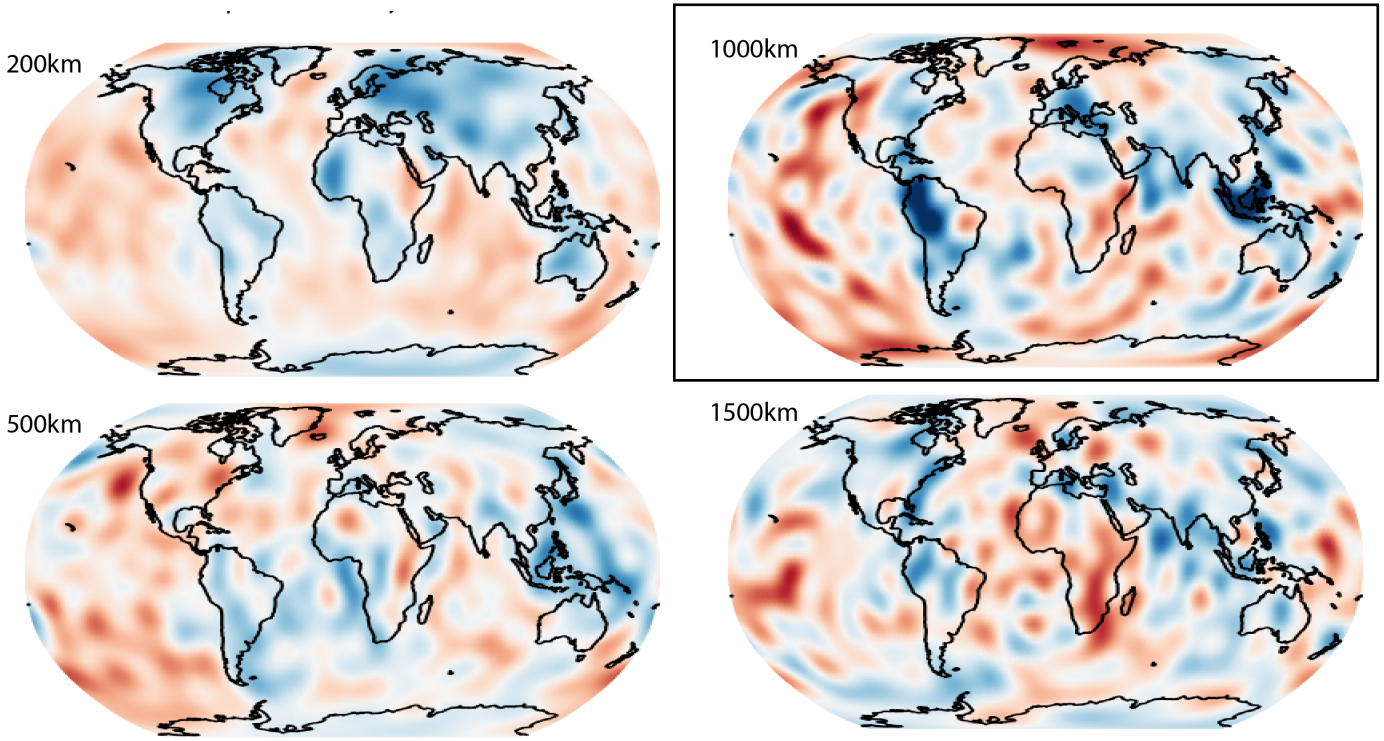
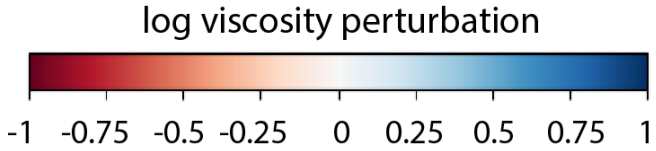


1000km

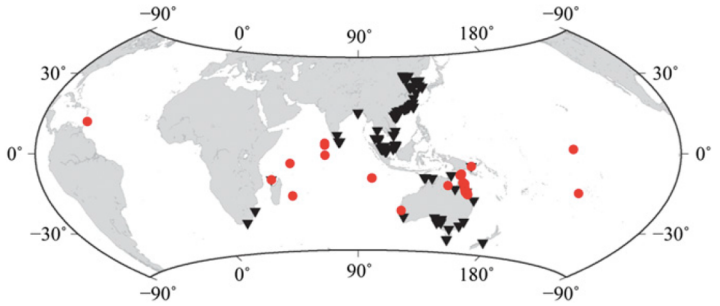




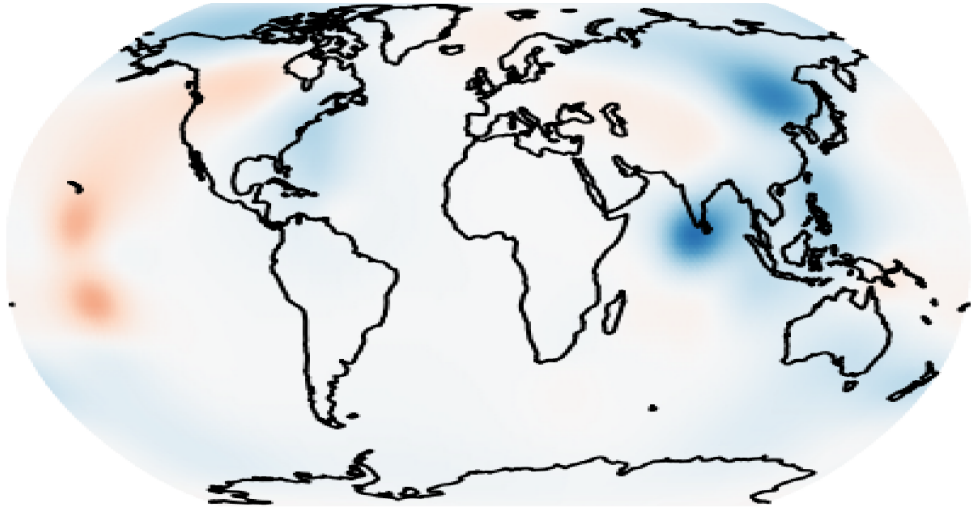


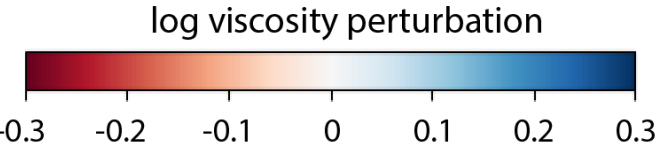


Synthetic test: resulting viscosity

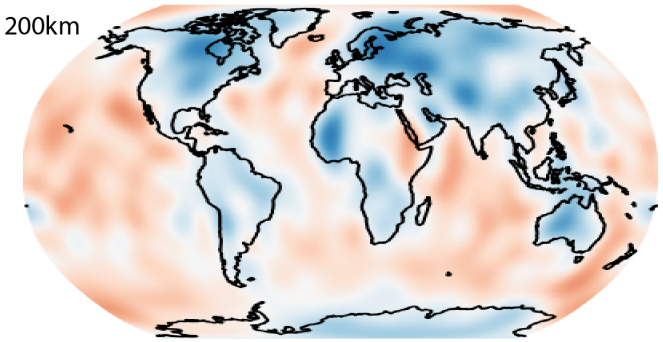


1500km

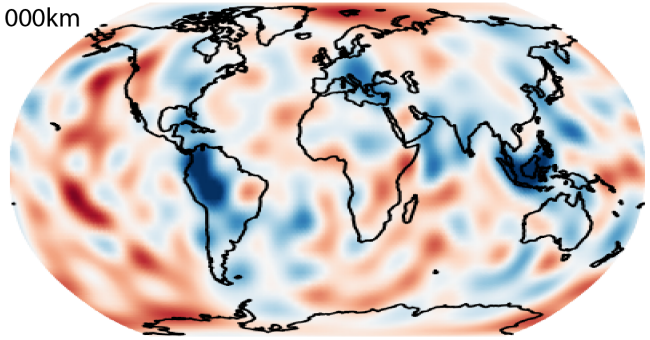




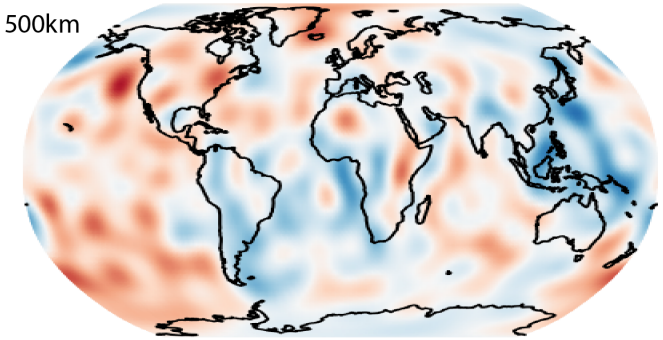
200km



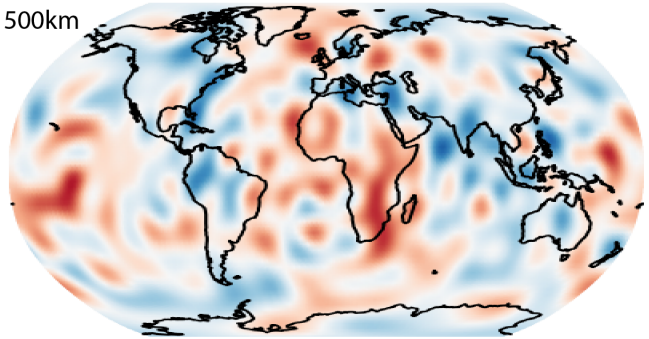
1000km

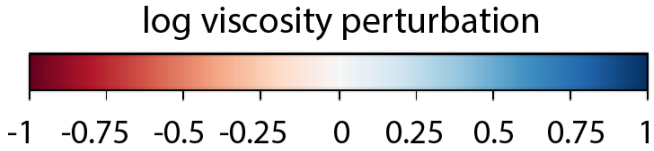


500km



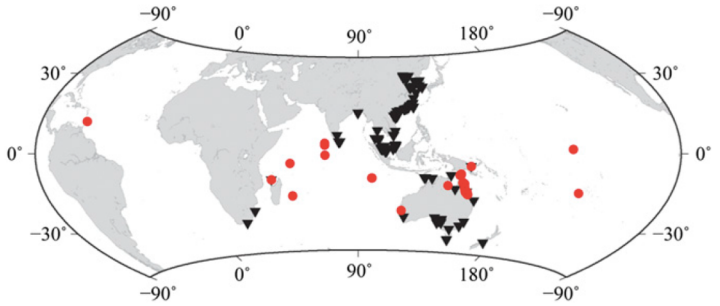
1500km

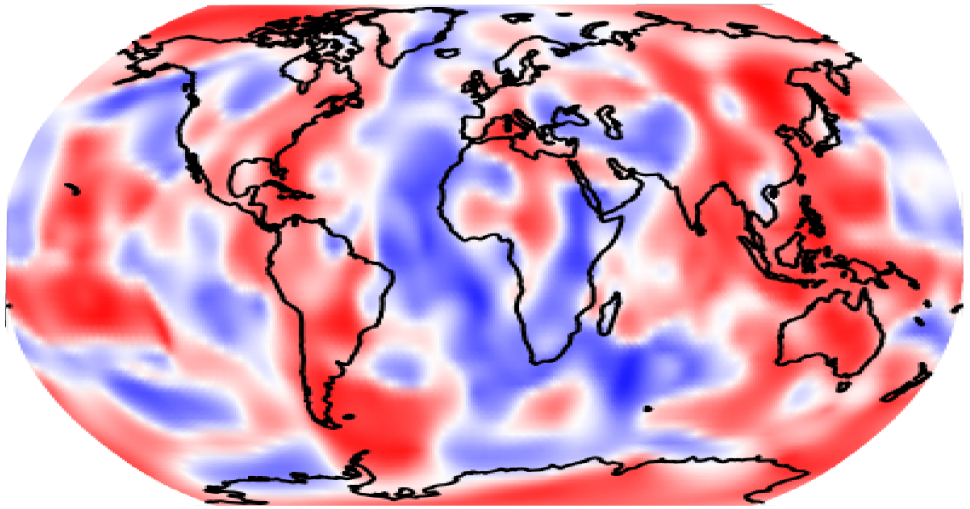




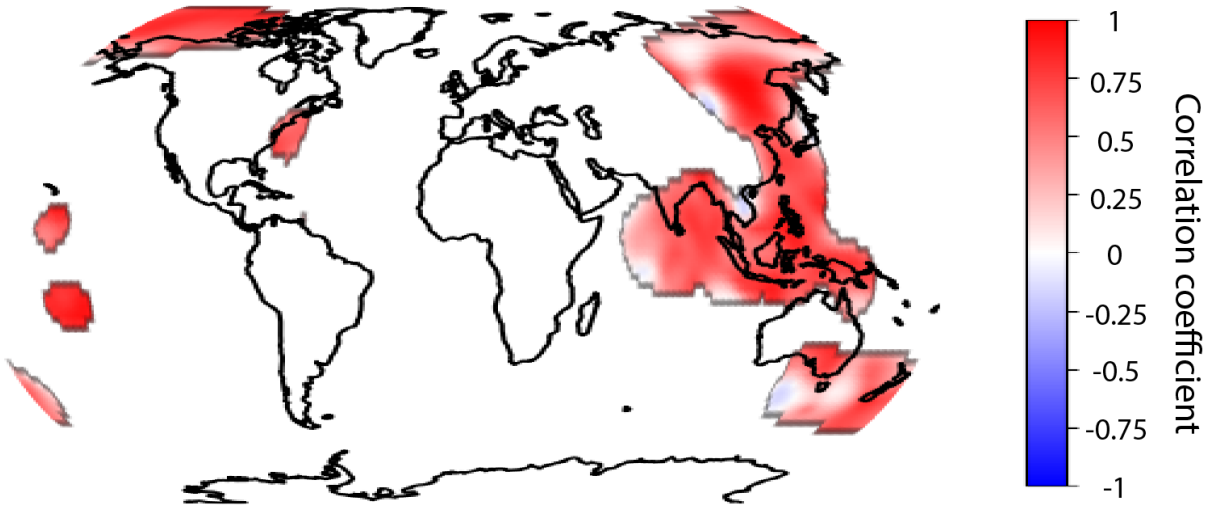
Synthetic test: correlation

Depth integrated correlation coefficient
between ‘true’ viscosity and inverted viscosity





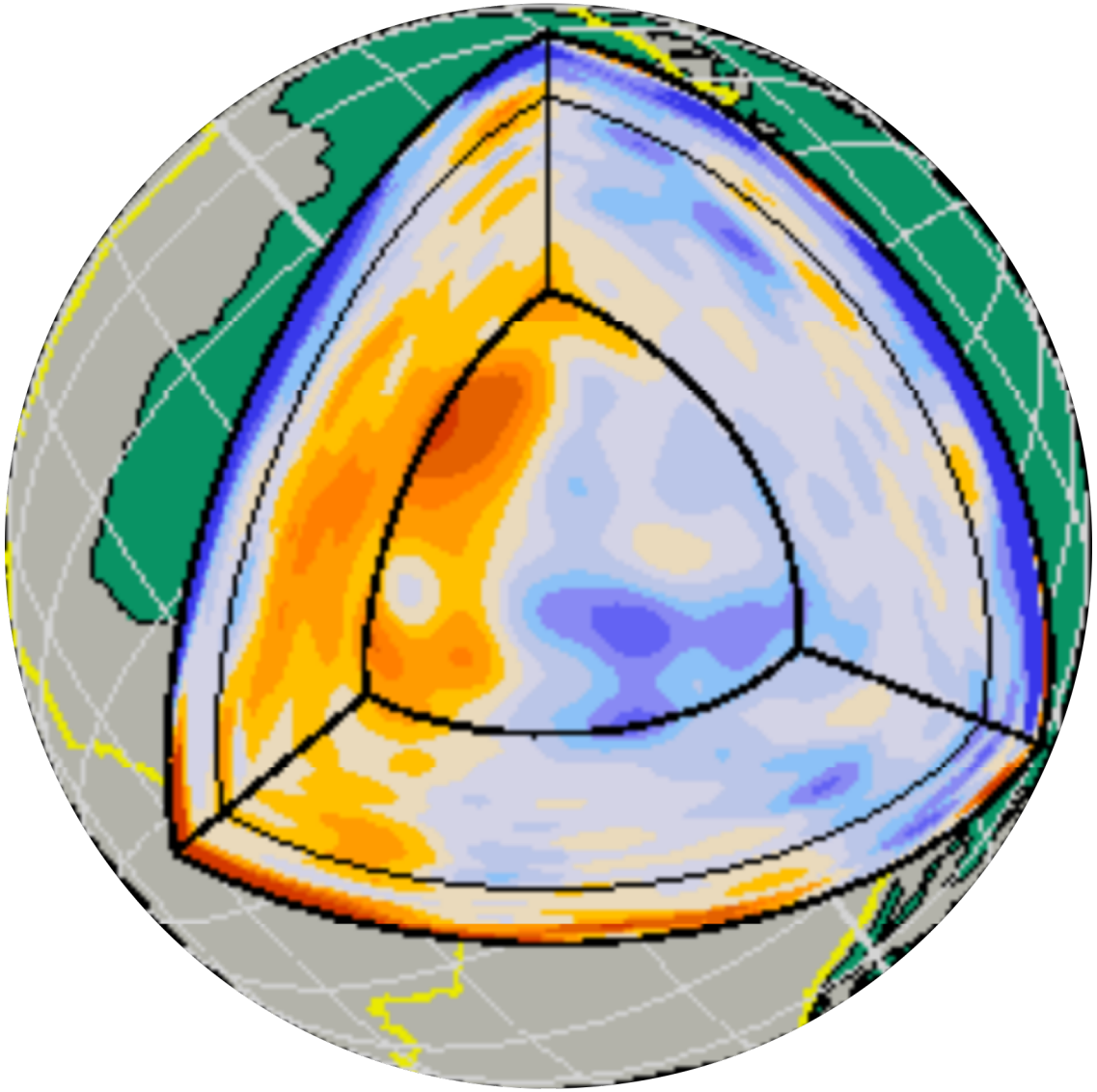
Everywhere



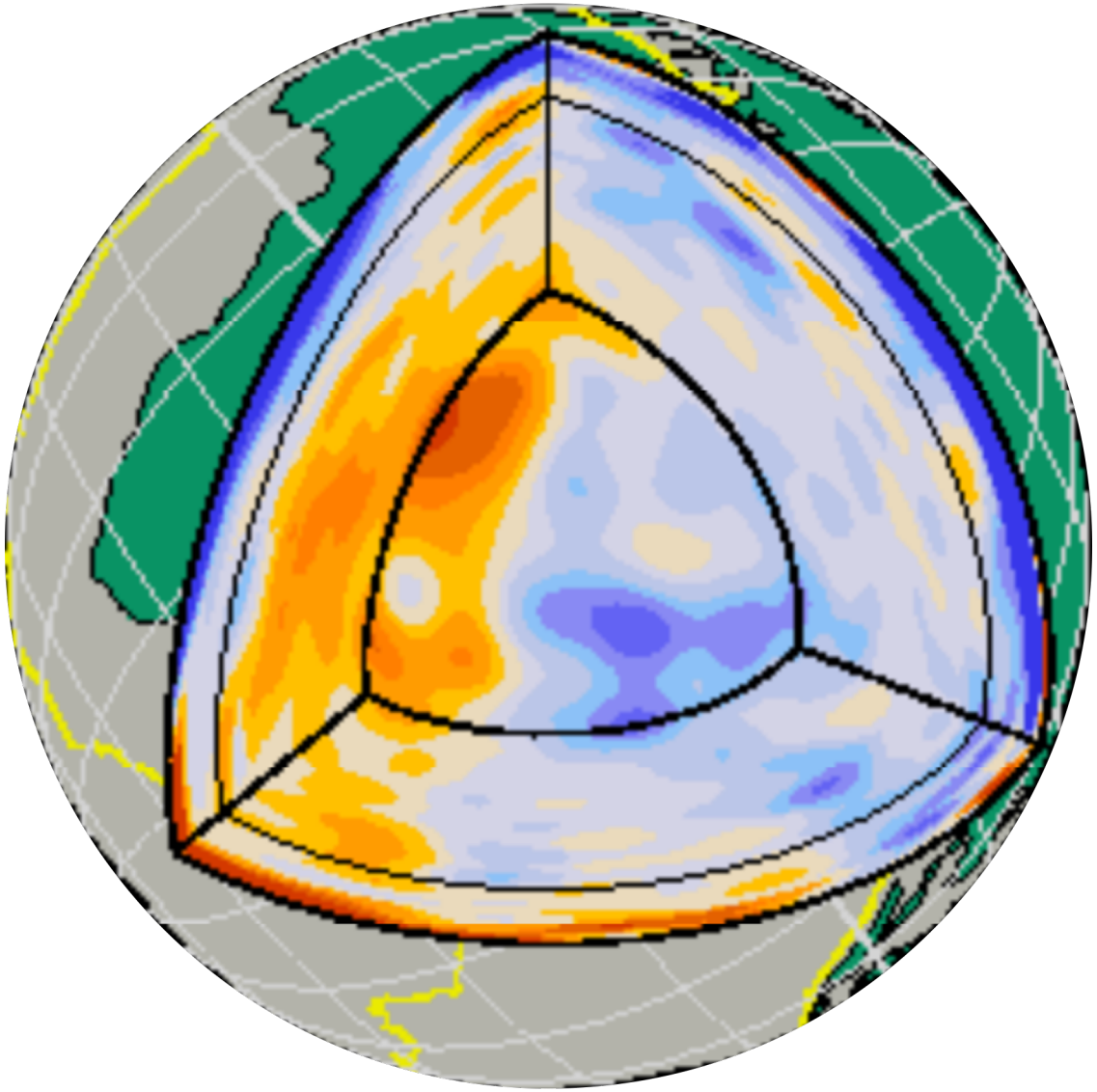
Only in regions in which the viscosity has actually been updated significantly

Crawford *et al.*, in prep

Towards a tomographic image of Earth's 3D viscosity

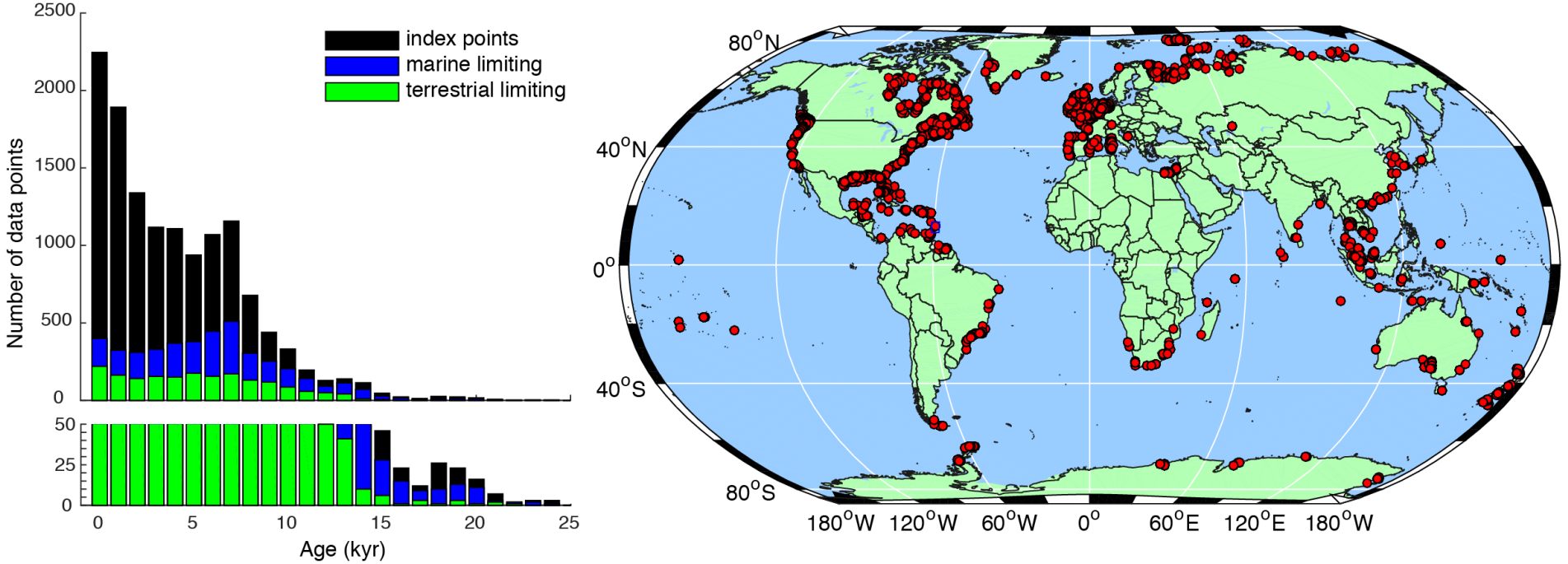


Towards a tomographic image of Earth's 3D viscosity



We need continued efforts in filling data gaps (HOLSEA)

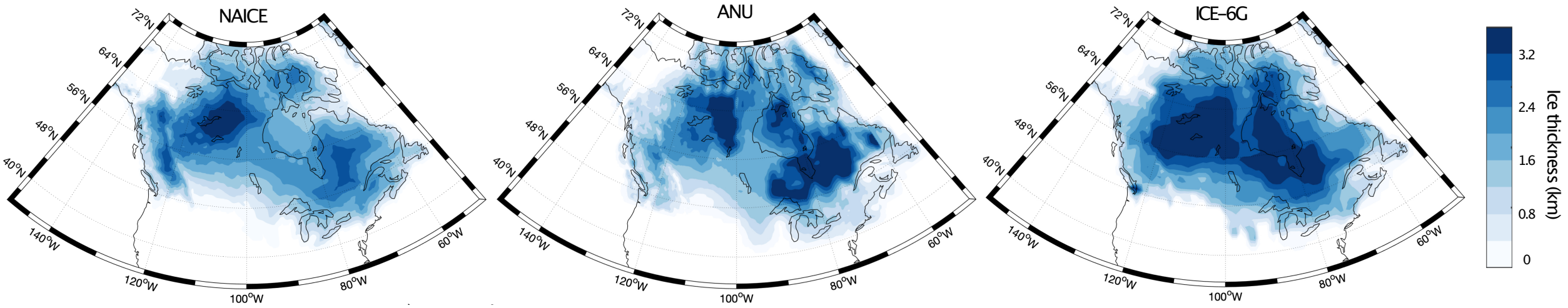
- Spatial and temporal data gaps need to be filled (early deglaciation)
- Data need to be recorded and shared in a useful way
- Present-day constraints can be incorporated (GPS, gravity)



Khan *et al.*, 2019

Ice sheet reconstructions need to be improved

Laurentide ice sheet at 18 ka



Gowan *et al.*, 2016

Lambeck *et al.*, 2017

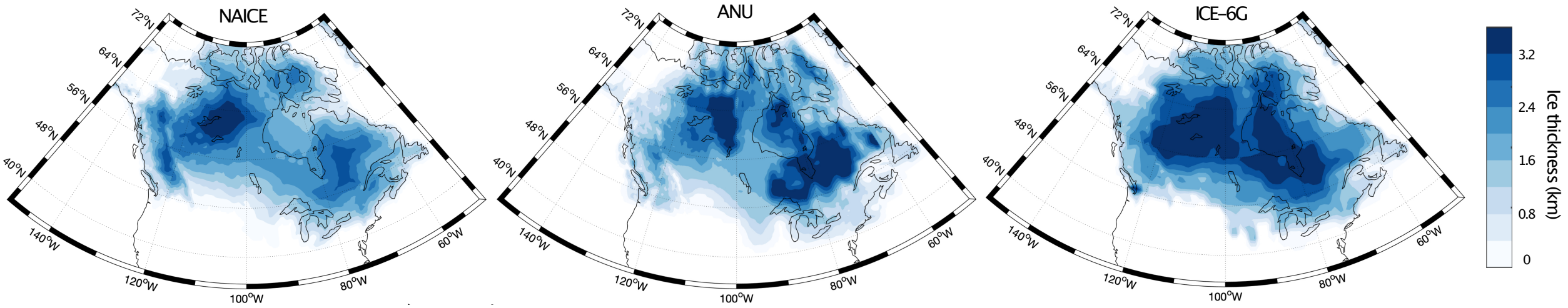
Peltier *et al.*, 2015

Outstanding questions:

- More detailed size and evolution of all ice sheets
- “Missing ice problem” at the Last Glacial Maximum
- Contribution from different ice sheets to Meltwater Pulse 1A and other meltwater events

Ice sheet reconstructions need to be improved

Laurentide ice sheet at 18 ka



Gowan *et al.*, 2016

Lambeck *et al.*, 2017

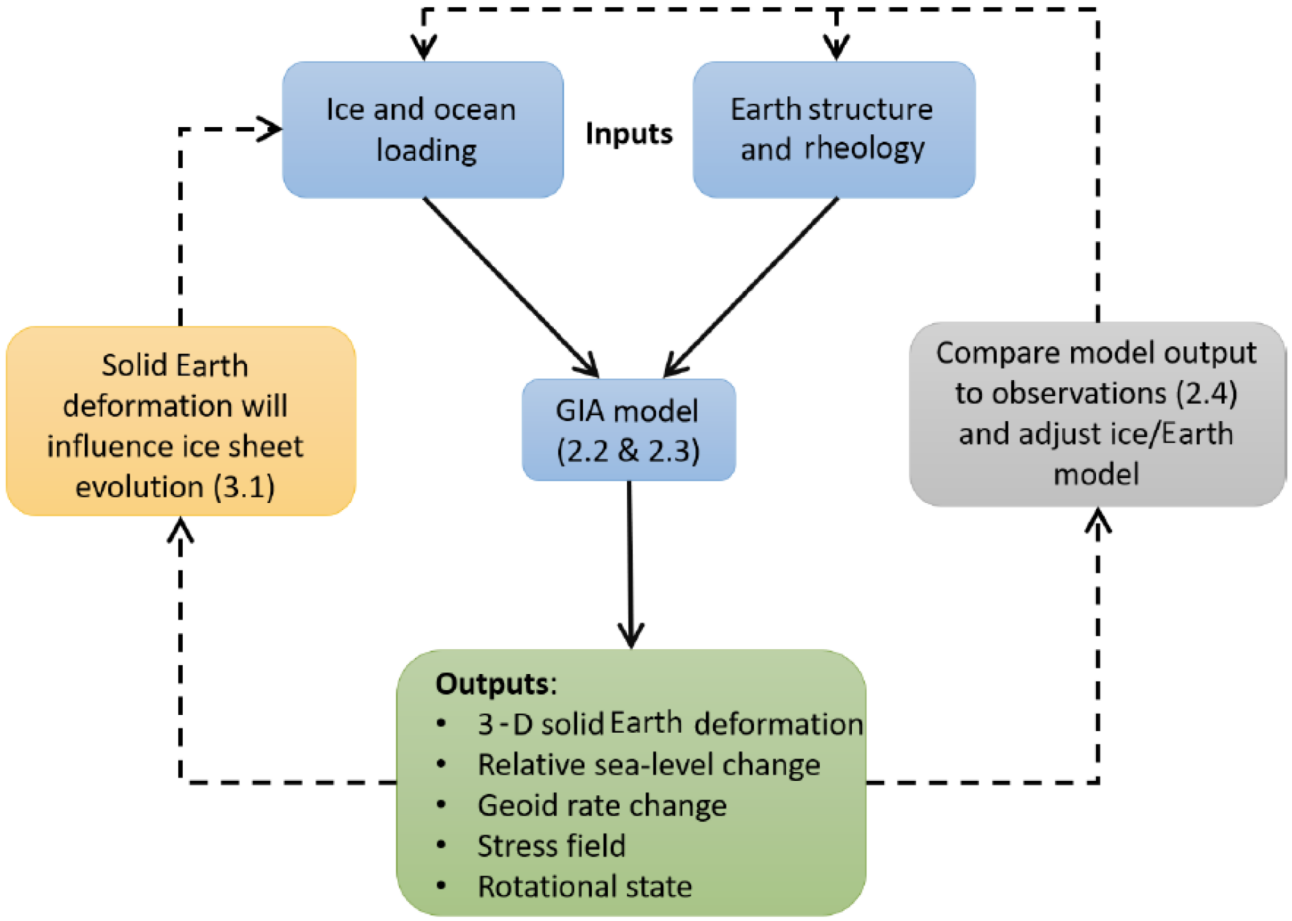
Peltier *et al.*, 2015

- Inversions can explore trade-offs between the ice reconstruction and Earth's viscosity
- Inversions require a comprehensive dataset (sea level data, present-day uplift and gravity, pluvial and proglacial lake shorelines, river routing, eskers, constraints from atmospheric circulation)
- Inversions require a physics based ice sheet

Data assimilation techniques need to be explored and expanded

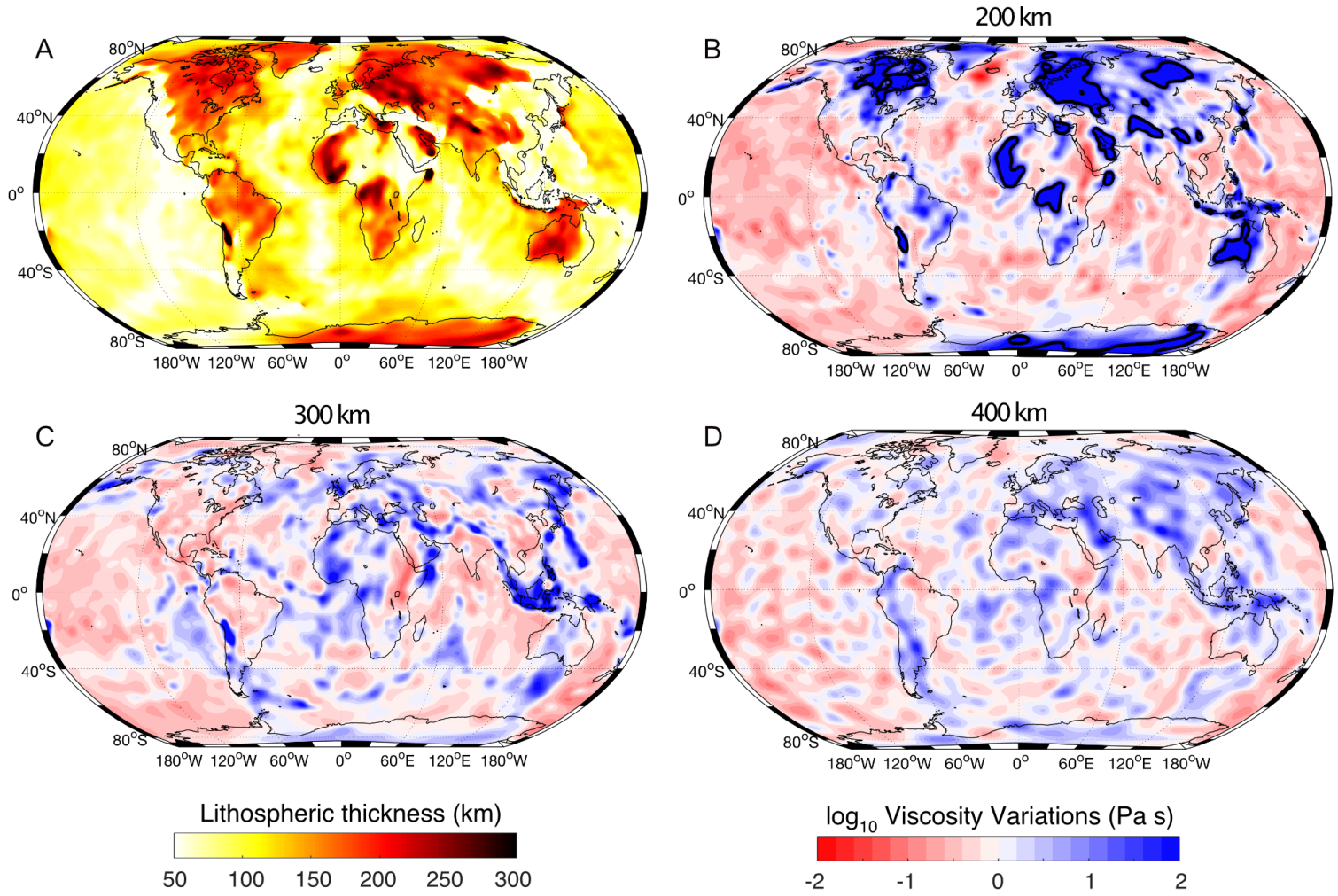
- GIA inversions are highly non-unique
- Gradient-based optimization finds the local misfit minimum, it does not produce a measure of uncertainty
- Proper error propagation remains a challenge in computationally expensive models (same challenges in seismic tomography)
- Explore inversions and trade-offs with different starting models
- Calculate 2nd order derivatives (Hessian) at local misfit minimum to determine which directions within the model space are best constrained

We need better benchmarking in the community

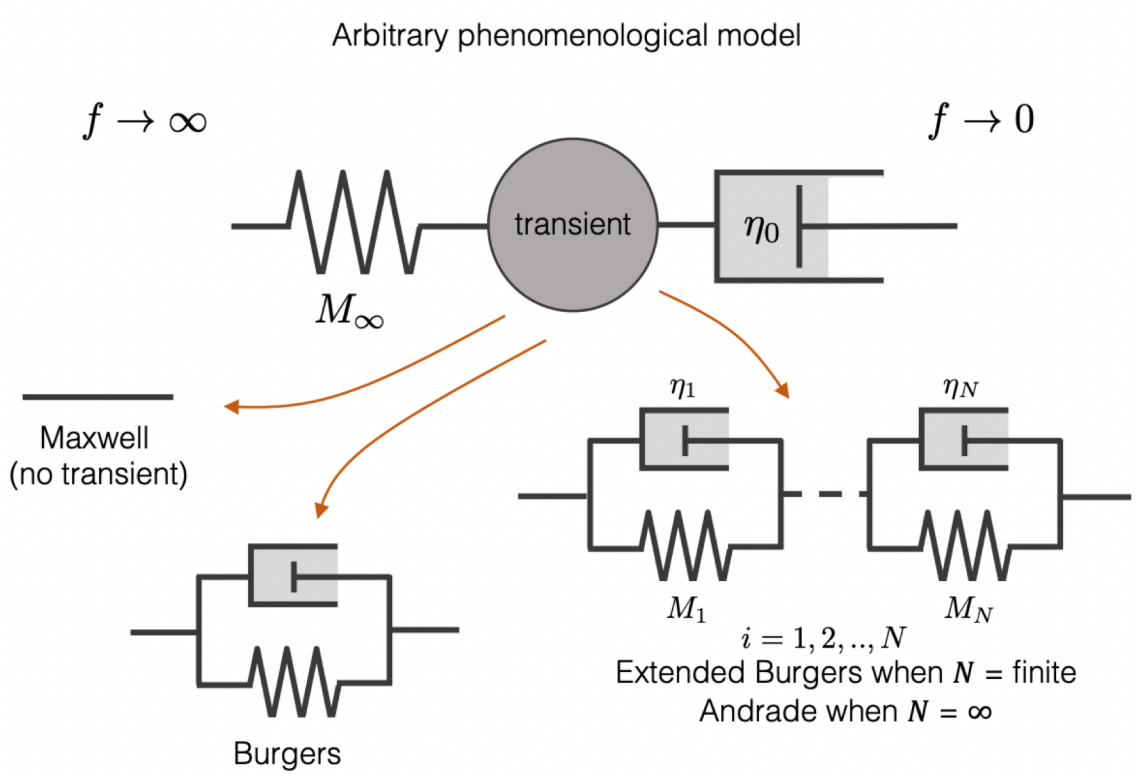


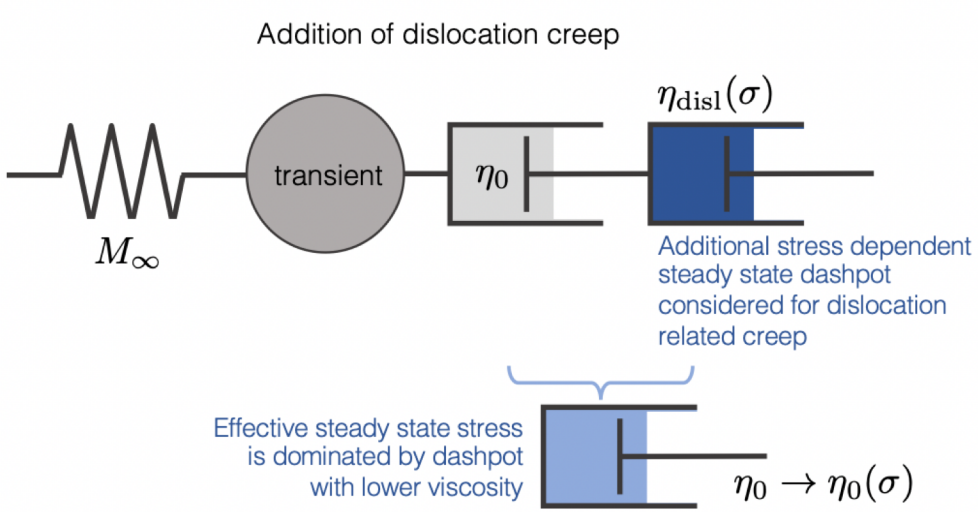
We need advances in understanding rheological properties

Can we jointly invert for 3D Earth structure (seismology, geodynamics)?



We need advances in understanding rheological properties

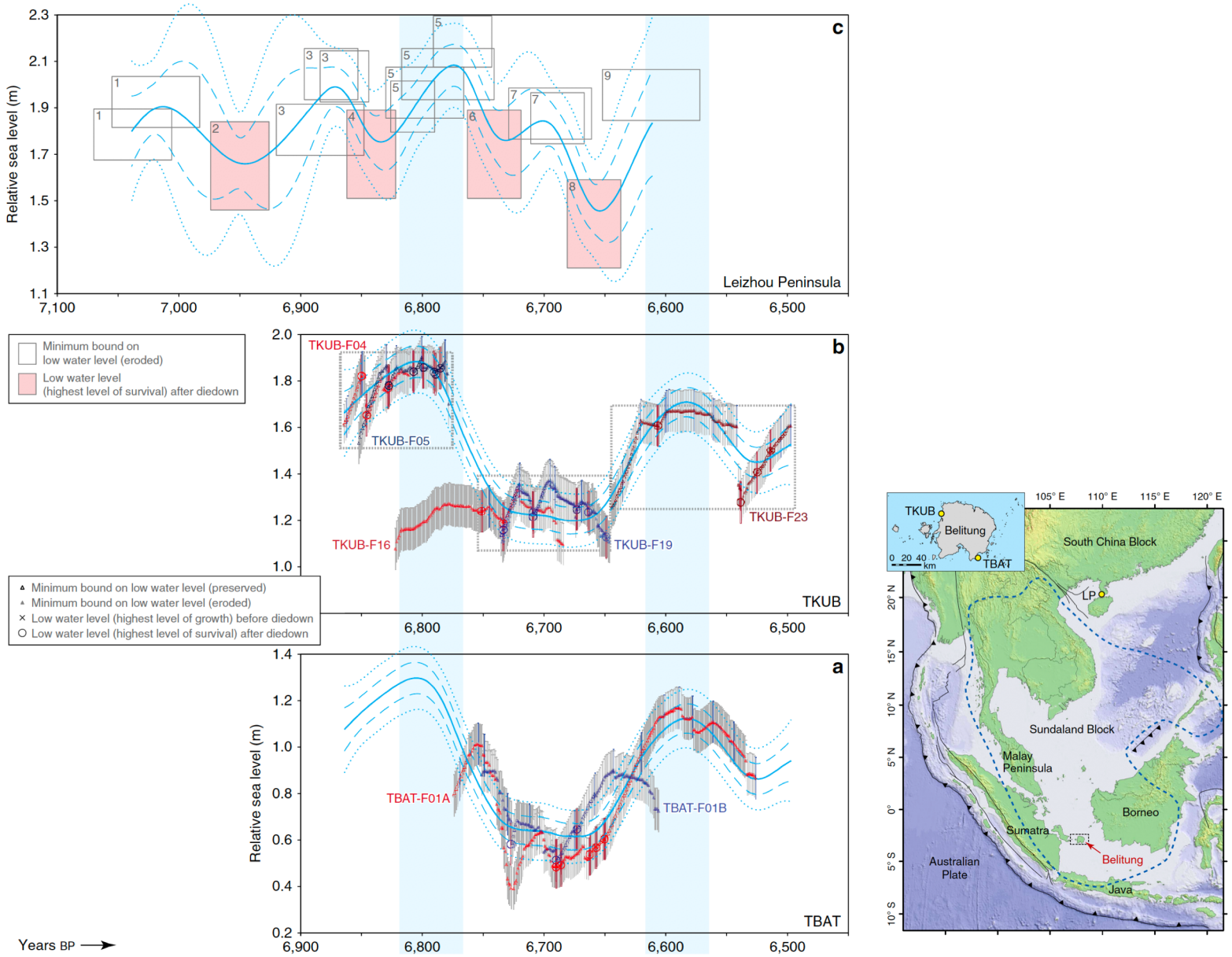




Lau *et al.*, in rev.

What else contributes to sea level change?

Records are starting to become good enough to possibly detect non-GIA sea level change, e.g. maybe related to ocean dynamics (requires separation by temporal and spatial wavelength of signal).



Meltzner *et al.*, 2017

Summary

- We understand the general deglacial ice sheet evolution and Earth's internal structure
- Improvements in data and models *are starting to* allow us to map 3D variations in Earth's viscosity, better understand ice dynamics, and interpret signals associated with ocean dynamics
- More work is needed:
  - Improved data assimilation techniques (including benchmarking & physics based ice models)
  - Assimilation of diverse ice and sea level related observables
  - Better data coverage in space and time
  - Connections to seismology, geodynamics, and mineral physics to integrate knowledge of rheological properties
- This work has implications for:
  - the contribution of GIA to present-day sea level change
  - the feedback between the solid Earth and ice sheets
  - the amount of sea level rise during past warm periods and periods of rapid change (e.g. meltwater events), which informs predictions of future sea level change