Structural seismology constraints for mantle dynamics

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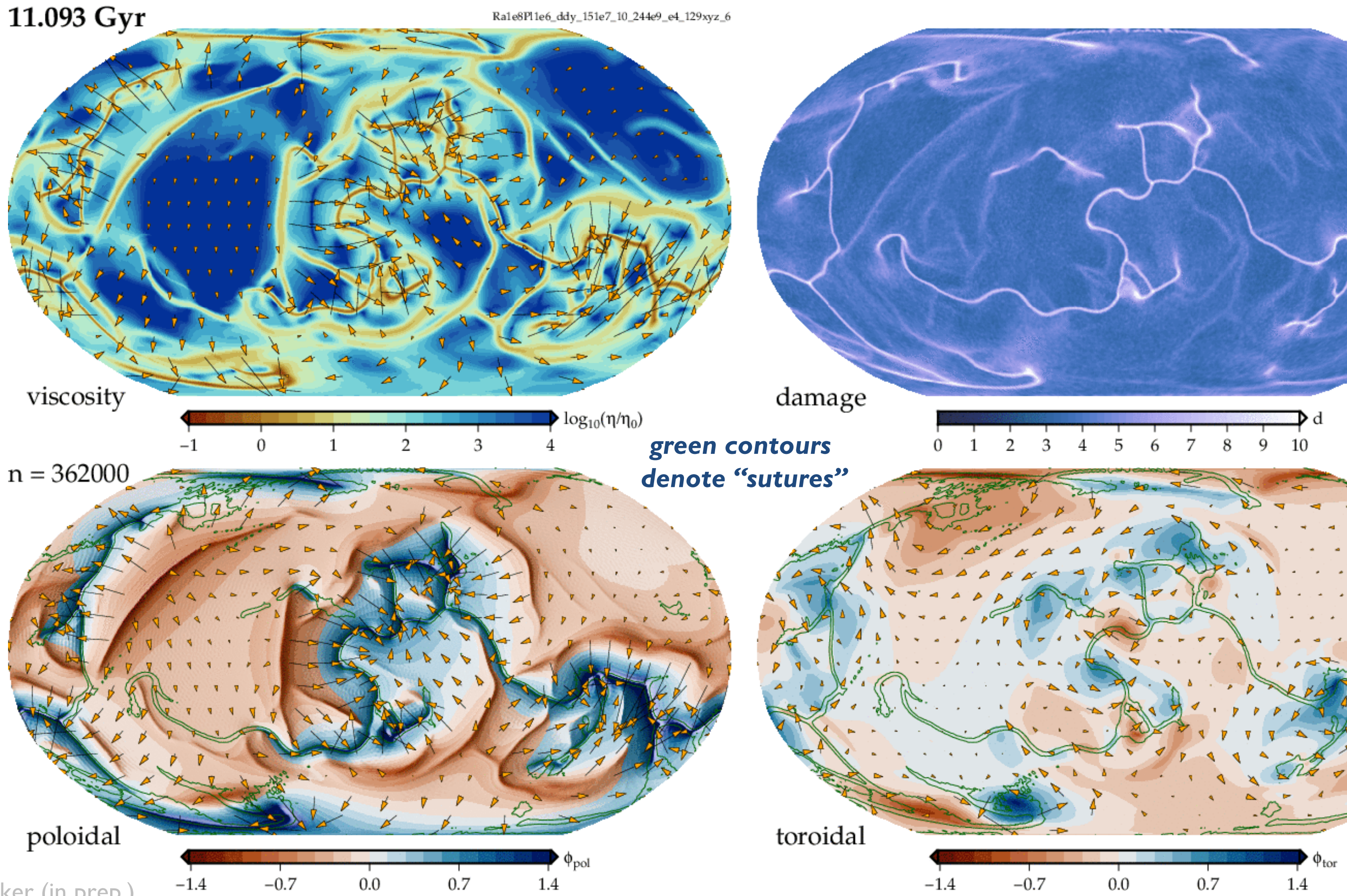
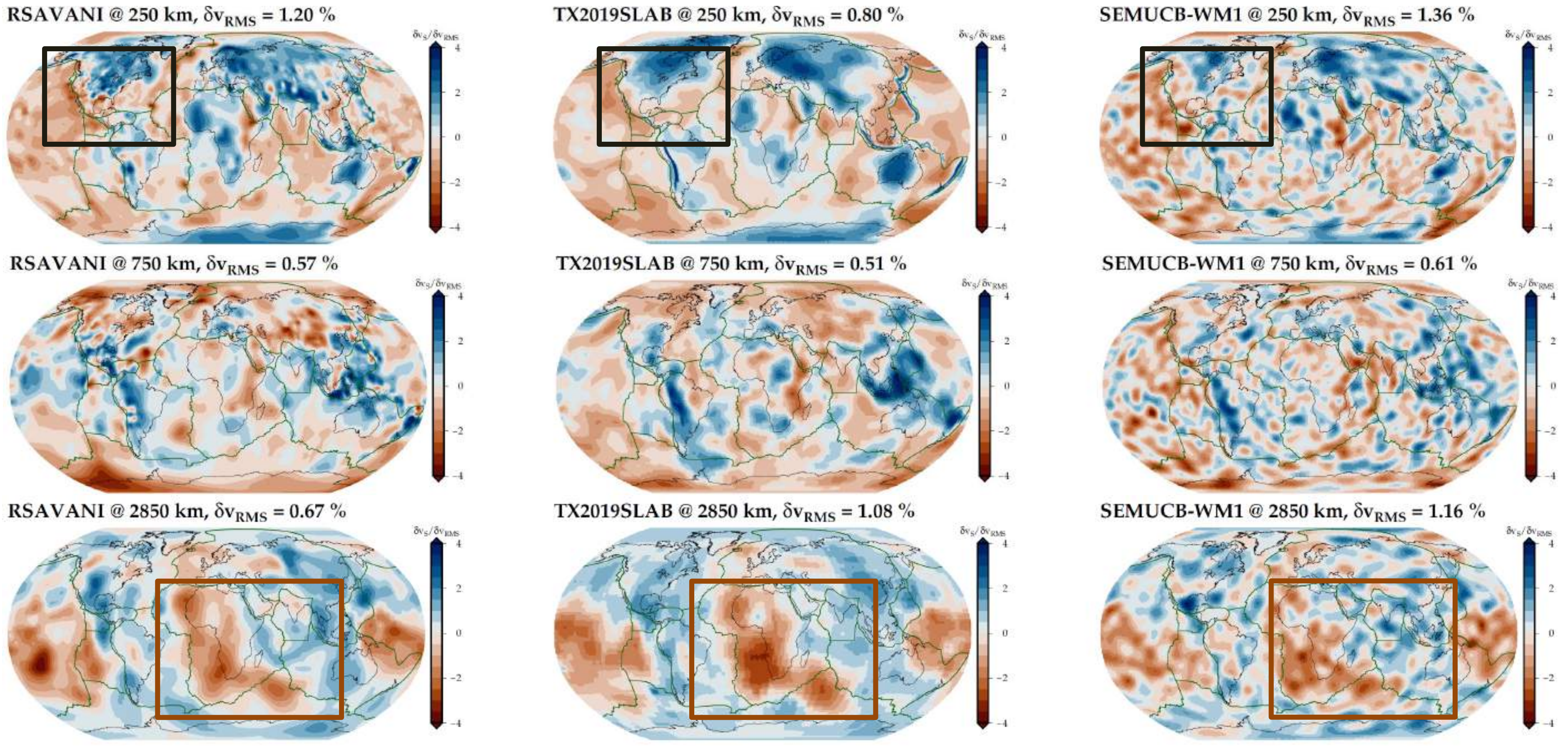
Role of rheology and memory for plate tectonics



Fuchs and Becker (in prep.)

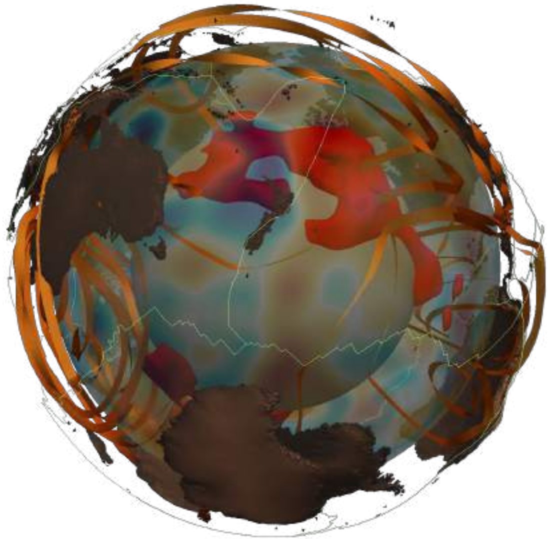
Global mantle convection computation using modified *CitcomS* (cf. Zhong et al., 2000), convective vigor ~ 0.1 Earth

Shear wave mantle tomography



Porritt et al. (2021) Lu et al. (2019) French et al. (2015)

Global mantle circulation models based on seismic tomography

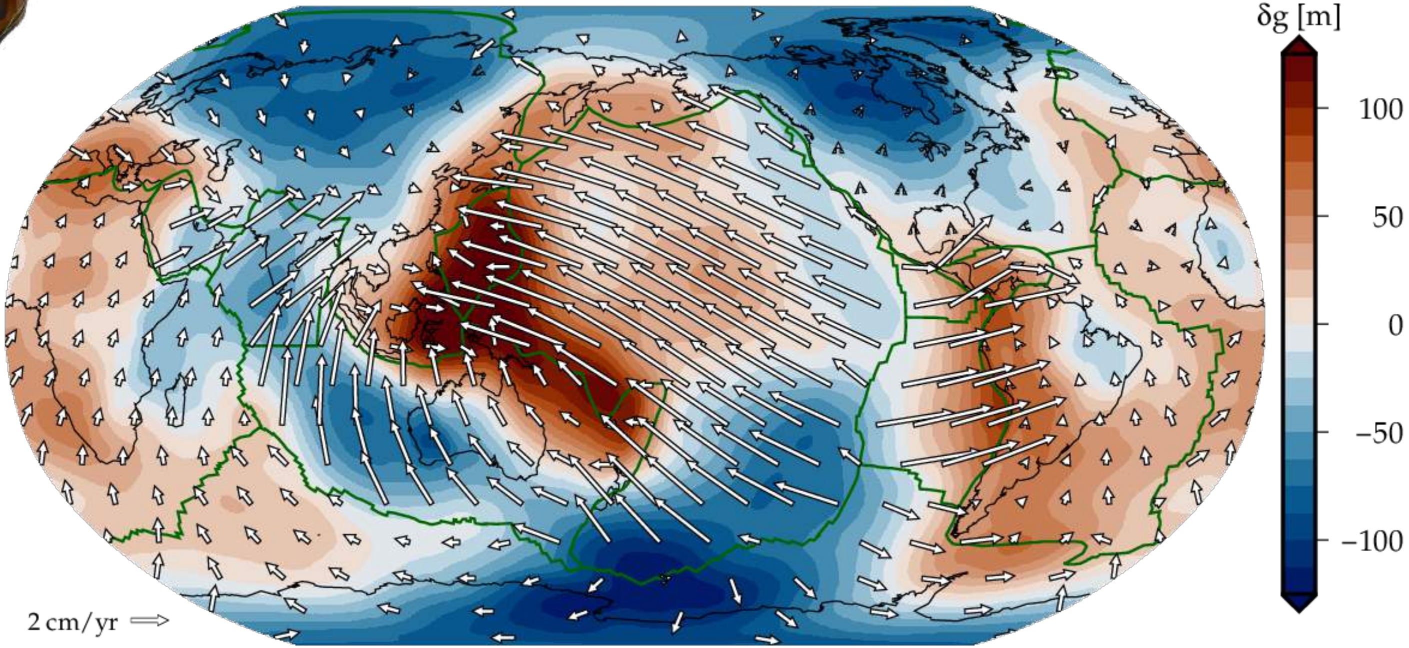


$$\text{velocities} \propto \frac{\text{density anomaly}}{\text{viscosity}}$$

$$\text{geoid and topography} \propto \text{density anomaly}$$

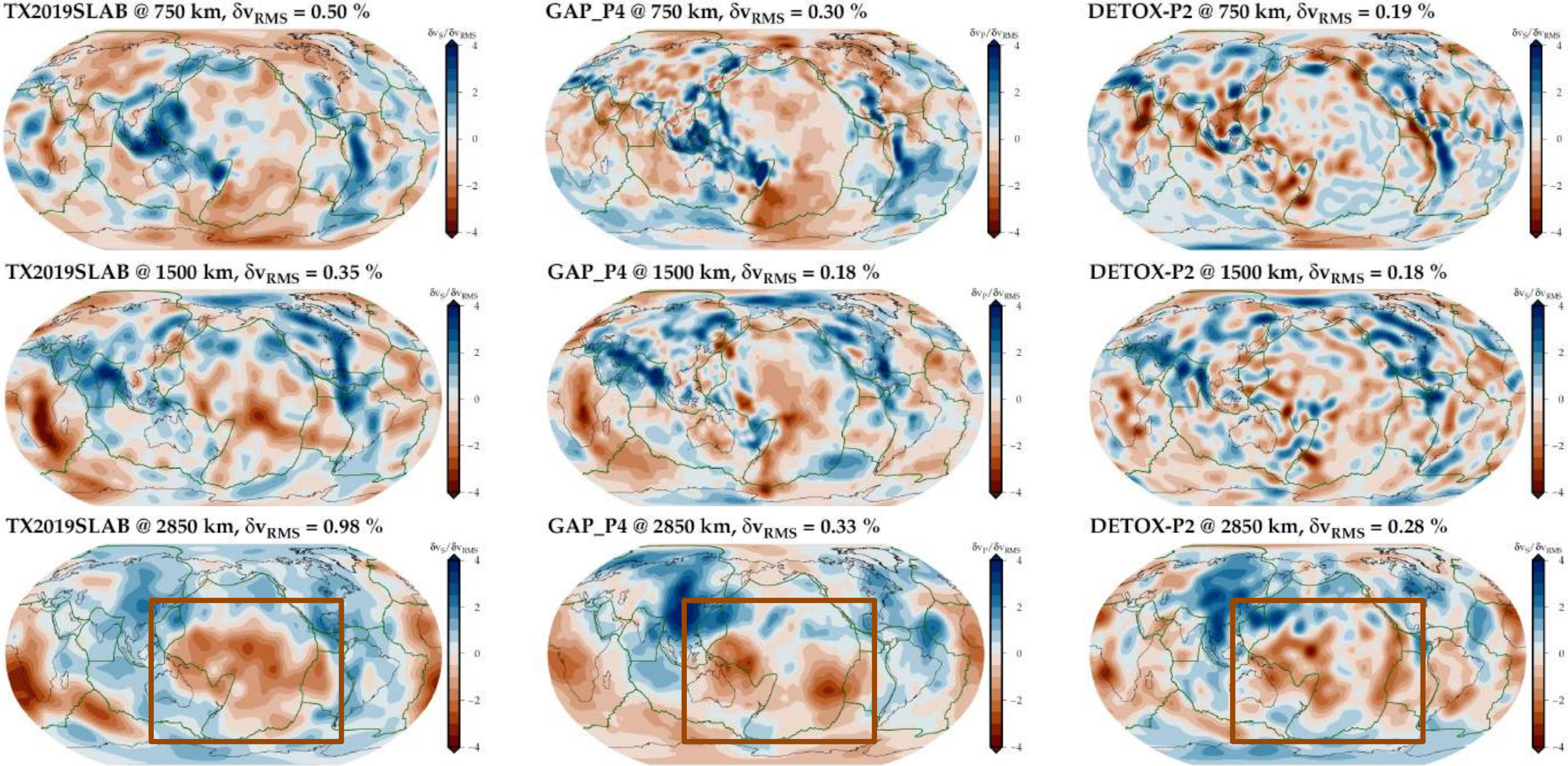
Correlation with
plate velocities: 0.89
geoid: 0.82

geoid anomaly



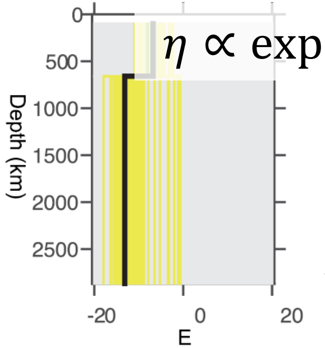
Dynamically consistent computation with prescribed weak zones and lateral viscosity variations based on TX2019

S vs *P* tomography: thermo-chemical effects



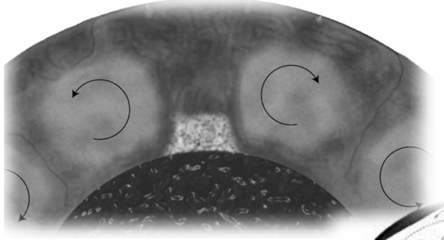
Lu et al. (2019) Obayashi et al. (2013) Hosseini et al. (2020)

Next level challenges: Inferring mantle rheology

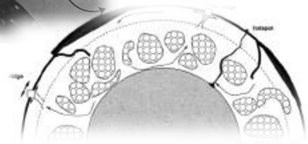


$$\eta \propto \exp(-E(T - T_0))$$

Yang and Gurnis (2016)

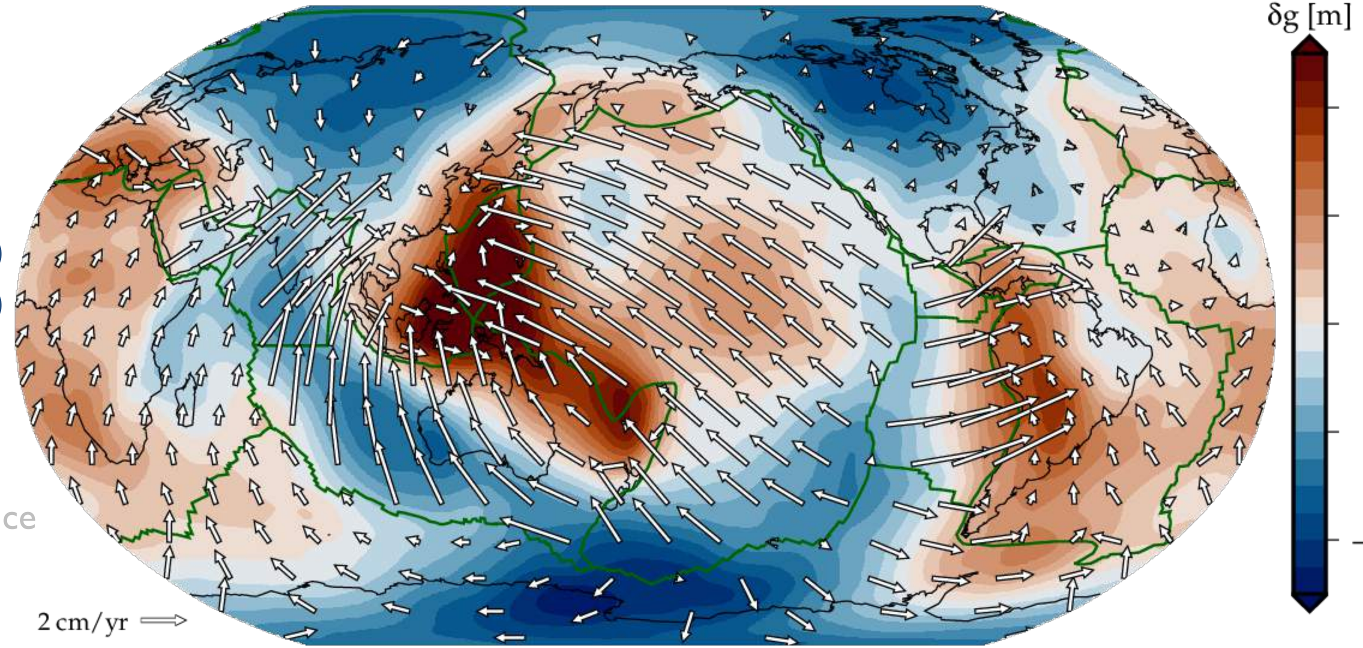


Ballmer et al. (2017)



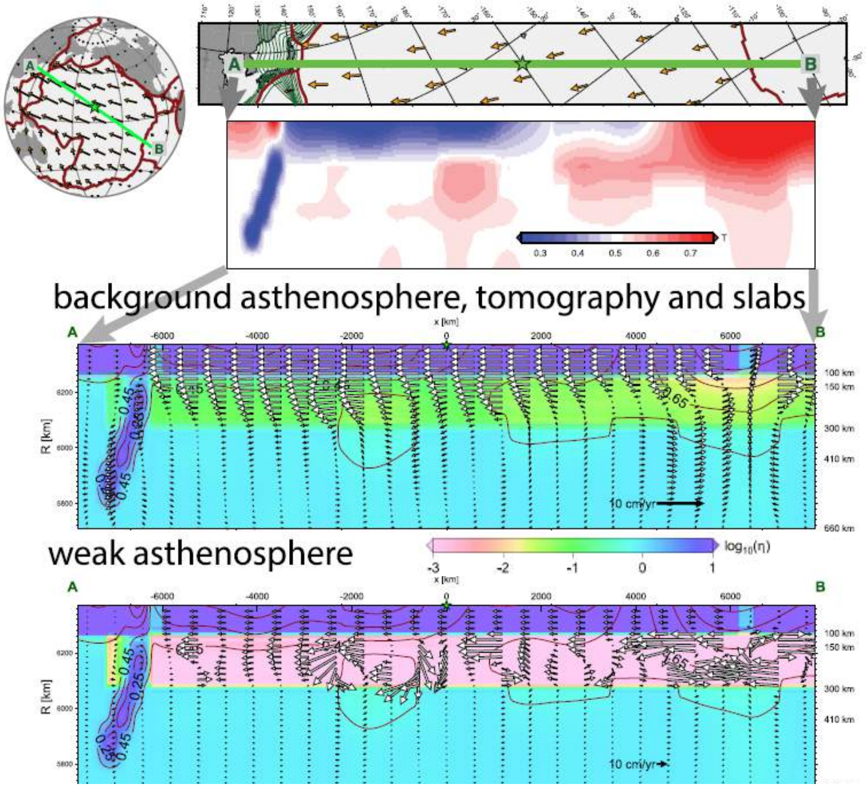
Becker et al. (1999)

Correlation with
plate velocities: 0.84 (0.89)
geoid: 0.84 (0.82)

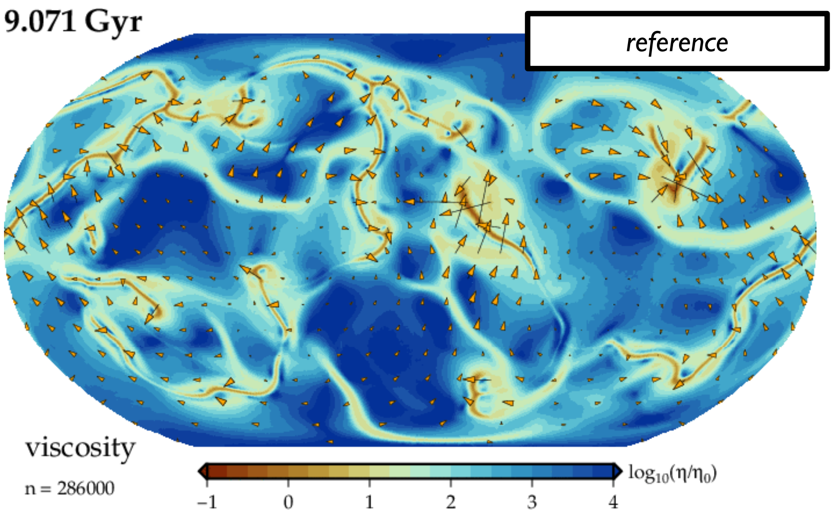


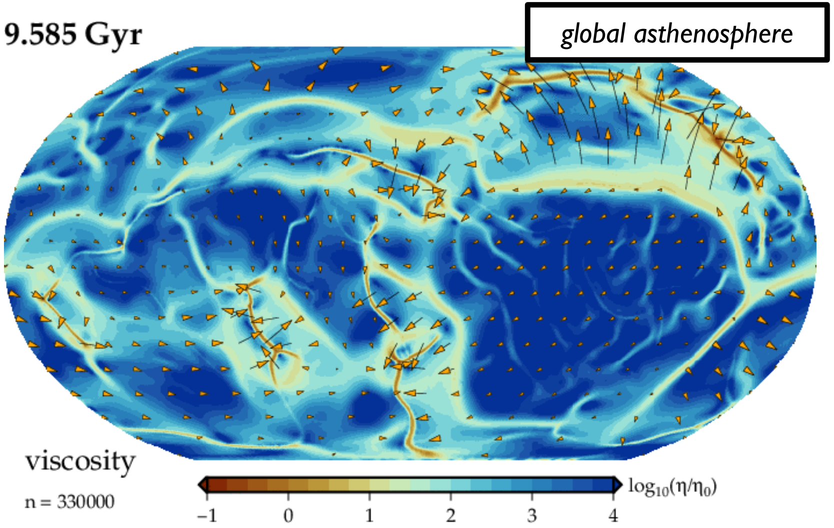
E = -7
Inverse temperature dependence interpreting slow regions as BEAMS

How weak is the asthenosphere?



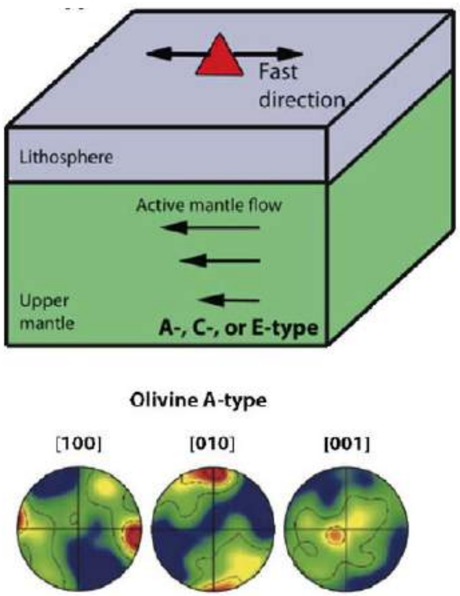
Becker (2017)



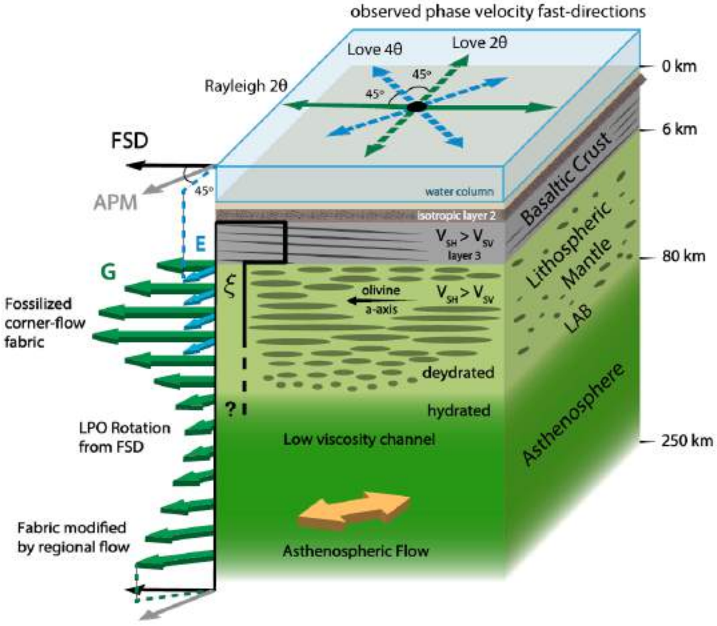


Fuchs and Becker (in prep.), cf. Richards et al. (2001), Tackley (2000a,b)

Upper mantle seismic anisotropy as a constraint for rheology



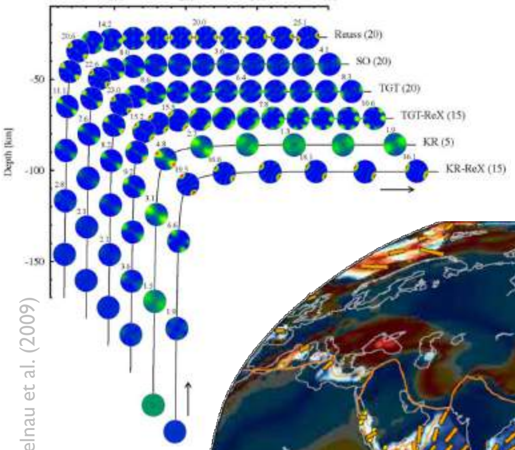
Long and Becker (2010)



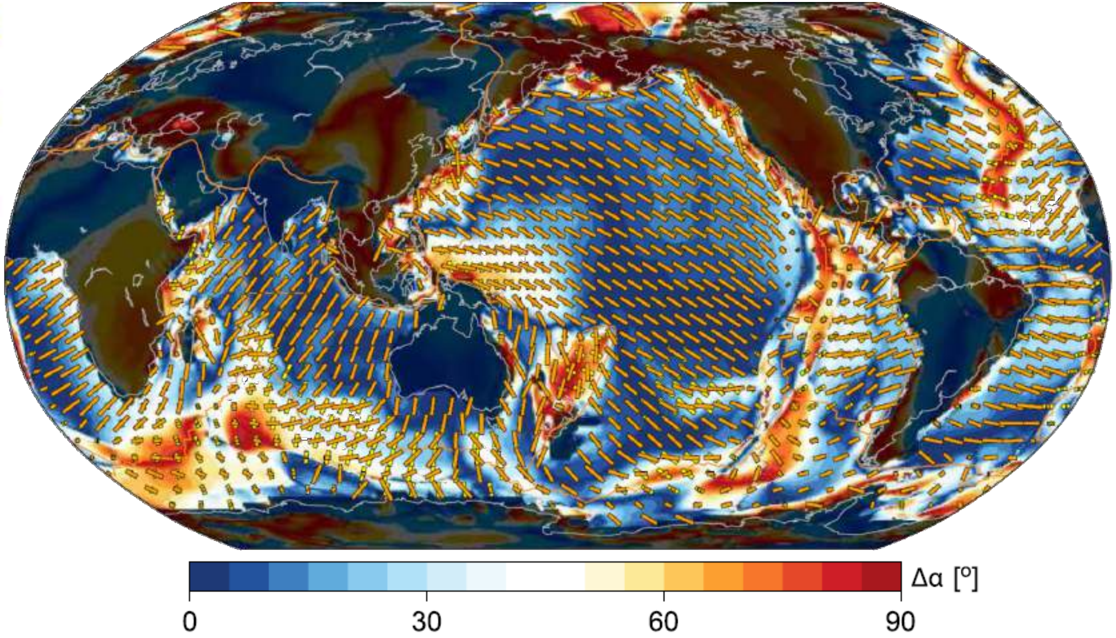
Russell et al. (2019)

- crystallographic preferred orientation (CPO) of olivine sensitive to time-integral of mantle circulation

Azimuthal anisotropy in oceanic basins

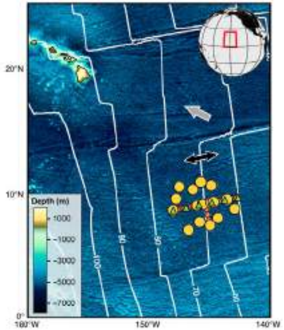


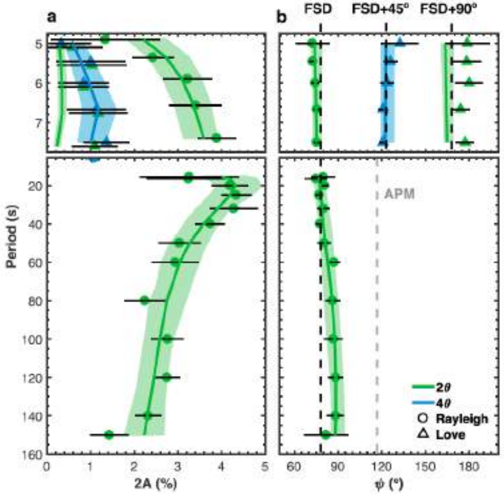
Castelnau et al. (2009)



good *bad*

Becker et al. (2003, 2008, 2014, 2015), Becker and Lebedev (2020)



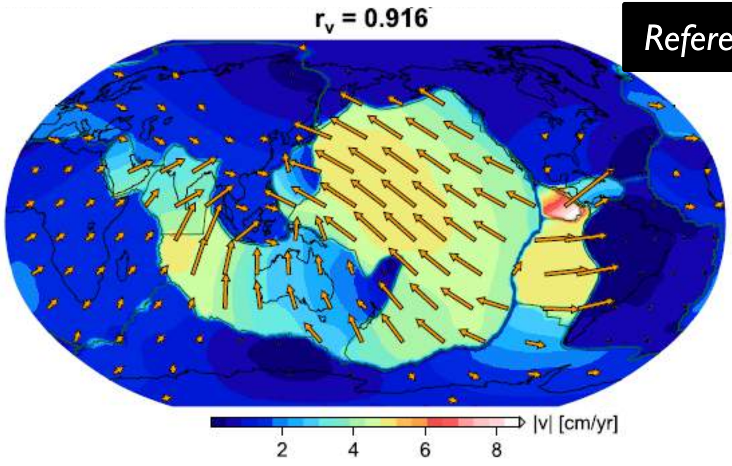


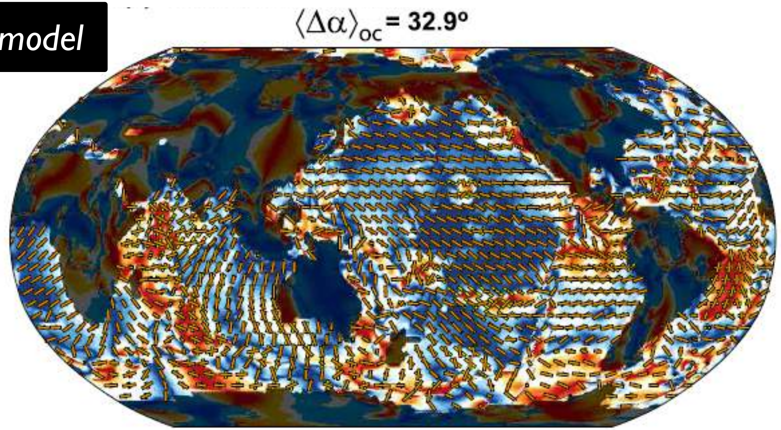
Russell et al. (2019)

Plate velocity predictions

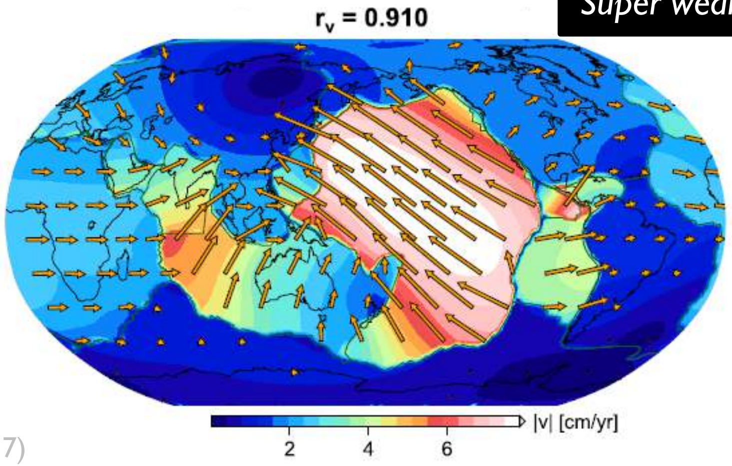
Azimuthal anisotropy match

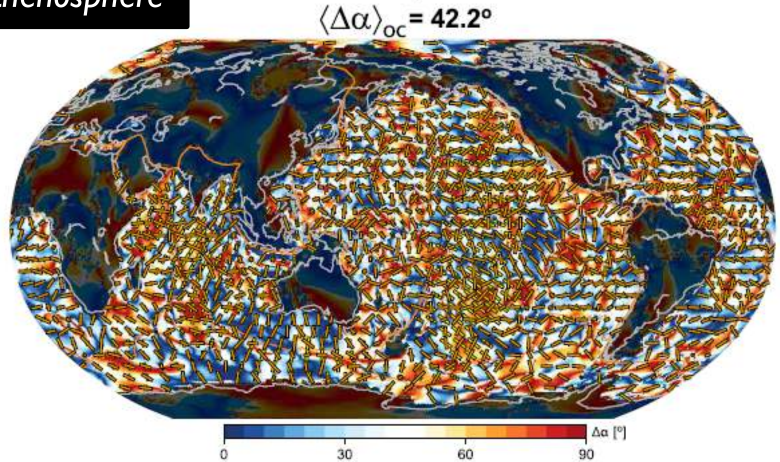
Reference model





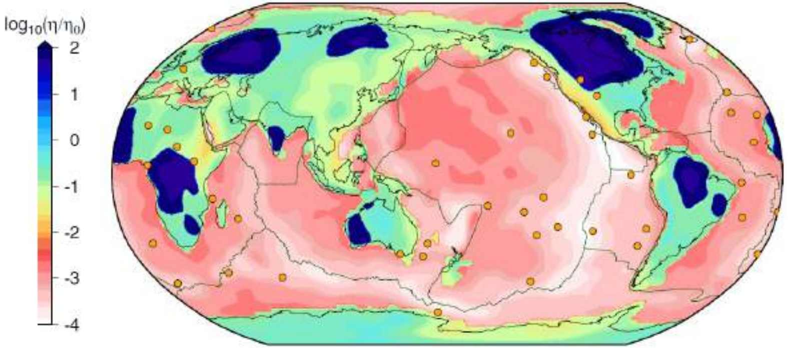
Super weak asthenosphere

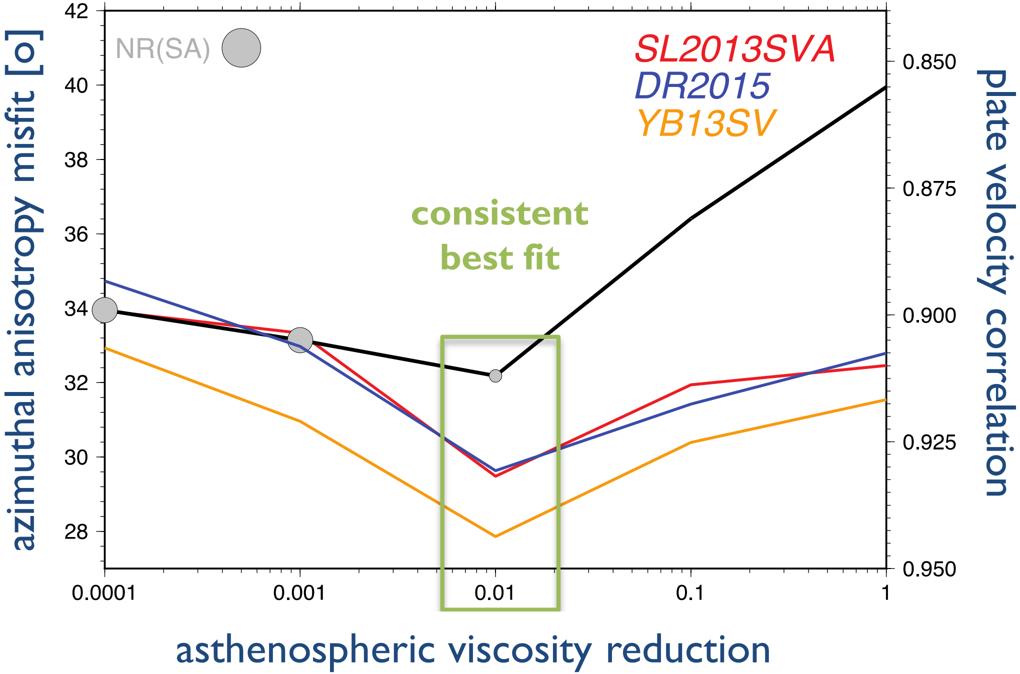




Becker (2017)

Predicting plate velocities and azimuthal anisotropy

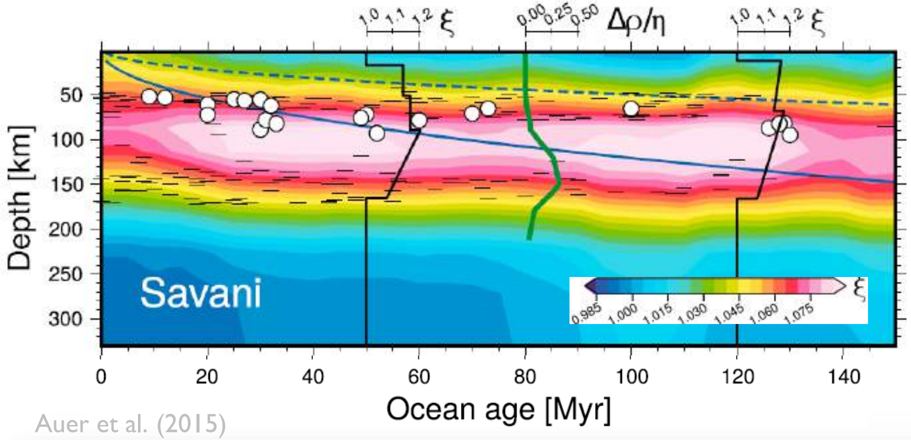




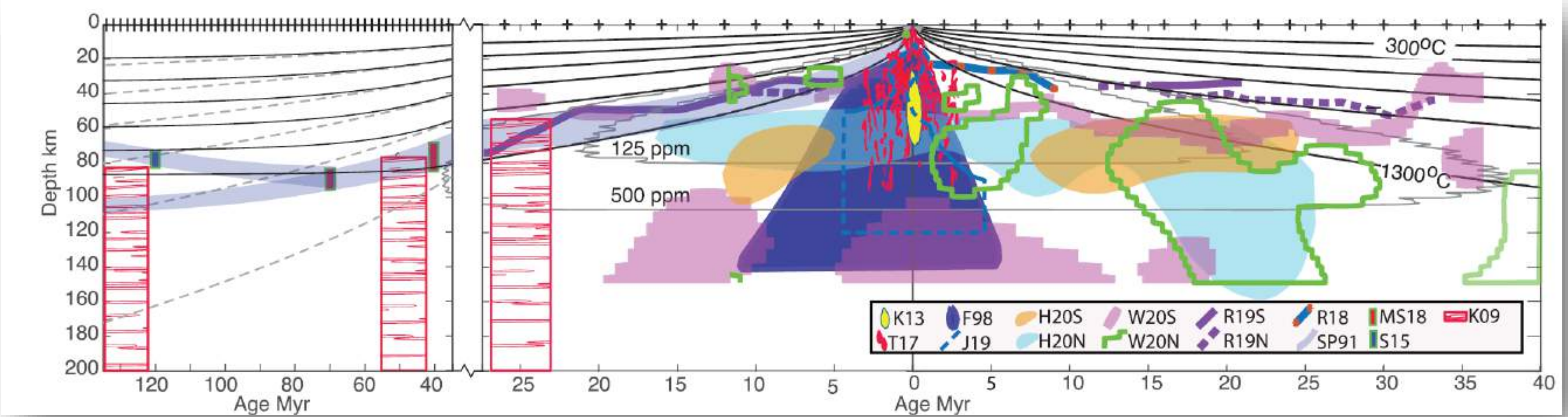
- sweet spot for oceanic asthenosphere viscosity reduction
- trade-off between thickness and strength of asthenosphere
- if melt affects rheology, should be local/not connected, else major disruption of anisotropy

Becker (2017)

Yet, melt may be required to explain seismic features?



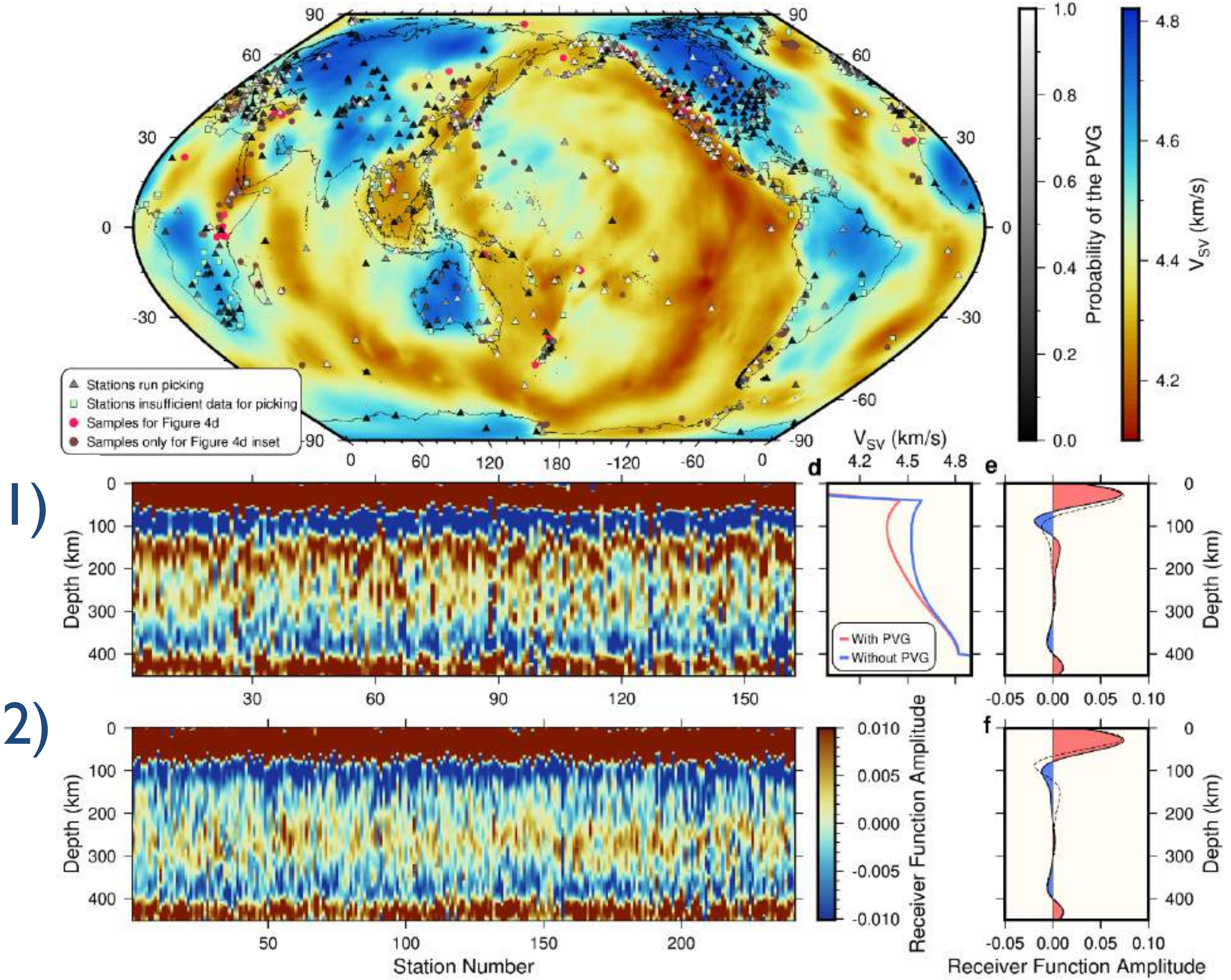
Auer et al. (2015)



Rychert et al. (2020)

Role of melt

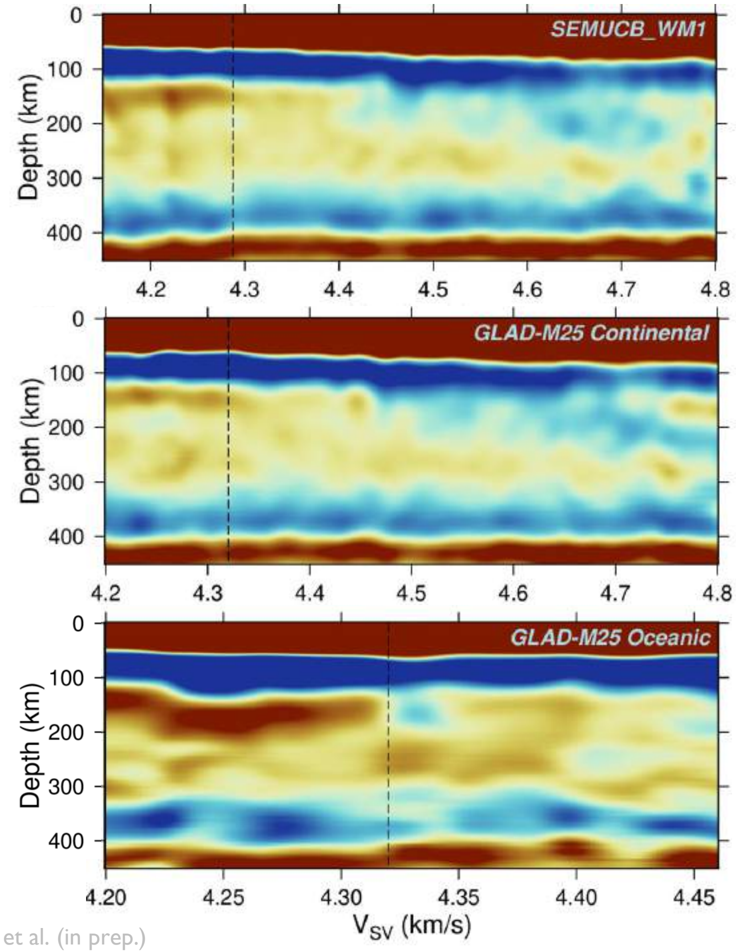
Two classes of velocity profiles from receiver function analysis



Hua et al. (in prep.)

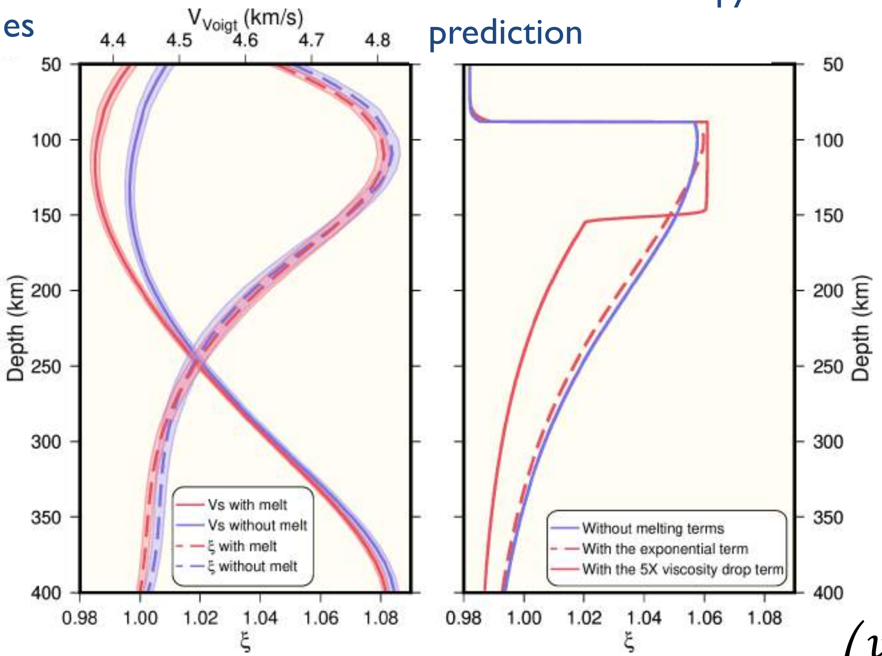
Partial melting associated with relative hot regions

receiver functions sorted by v_S



Observed profiles

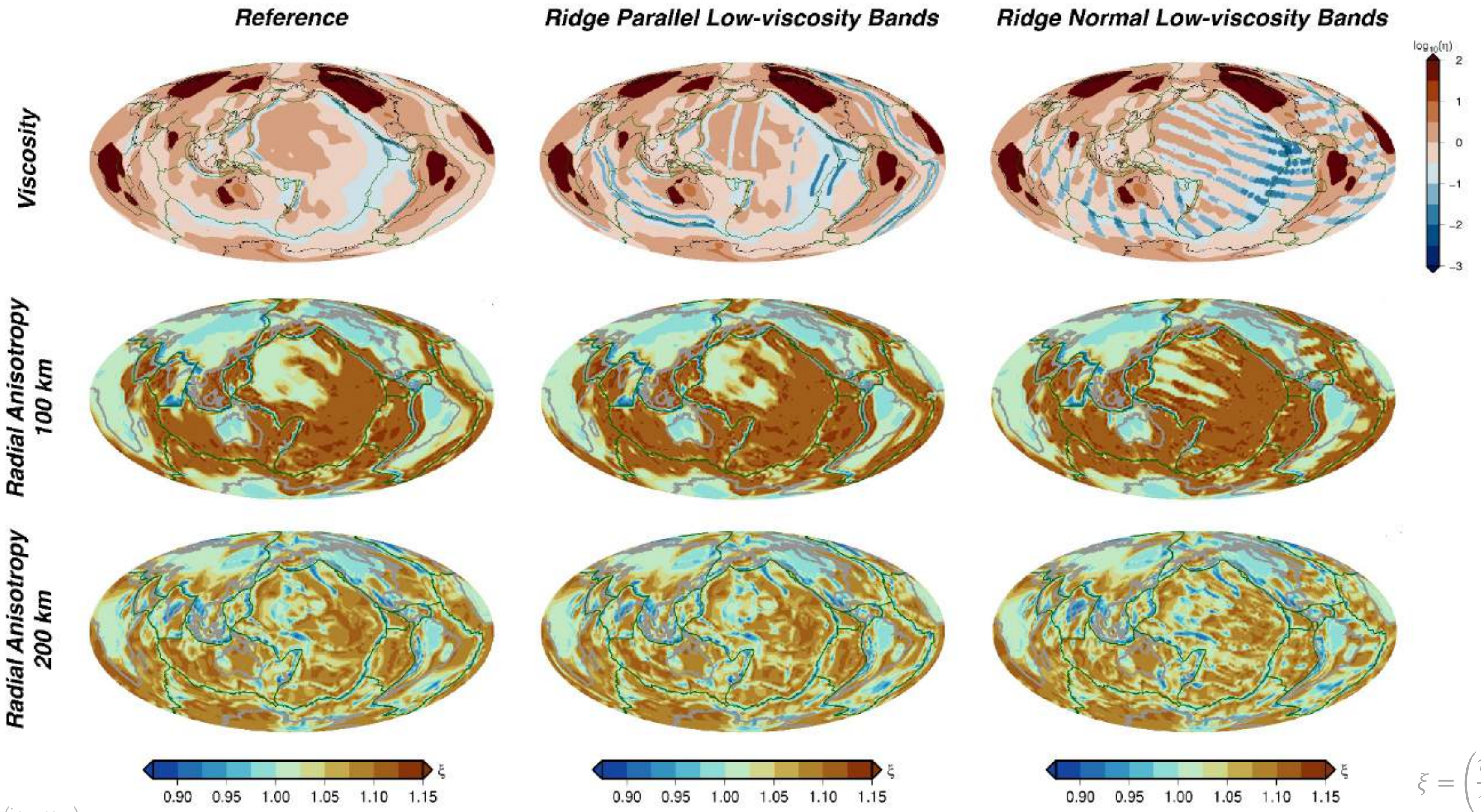
1-D radial anisotropy prediction



$$\xi = \left(\frac{v_{SH}}{v_{SV}}\right)^2$$

Hua et al. (in prep.)

Asthenospheric low viscosity channels and radial anisotropy



$$\xi = \left(\frac{v_{SH}}{v_{SV}}\right)^2$$

Hua et al. (in prep.)

Upper mantle radial anisotropy

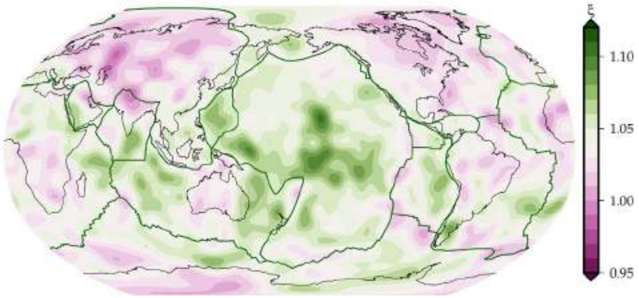
For isotropic shear wave speeds:

$$\langle r_8 \rangle \geq 0.7$$

$$\xi = \left(\frac{v_{SH}}{v_{SV}}\right)^2$$

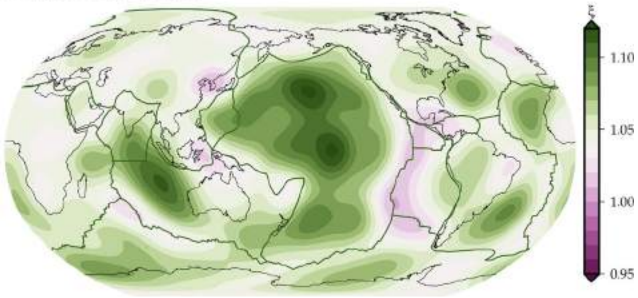
150 km depth

RSAVANI



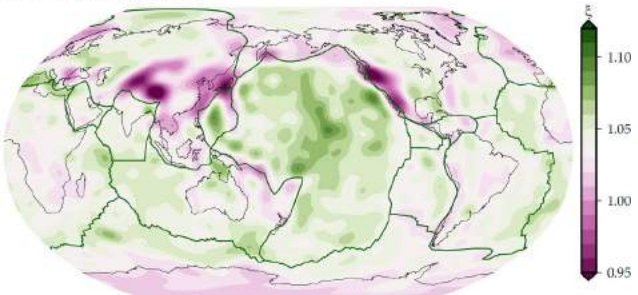
Porritt et al. (2021)

SEMUCB-WM1



French et al. (2015)

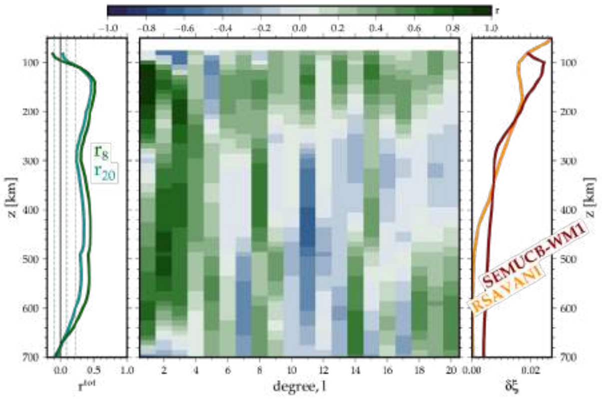
SGLOBE-RANI



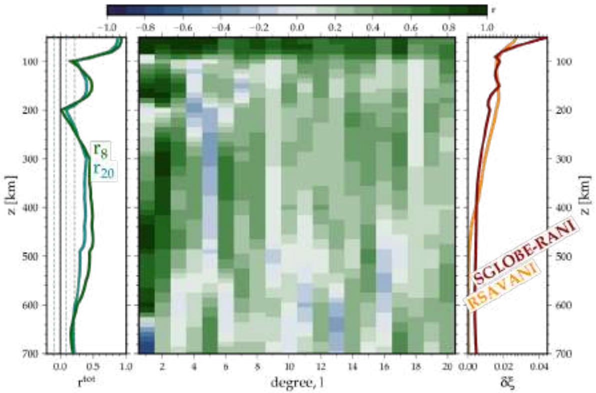
Chang et al. (2015)

radial anisotropy correlation

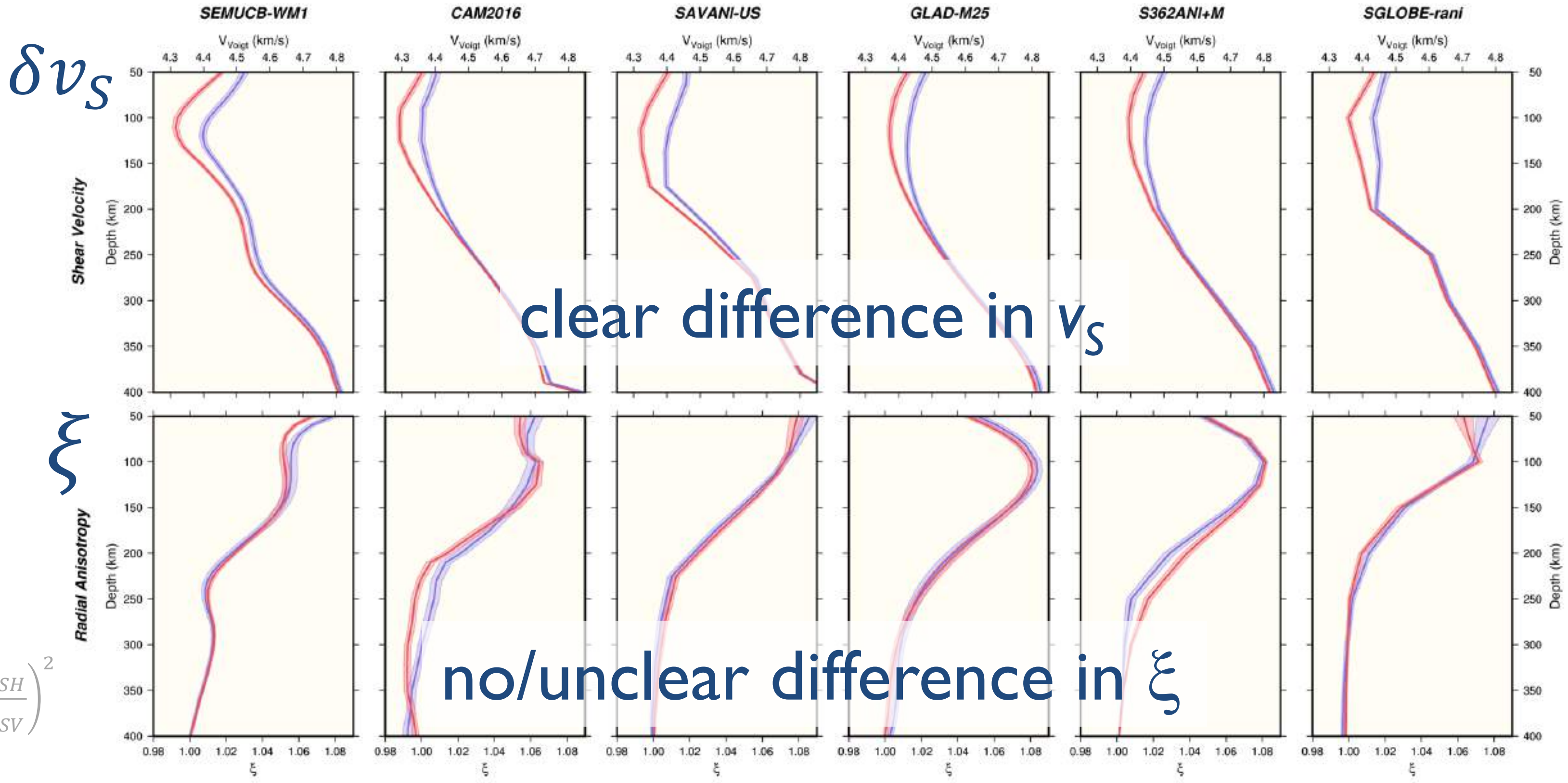
RSAVANI vs. SEMUCB-WM1, $\langle r_{20} \rangle$=0.28, $\langle r_8 \rangle$=0.34



RSAVANI vs. SGLOBE-RANI, $\langle r_{20} \rangle$=0.34, $\langle r_8 \rangle$=0.39



Asthenospheric melt != low viscosity

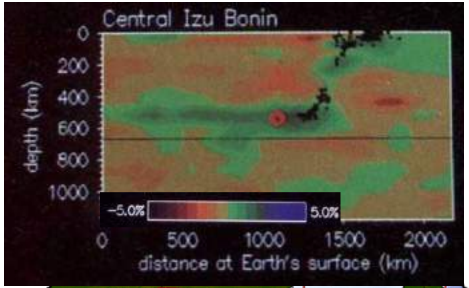


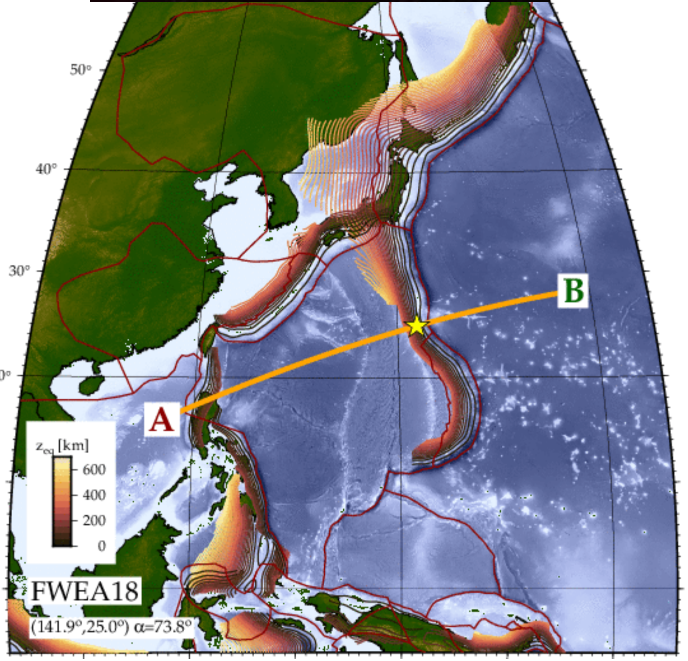
$$\xi = \left(\frac{v_{SH}}{v_{SV}}\right)^2$$

red = RF profile with melt phase   **blue** = RF profile without melt phase

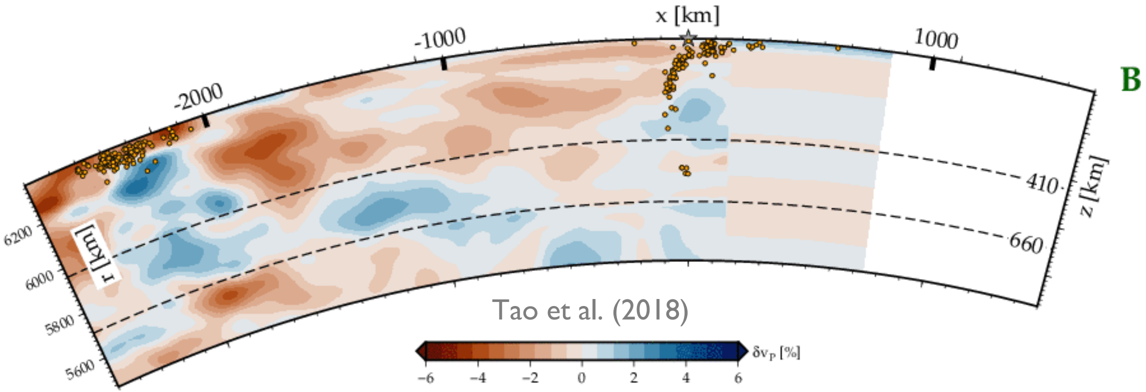
Hua et al. (in prep.)

Hilst et al. (1991)

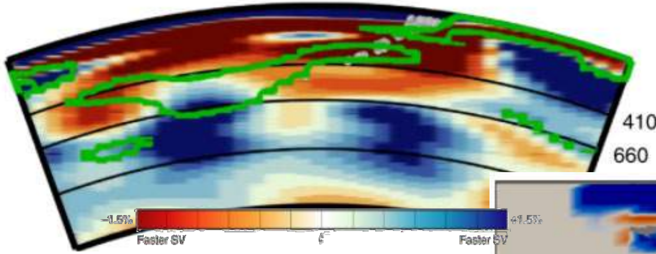


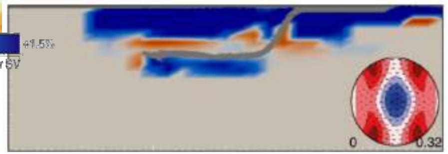


Subduction engine



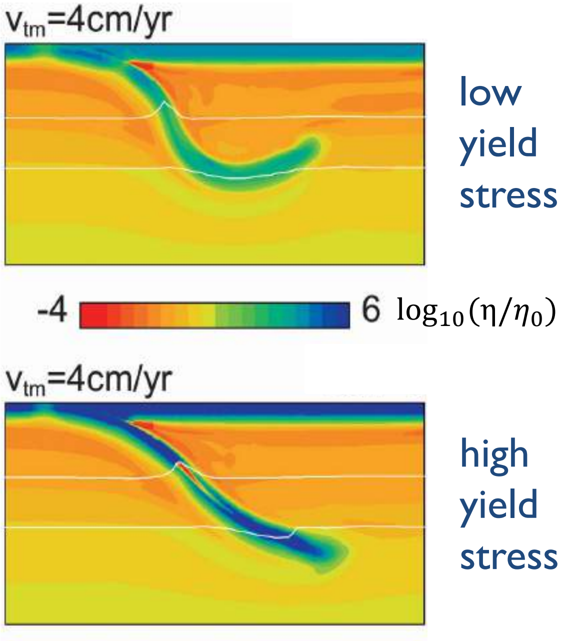
Tao et al. (2018)



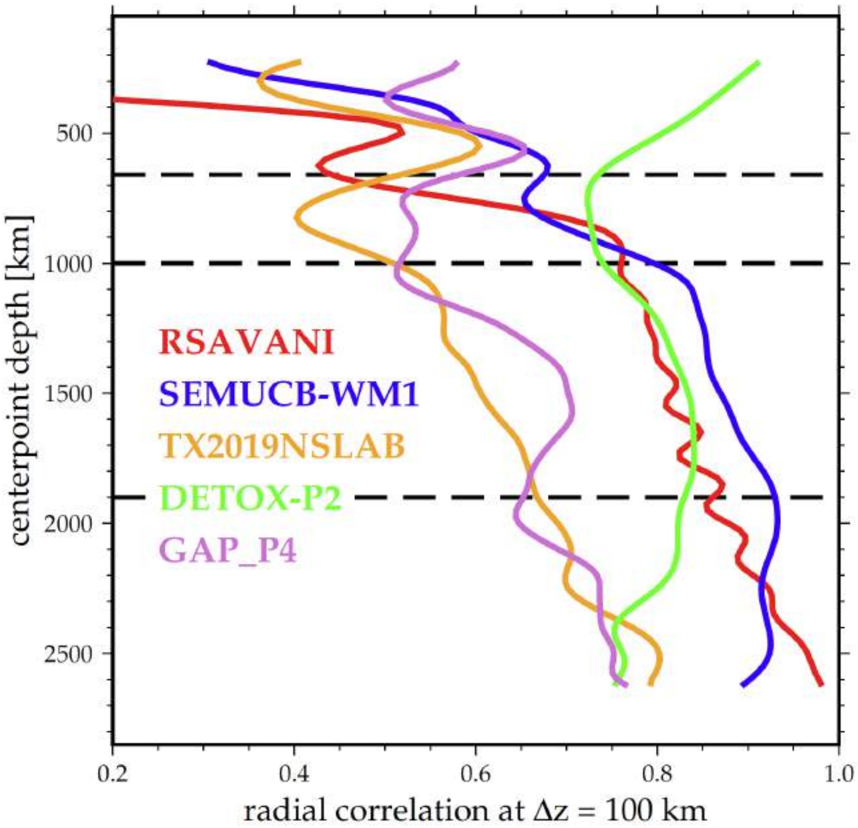


Ferreira et al. (2019)

Role of slab rheology for transition zone dynamics

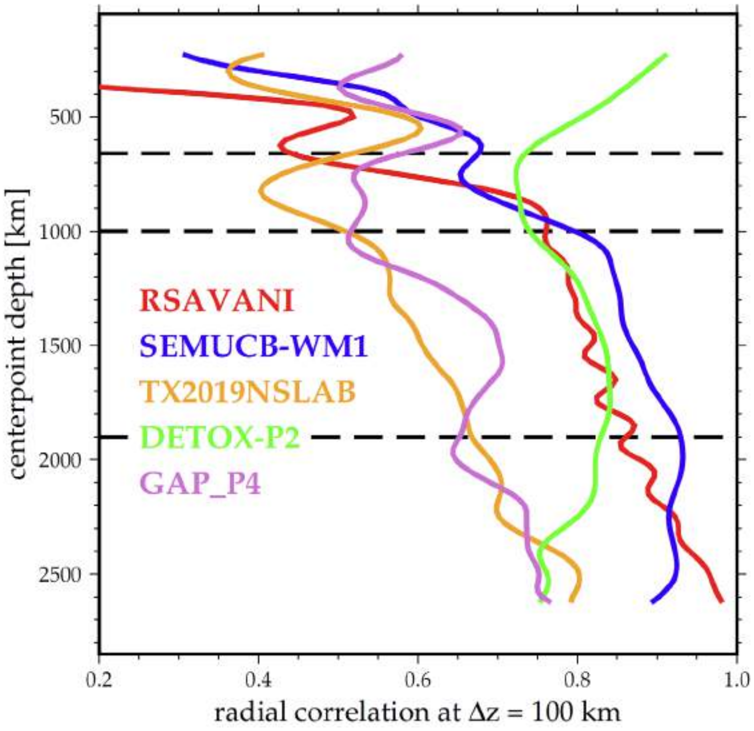


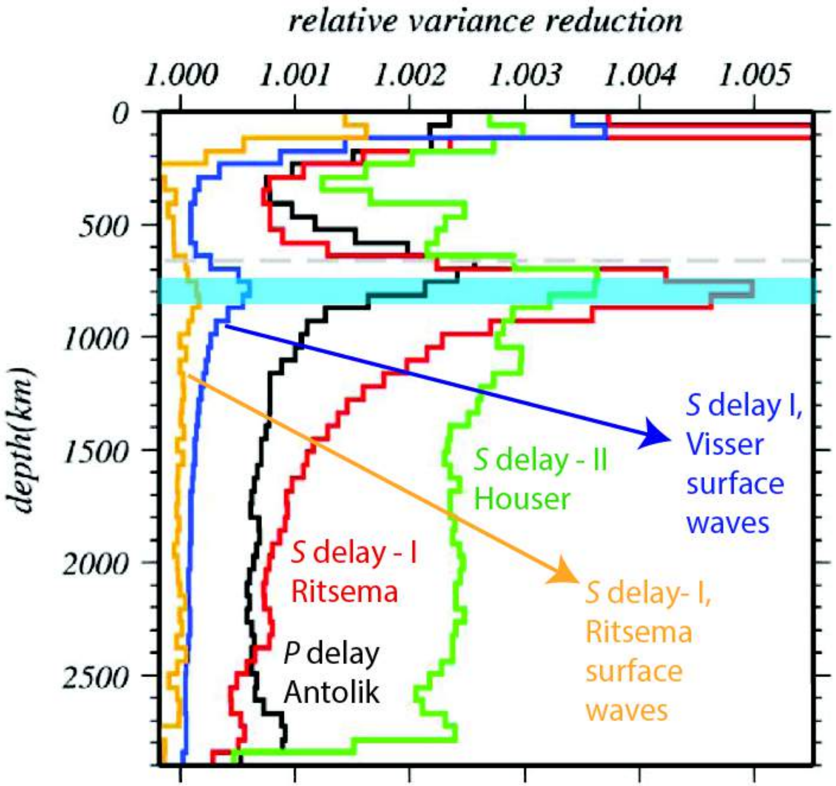
Čížková et al. (2002)



cf. Puster and Jordan (1997), Tackley (1998, 2002)

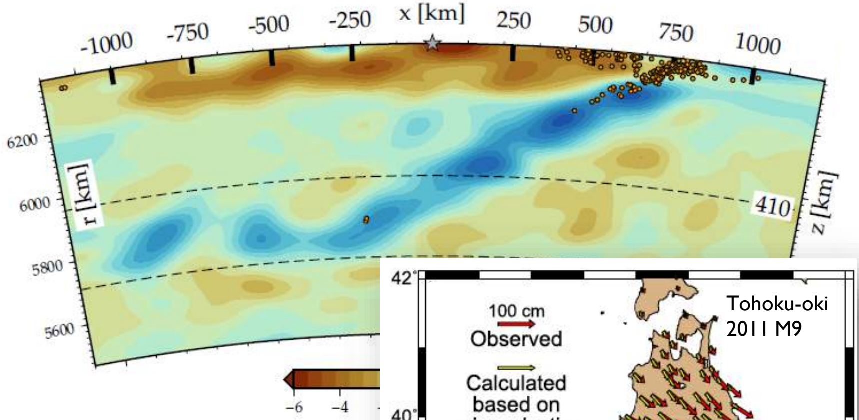
Seismic data prefers decorrelation at ~800 km

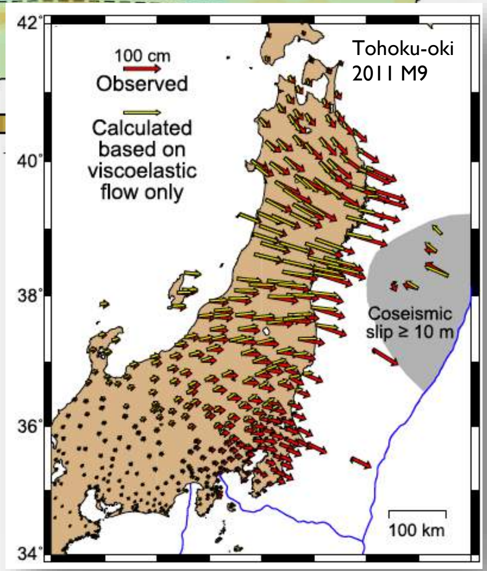


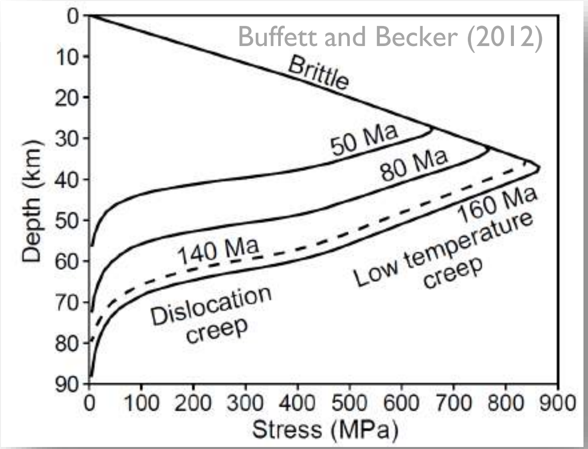


Becker and Boschi (2011)

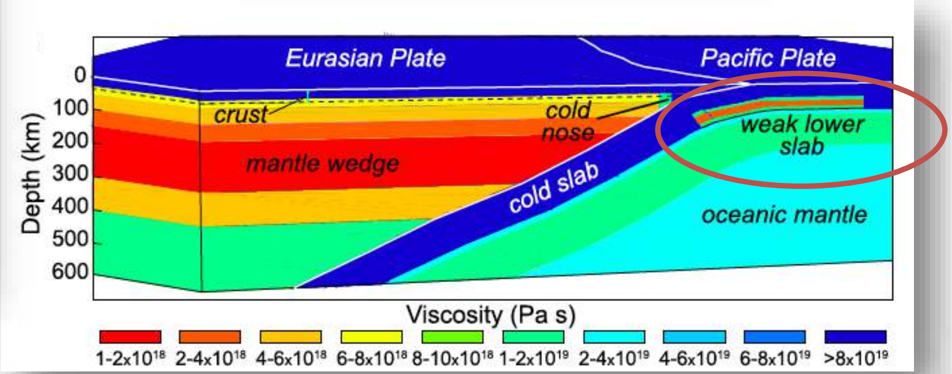
How are slabs weakened?







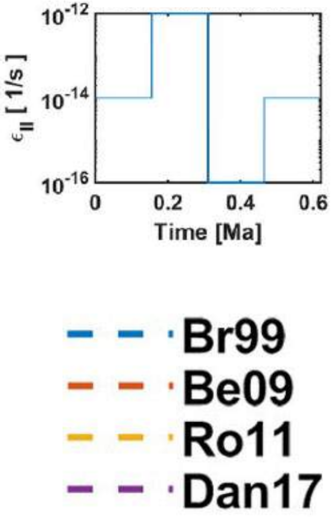
Freed et al. (2017)

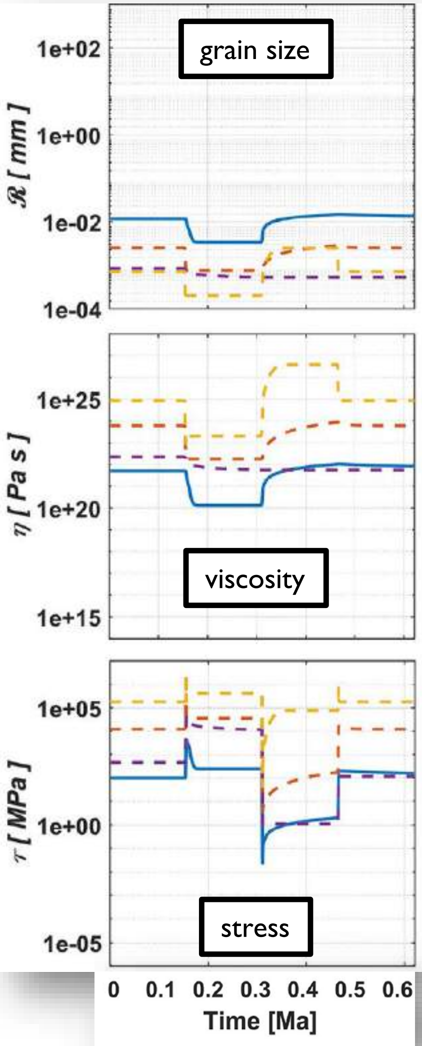


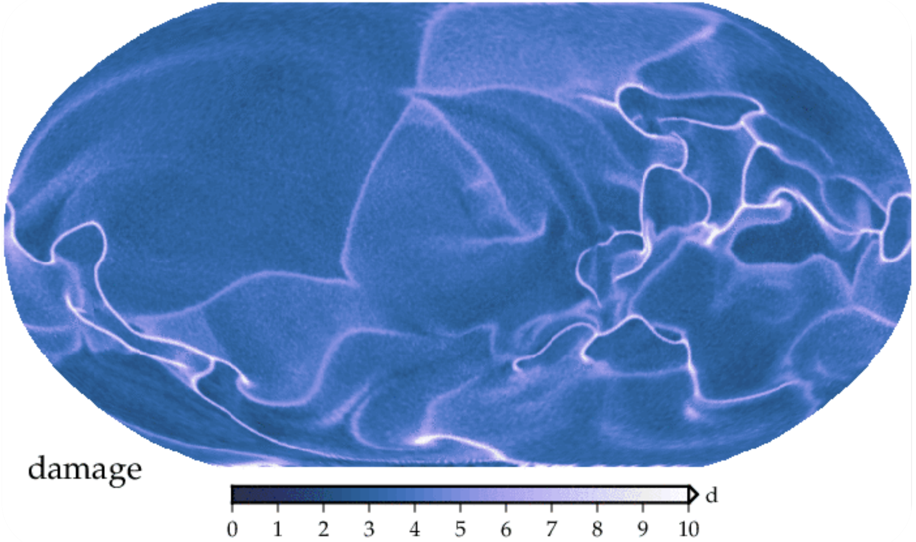
- ➢ Short timescale constraints on viscosity

Grain size evolution and ductile damage

Slide-hold-slide test for different grain size evolution laws

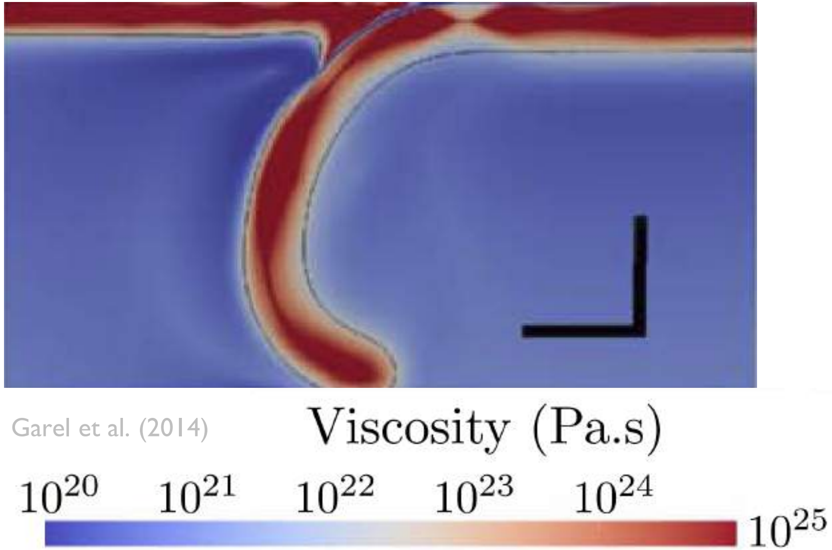




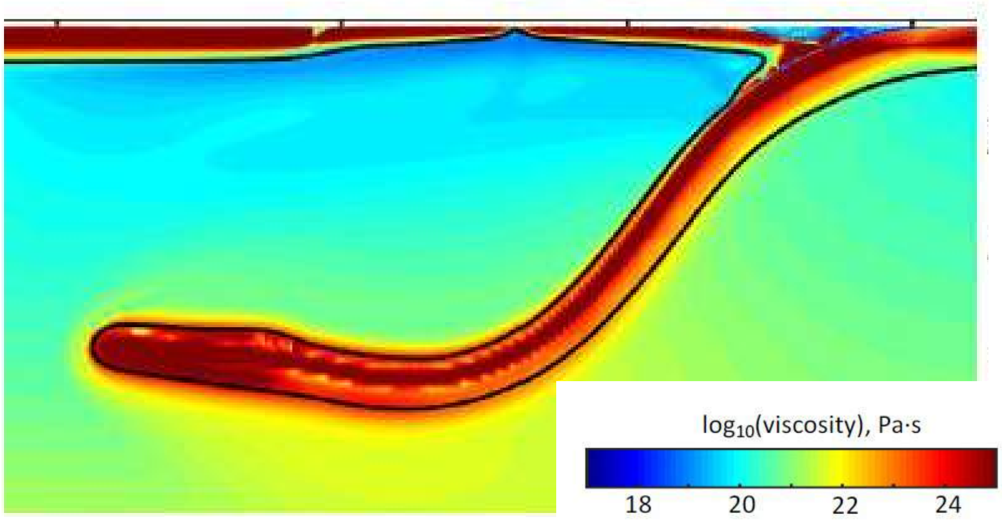


Fuchs and Becker (2020)

Free subduction models with brittle and ductile damage



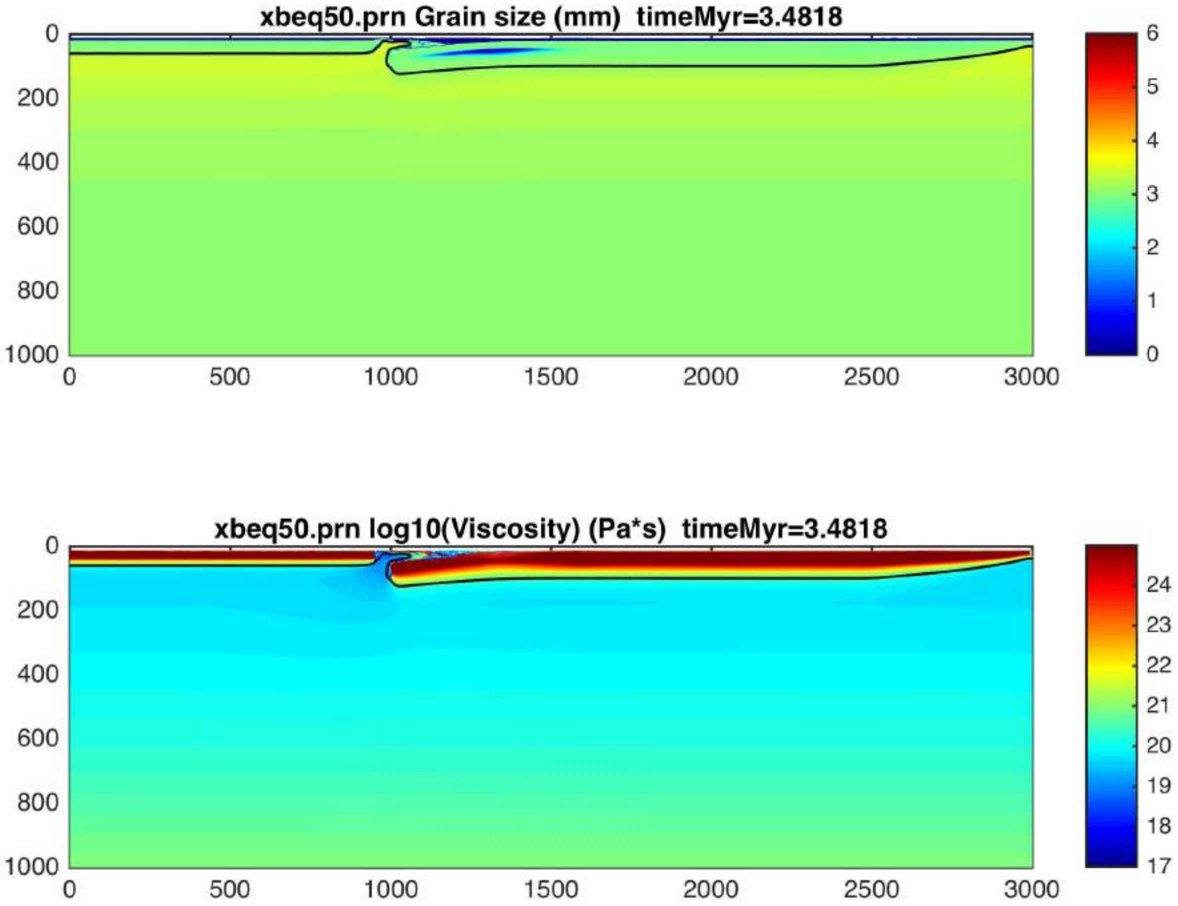
Garel et al. (2014)



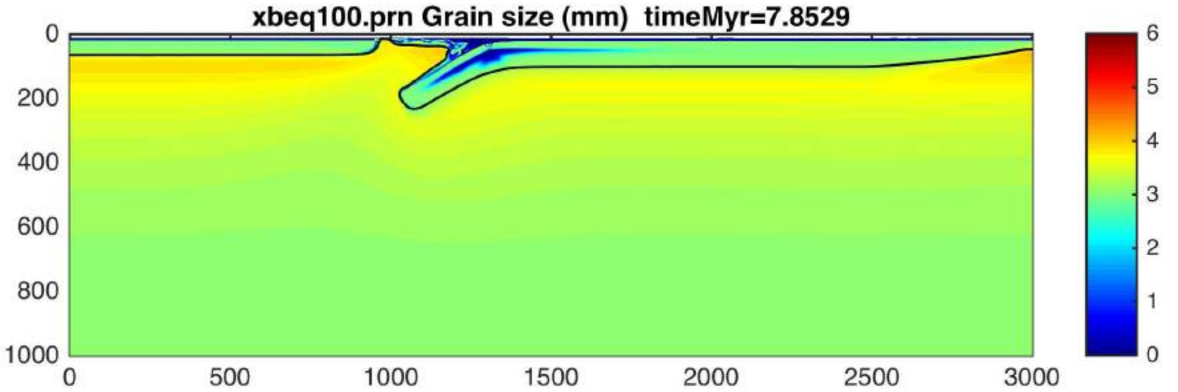
- Brittle domain damage by fault weakening
- Ductile domain grain-size evolution following Rozel, Bercovici et al. including Zener pinning

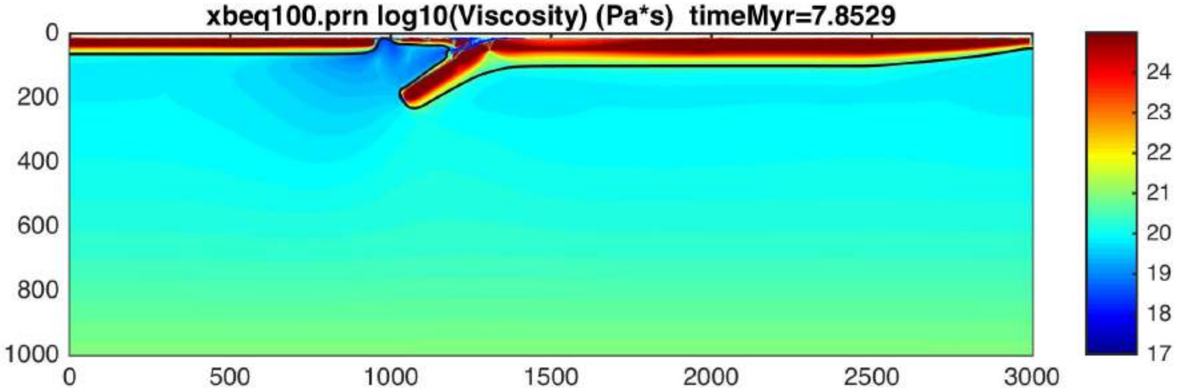
Gerya et al. (in press)

plate age = 40 Myr, initial grainsize = 3 mm

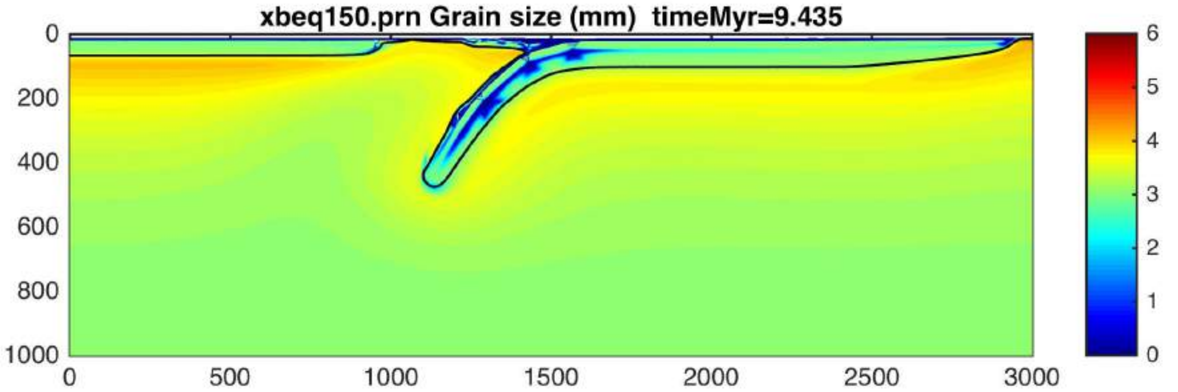


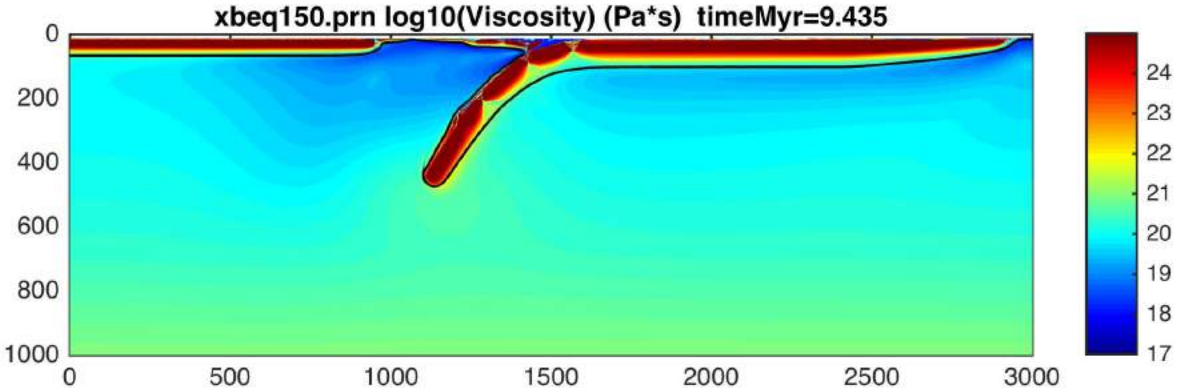
Gerya et al. (in press)



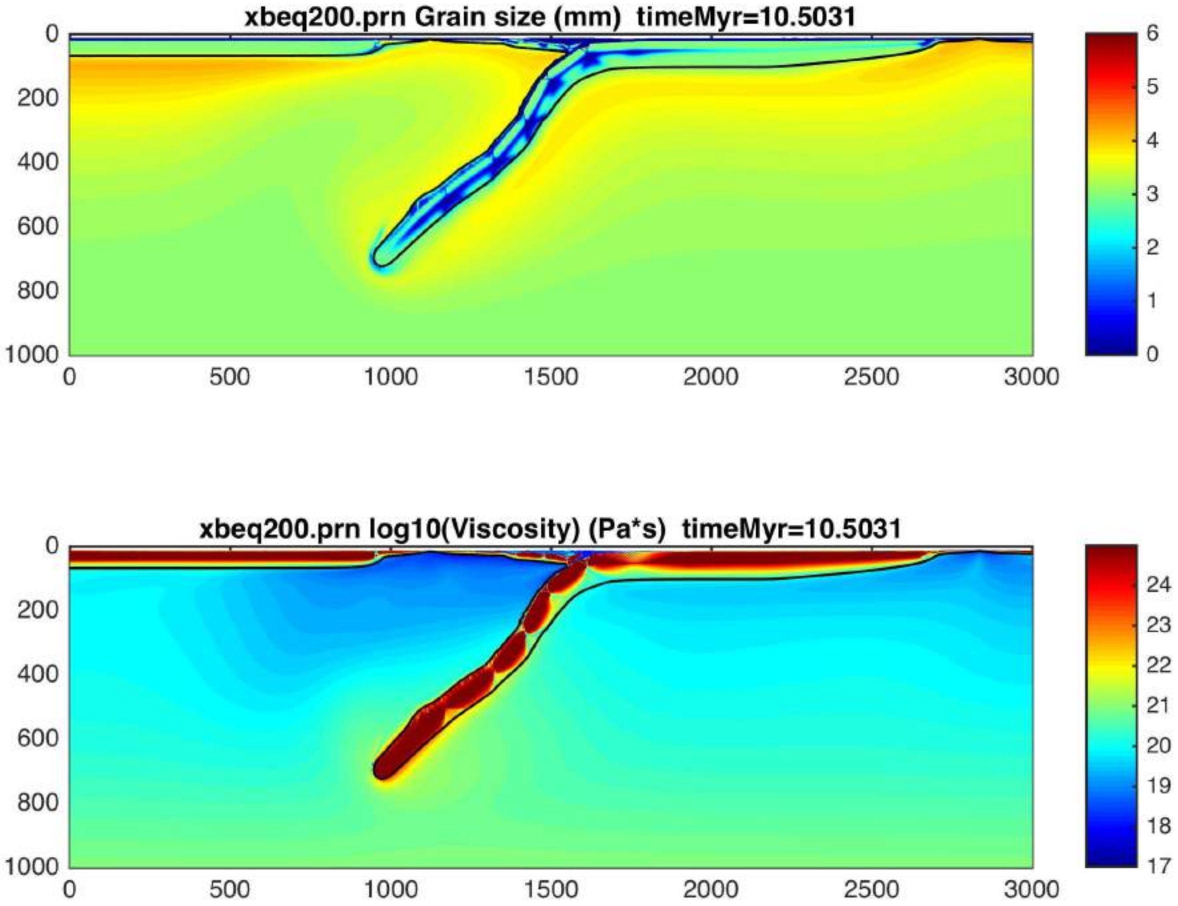


Gerya et al. (in press)



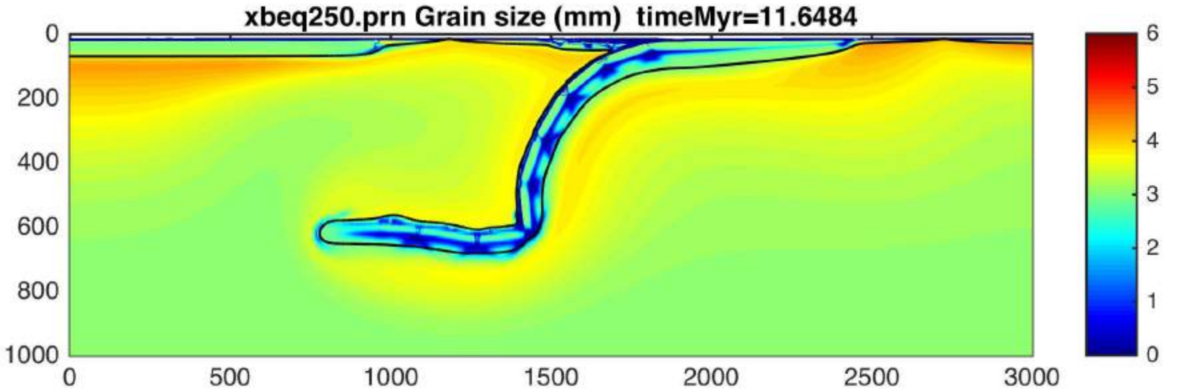


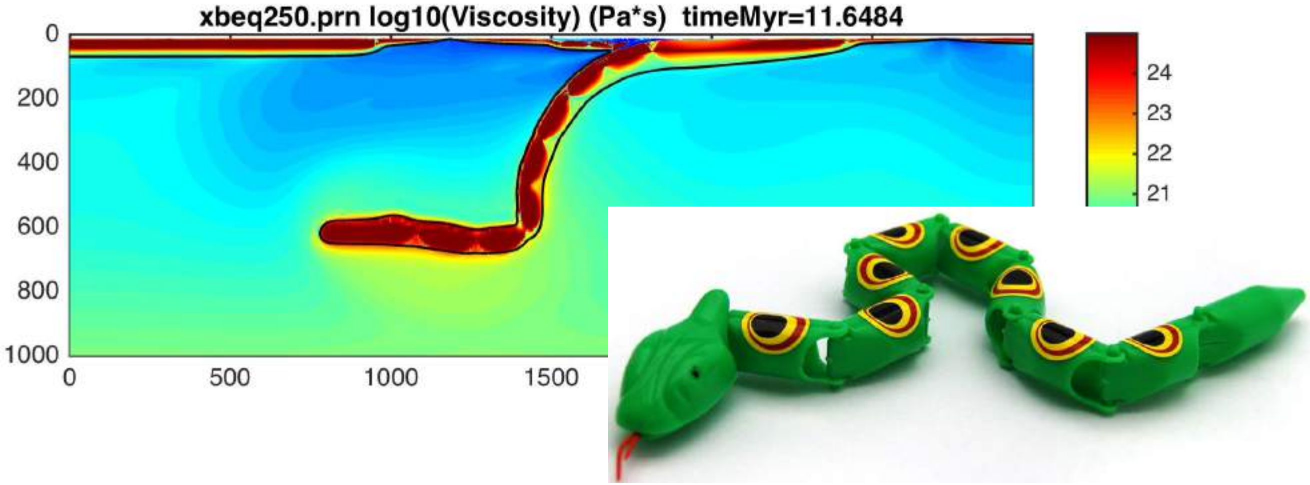
Gerya et al. (in press)



Gerya et al. (in press)

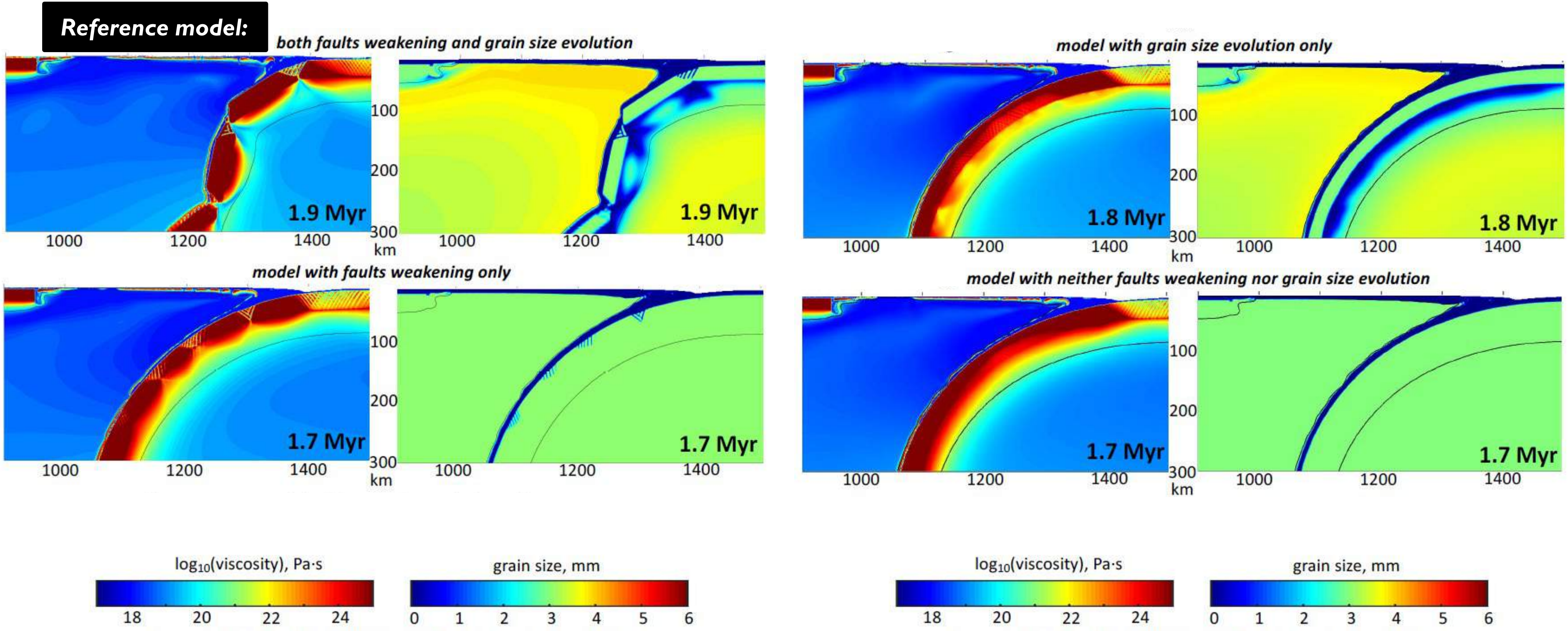
➢ Segmentation of slab facilitates bending and slab contortion, but allows for efficient force transmission





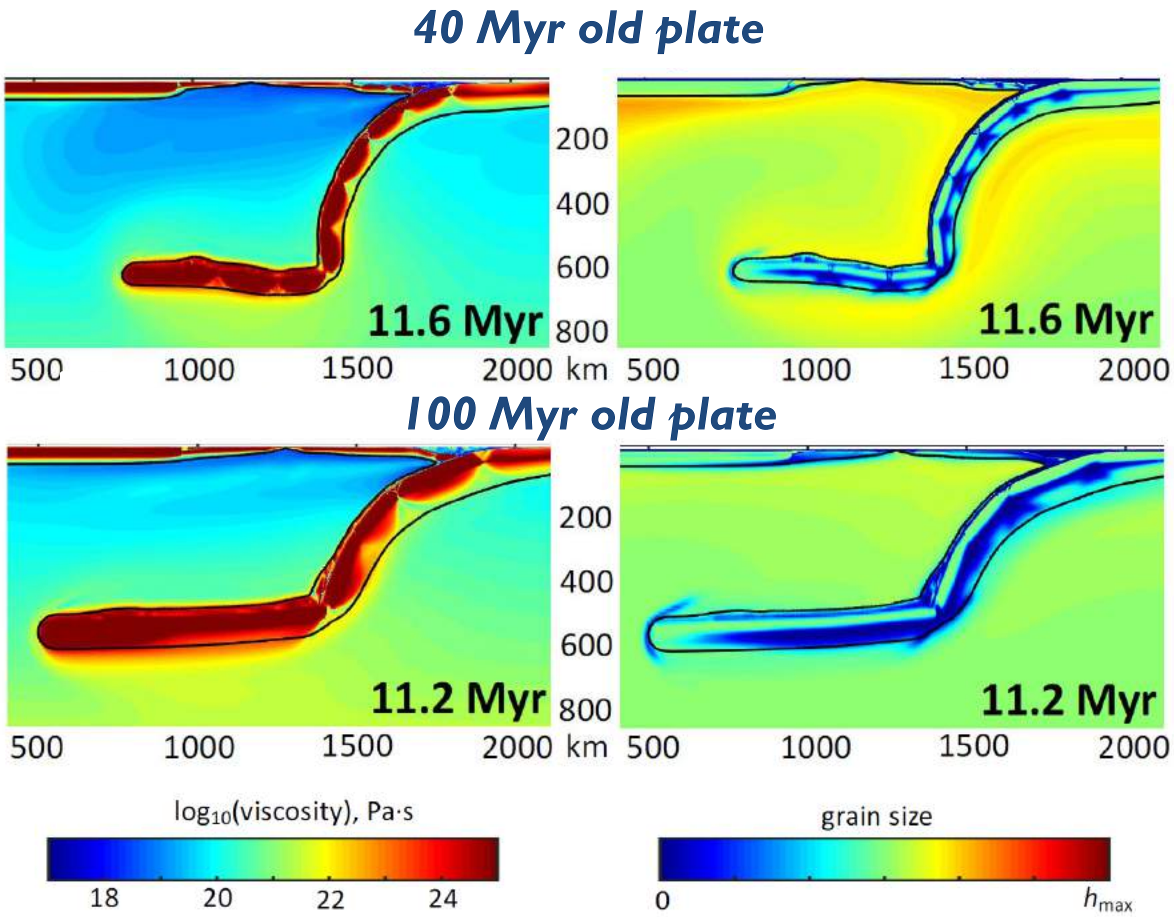
Gerya et al. (in press)

Interaction between brittle and ductile damage required for segmentation



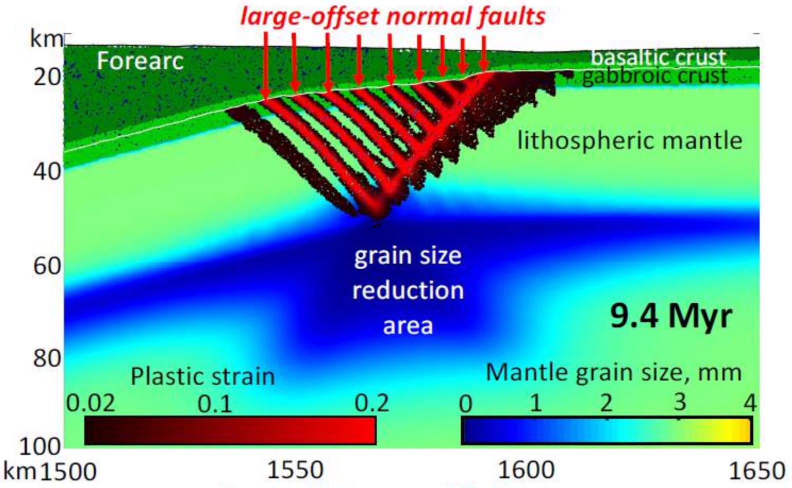
Gerya et al. (in press)

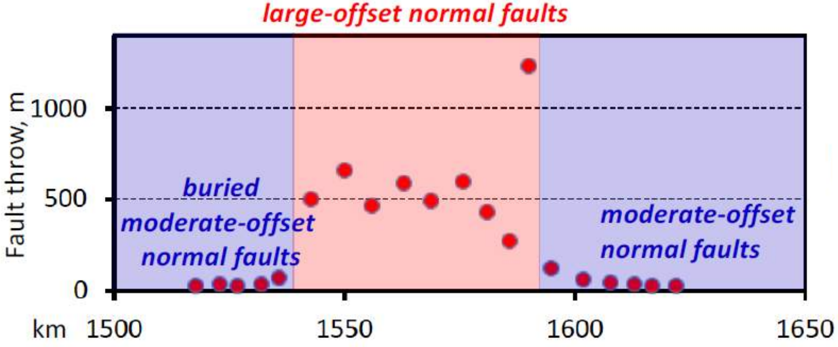
Plate age controls spacing of segments



Gerya et al. (in press)

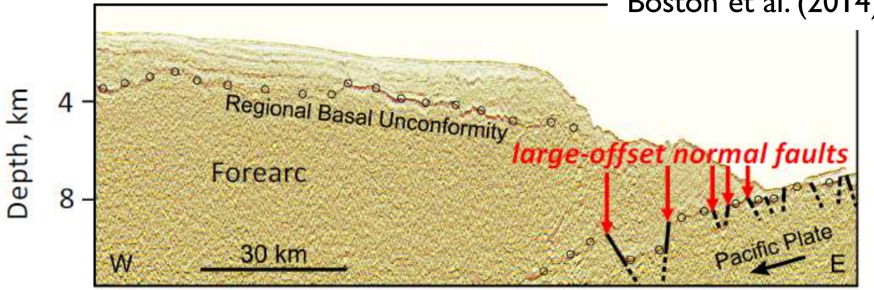
Large offset normal faults in bending region



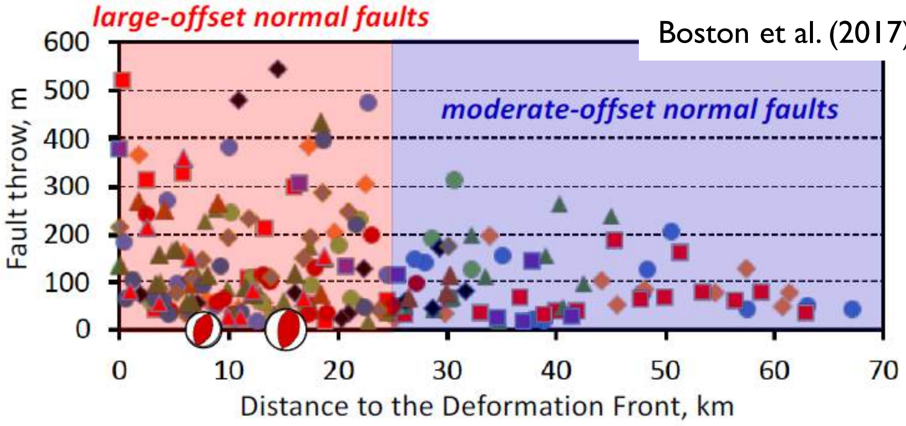


Japan trench

Boston et al. (2014)

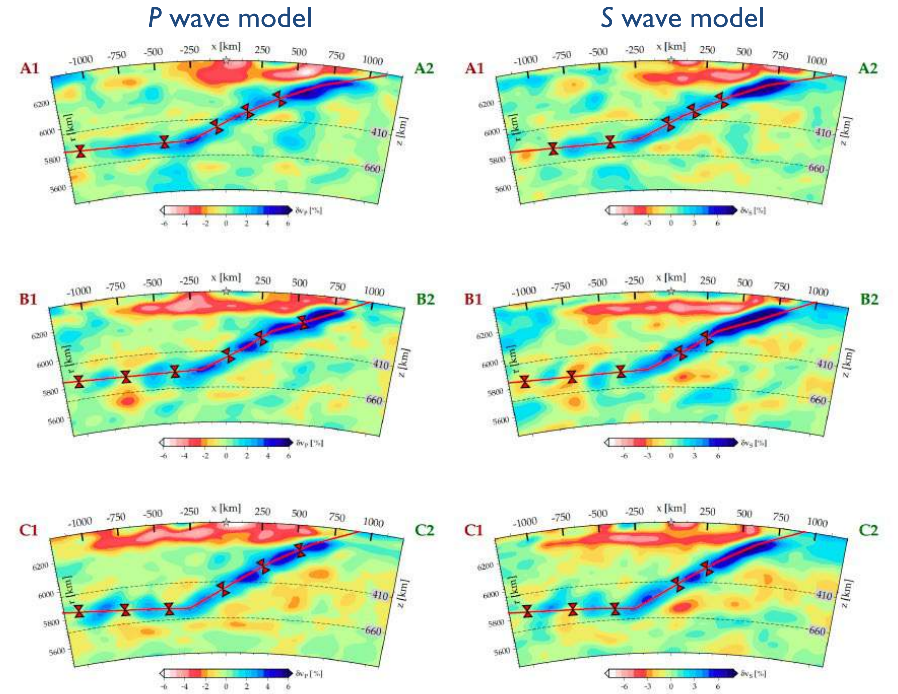


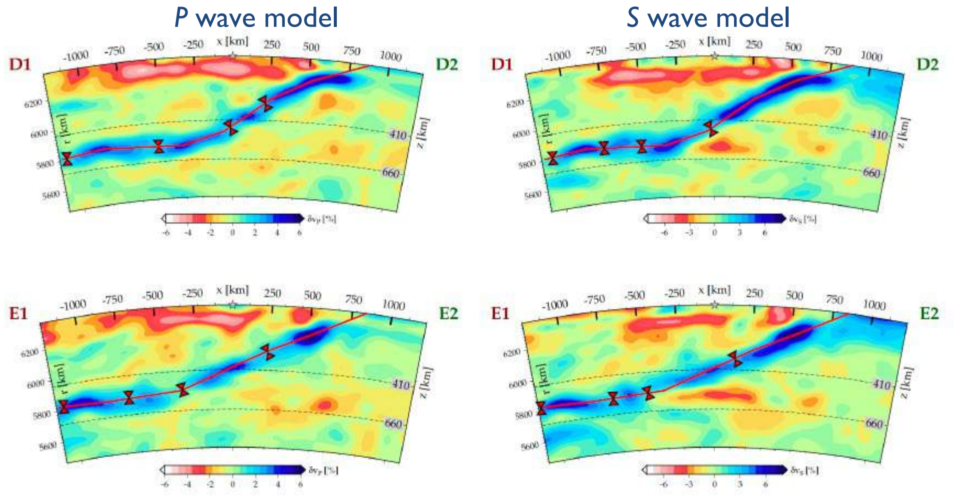
Boston et al. (2017)



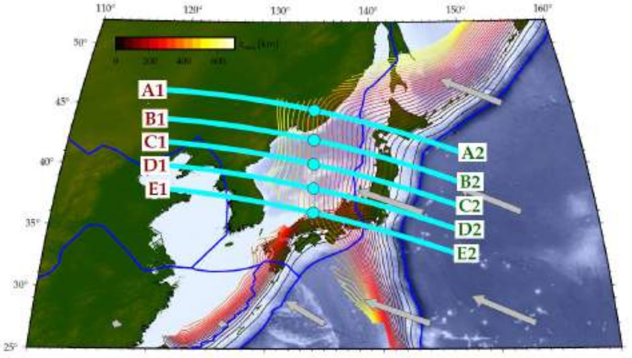
Gerya et al. (in press)

Slab complexity under Japan



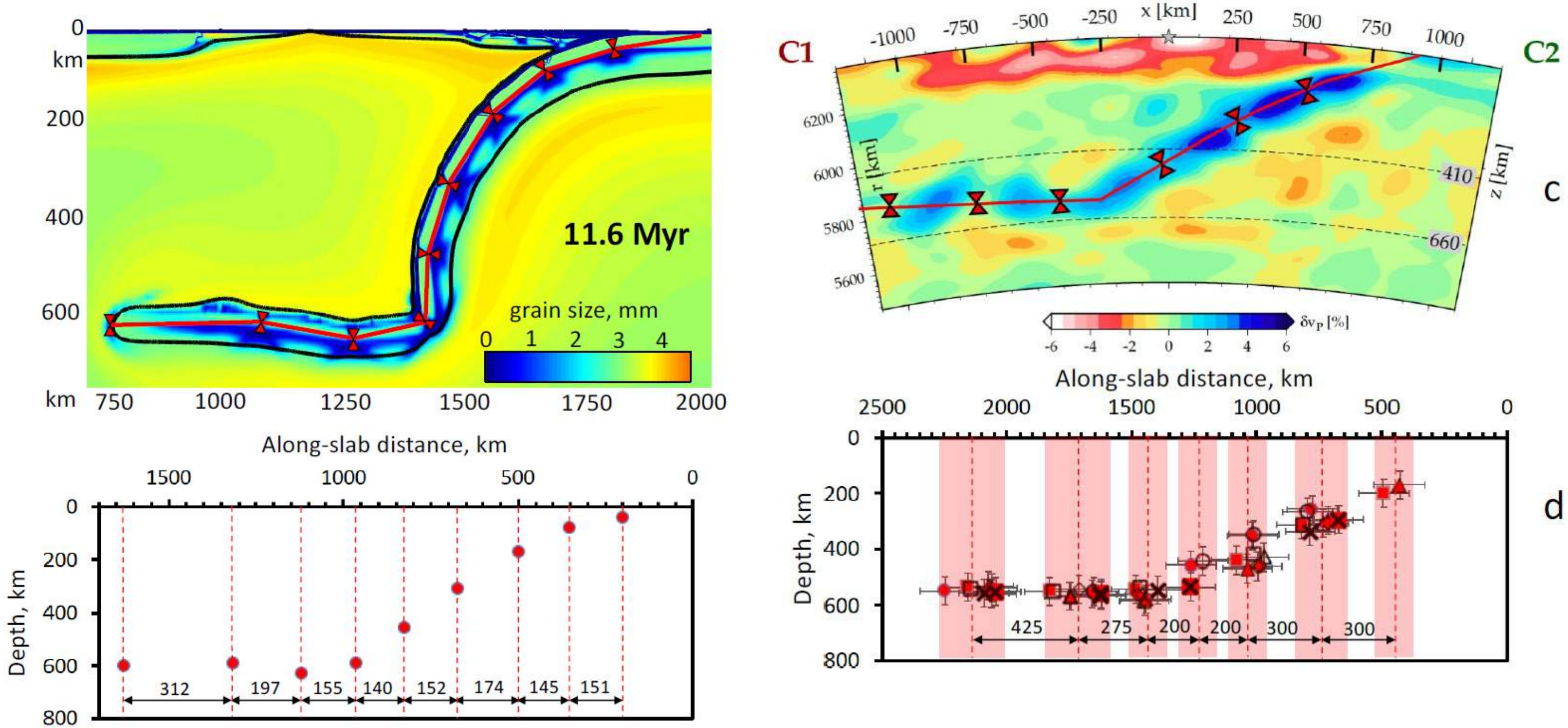


Tao et al. (2018)



cf. Richard and Iwamori (2010), Zhao (2012), Honda (2014)

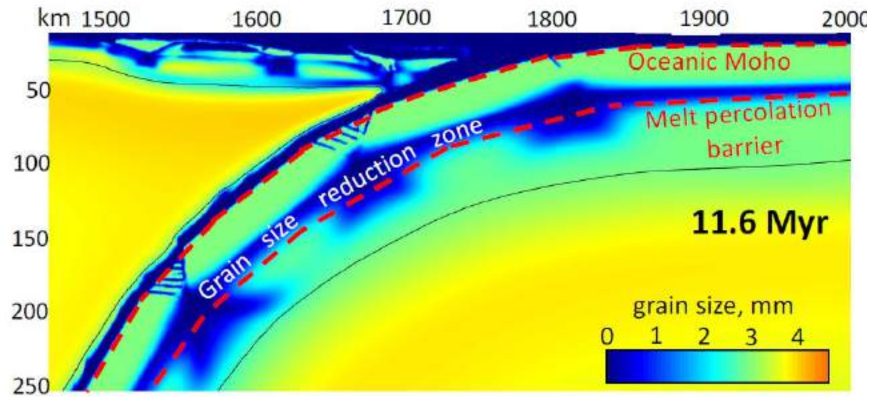
Comparable segmentation signatures?

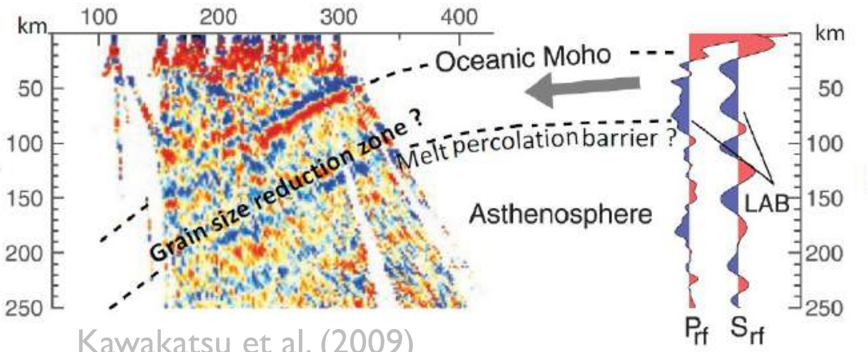


Gerya et al. (in press)

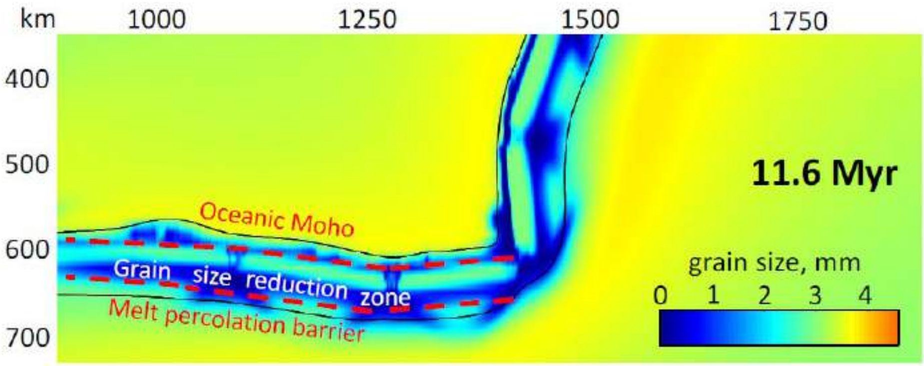
Seismic interface signature

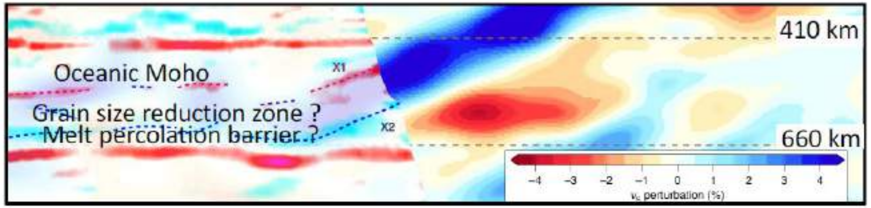
- Melt as marker: control on seismic wave speed but not viscosity





Kawakatsu et al. (2009)





Wang et al. (2020)
Tao et al. (2018)

Gerya et al. (in press)

Slabs are segmented due to coupled brittle-ductile damage

Slab segmentation explains:

1. dichotomy of strong plates and weak slabs
2. large-offset normal faults near trenches
3. segmented slab seismic velocity anomaly
4. low-viscosity region below the outer rise

Gerya et al. (in press)

Conclusions

- Global geodynamics/seismology models allow hypothesis testing
- Regional observations holds important clues for refinement
- Melt effects secondary for viscosity
- Full waveform hypothesis testing promising