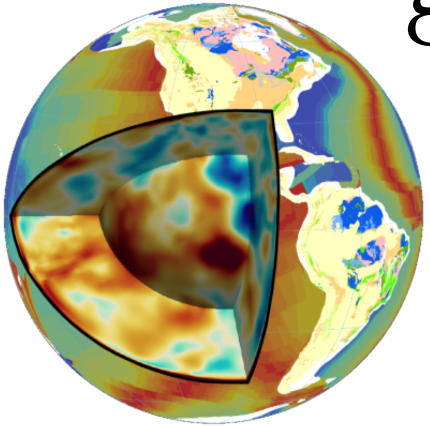
Geodynamics I:

Subduction zone dynamics and global mantle flow



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CIDER Summer School

Subduction Zone Dynamics

Berkeley CA

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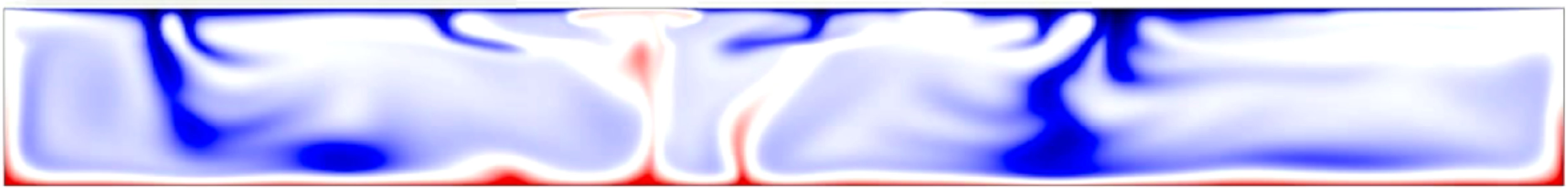
TEXAS Geosciences
The University of Texas at Austin
Jackson School of Geosciences

Contents

- Plate driving forces
- Some fluid dynamics
- Global models
- Regional models
- Conveyor belts

Plate tectonics is the top boundary layer of mantle convection

Subduction: cold plume dynamics



fluid heated from below – Rayleigh-Benard convection

computation by A. McNamara

- Rayleigh number, *Ra*, controls the vigor of convection
- Symmetry of upwellings and downwellings broken by
  - ➔ *temperature dependence of viscosity*
  - ➔ *depth-dependent viscosity*
  - ➔ internal vs. bottom heating
  - ➔ fractionation (e.g. continents and thermo-chemical piles)

Top thermal boundary described by half space cooling

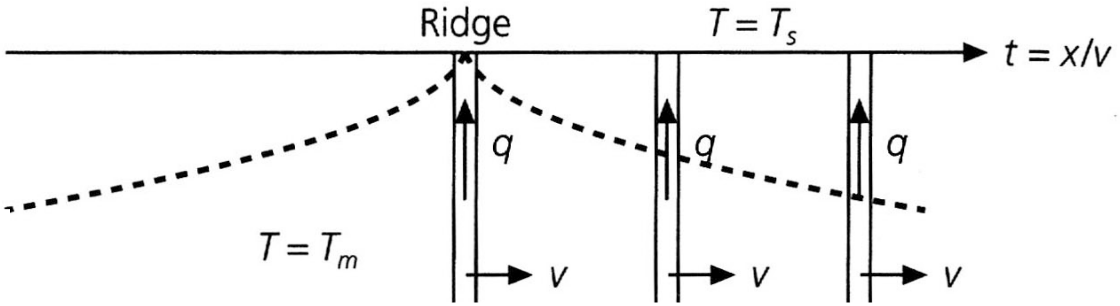
$$\mathbf{q} = -k\nabla T$$

Fick's law for heatflow

$$\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial z^2}$$

thermal diffusion in 1-D
(no heat sources)

$T = T_m$ at $x = 0$
$T = 0$ at $z = 0$
$T = T_m$ at $z \rightarrow \infty$

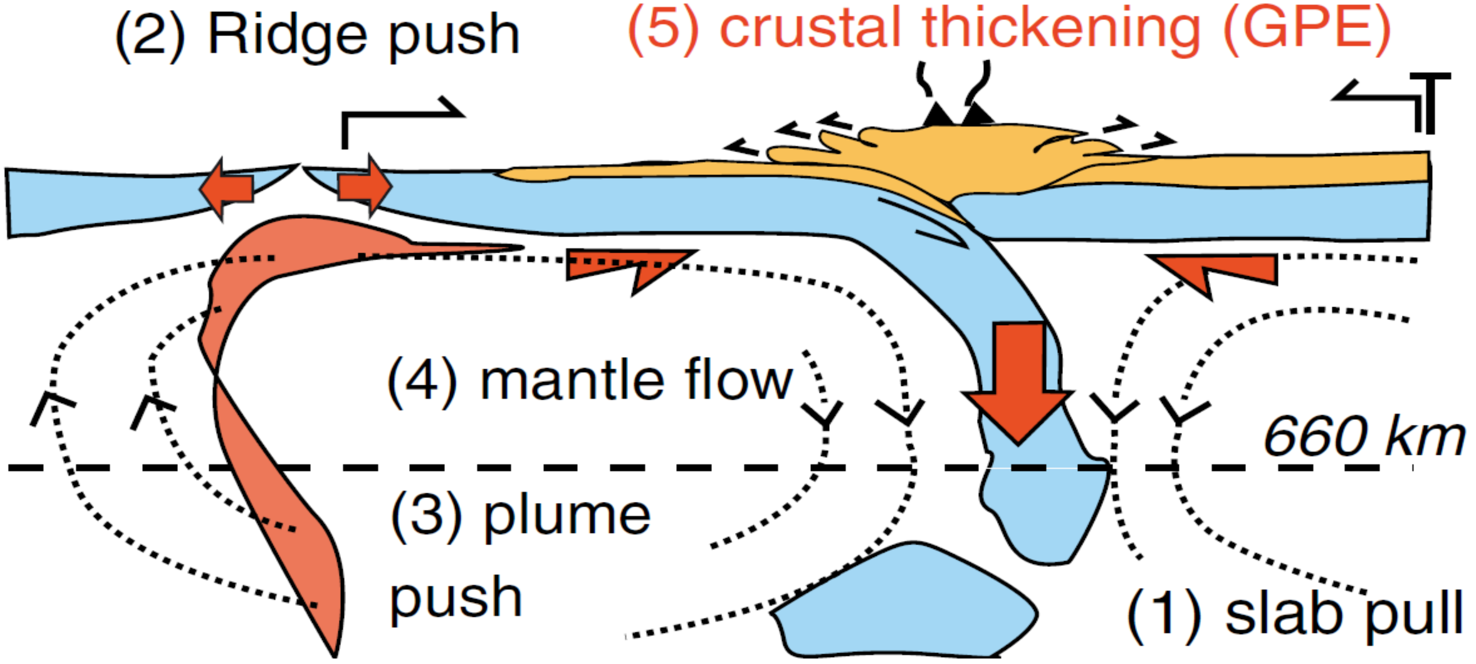


κ = thermal diffusivity
length ~ √(κ × time)

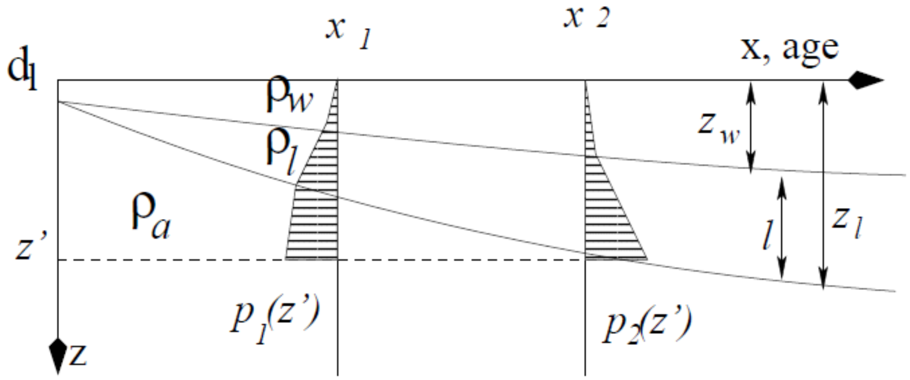
$$T(x,z) = T_m \, erf\left(\frac{z}{2\sqrt{\kappa t(x)}}\right)$$

Plate driving forces:
Integrals over components of thermo-chemical convection

GPE = gravitational potential energy



Lithospheric thickening
(AKA *ridge push*, oceanic GPE)



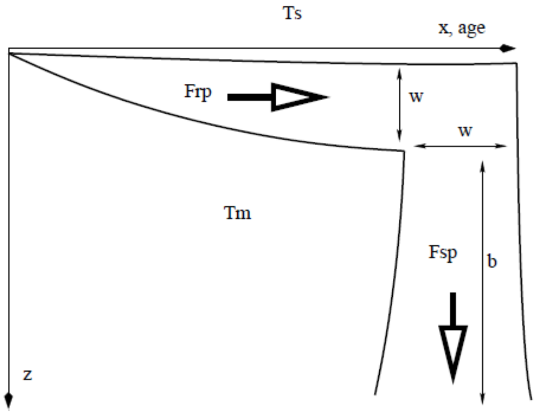
$$l = a(z_w - d_l) = a\Delta z_w$$

$$a = \frac{\rho_w - \rho_a}{\rho_a - \rho_l}$$ (from isostasy)

$$z_w(x) = c\sqrt{\frac{x}{u_0}}$$

$$F = \frac{ac^2}{2u_0} g\Delta\rho\Delta x$$

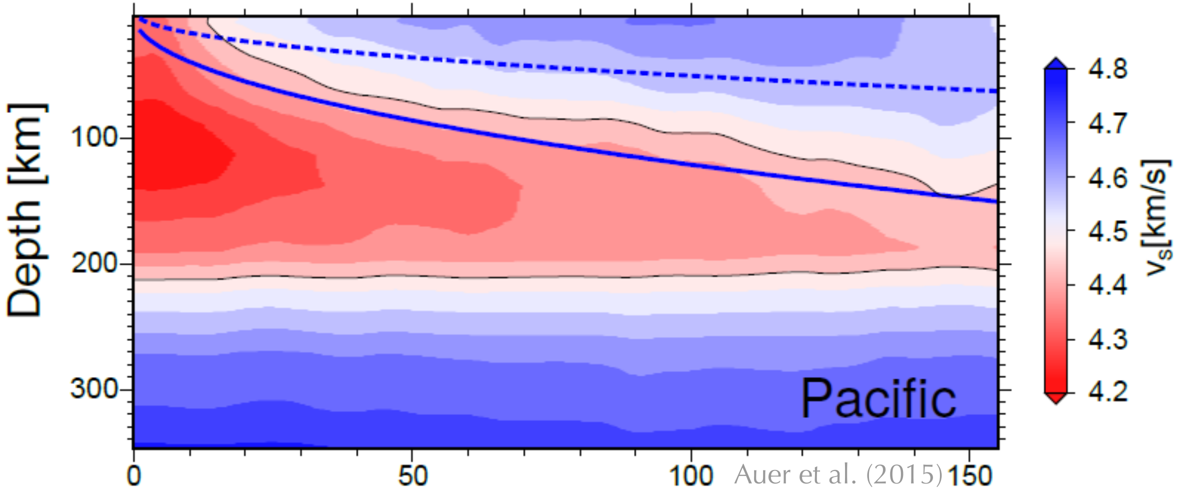
Subducting thermal boundary layer: *Slab pull*



$$F_b = -2\rho_0 g \alpha b (T_m - T_s)\sqrt{\frac{\kappa t_s}{\pi}}$$

Force estimates from half-space cooling

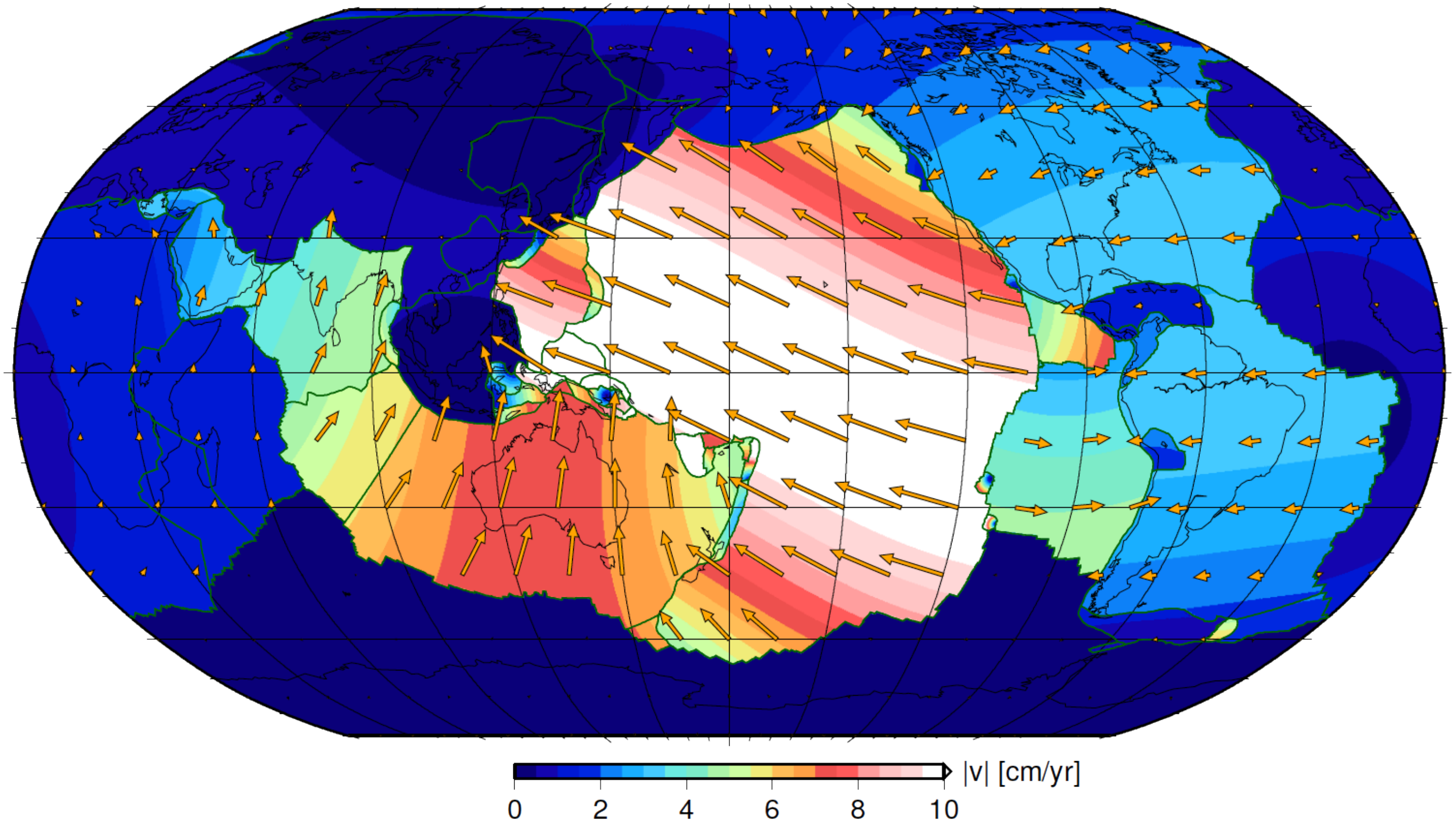
- ridge push (lithospheric thickening) ~ 10^{12} N/m
- slab pull ~ 10^{13} N/m
- worried about tectonics? worry about subduction



Auer et al. (2015)

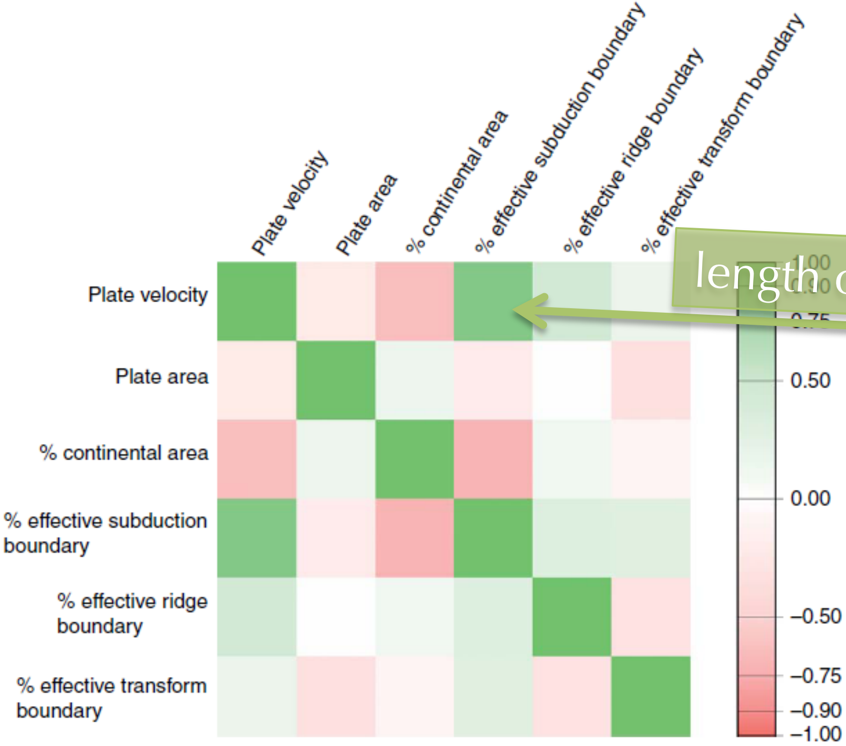
seafloor age [Ma]

How to explain present-day plate tectonics and test our models?



Bird (2002) plate boundaries and MORVEL56 velocities by Argus et al. (2011) in spreading-aligned reference frame (Becker et al., 2015)

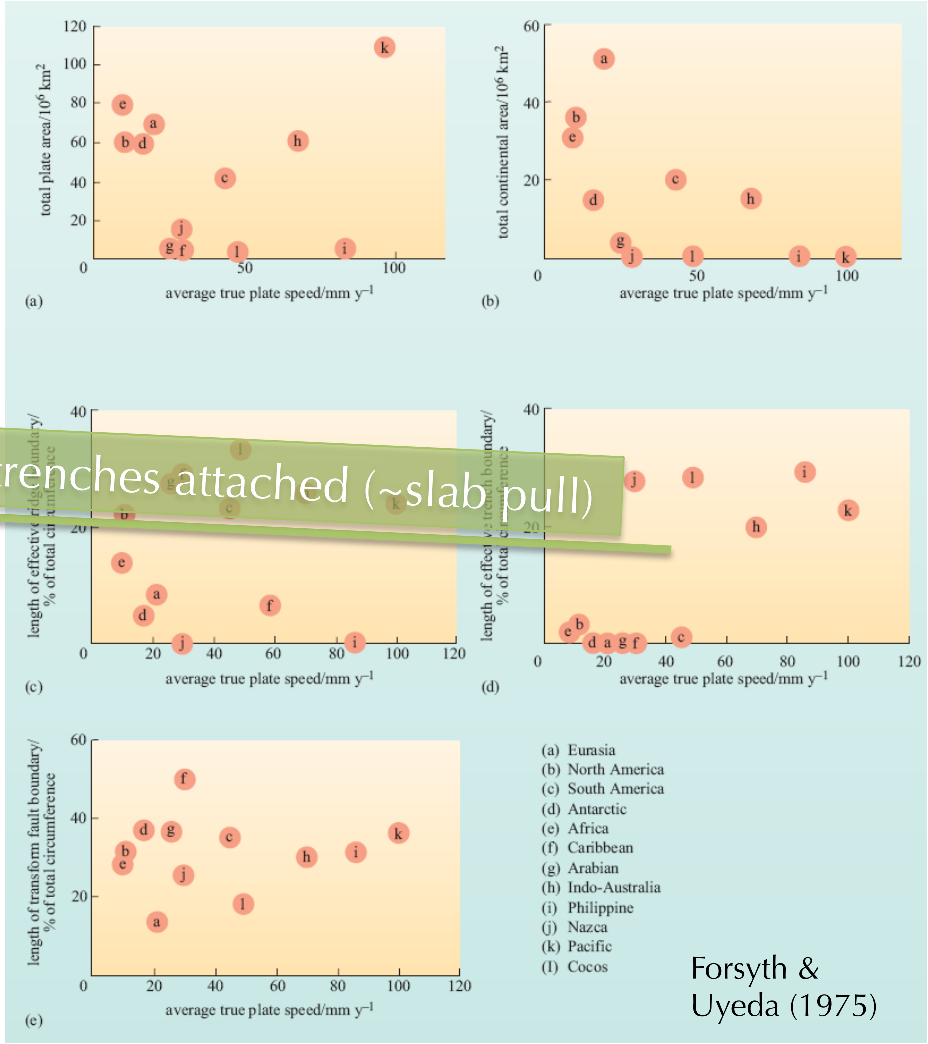
Different natural experiments in space: Plate speed correlation with various geometric/kinematic parameters



King (2008)

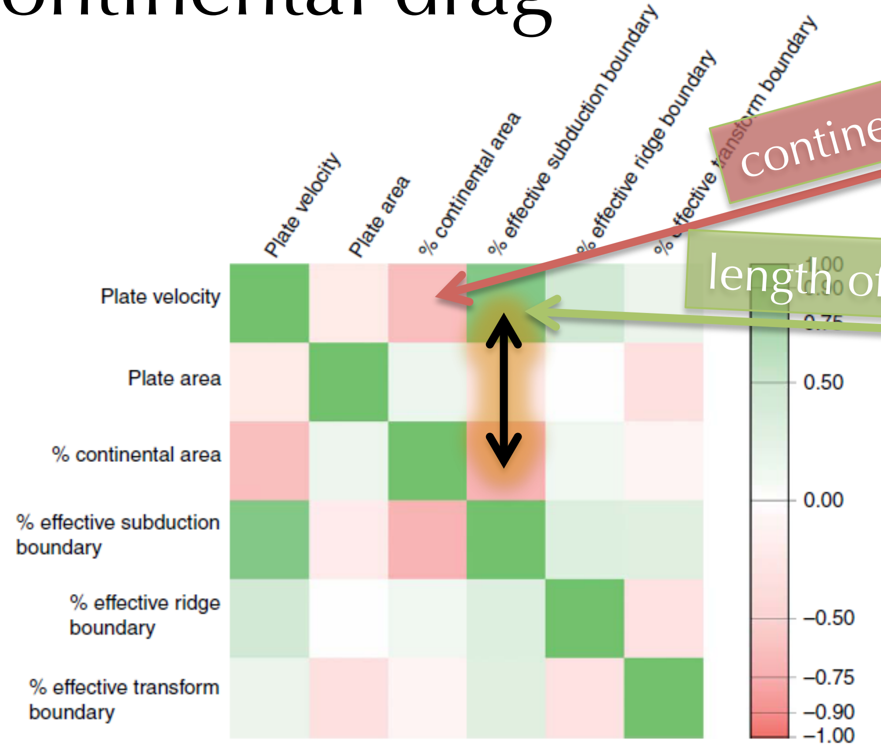
correlation

length of trenches attached (~slab pull)



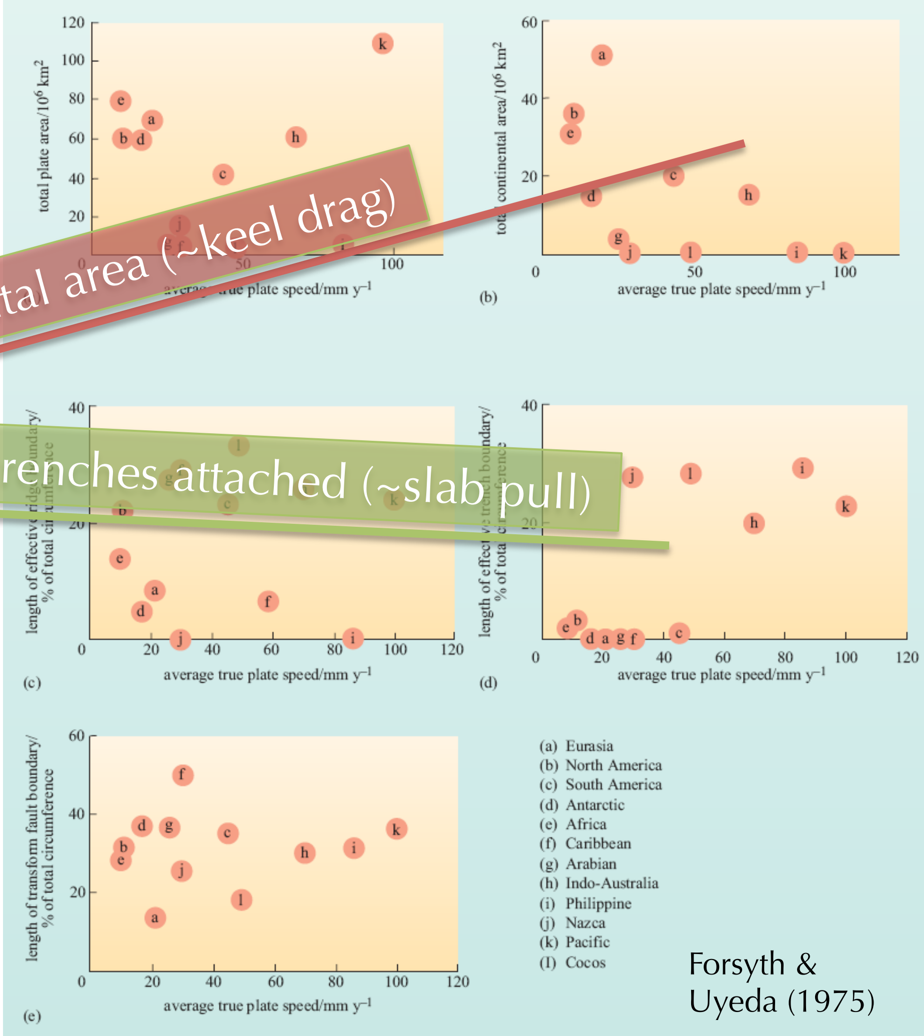
Forsyth & Uyeda (1975)

Slab pull vs. continental drag



King (2008)

correlation



Forsyth & Uyeda (1975)

Some fluid dynamics to build our own models

Static force balance (conservation of momentum) in any continuum

stress tensor

$$\frac{\partial \sigma_{ij}}{\partial x_j} = -f_i = -\Delta\rho g_i$$

body forces e.g. buoyancy

Constitutive law for an incompressible, Newtonian fluid

$$\frac{\partial v_i}{\partial x_i} = 0$$

conservation of mass

$$\sigma_{ij} = -p\delta_{ij} + 2\eta\dot{\varepsilon}_{ij} = -p\delta_{ij} + \eta\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right)$$

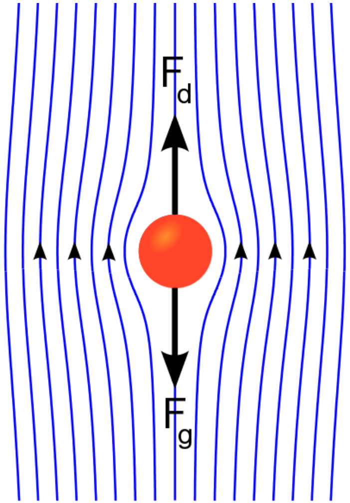
dynamic pressure; Newtonian viscosity; 2 x strain-rate

Stokes equation for constant viscosity (neglect inertia, OK at 10^{-25} level ($1/Pr$))

$$2\eta\frac{\partial \dot{\varepsilon}_{ij}}{\partial x_j} - \frac{\partial p}{\partial x_i} + \Delta\rho g_i = 0$$

viscous drag; dynamic pressure gradient; buoyancy force

Stokes sphere / Stokes sinker

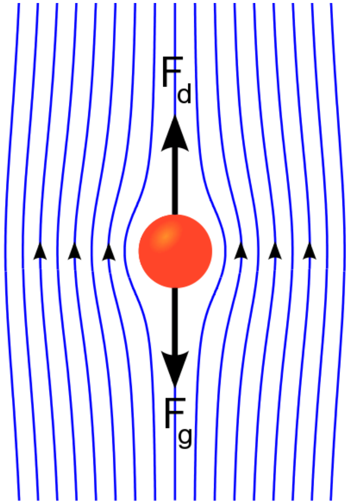


F_d = area × stress = area × strain-rate × viscosity (η)
= area × velocity (v)/radius (a) x viscosity

F_g = density contrast ($\Delta\rho$) × gravitational acceleration (g) x volume

$$V_{\mathrm{Stokes}} = C\frac{\Delta\rho g a^2}{\eta_m}$$

A Stokes solution: Stokes sphere



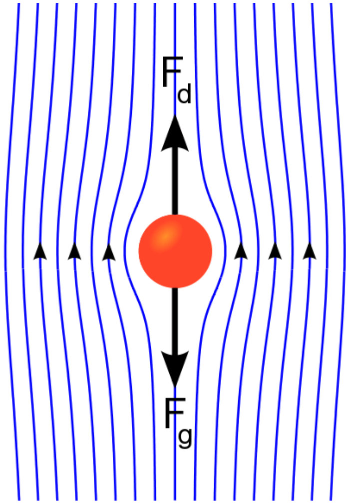
$$V_{\mathrm{Stokes}} = C\frac{\Delta\rho g a^2}{\eta_m}$$

$$C = \frac{2+2\eta'}{6+9\eta'} \qquad \eta' = \frac{\eta_s}{\eta_m}$$

Aside I:

- A needle, as opposed to sphere, will sink with 0.5…2 v_{Stokes}

Stokes sets the advective scale



$$V_{\text{Stokes}} = C\frac{\Delta\rho g a^2}{\eta_m}$$

Aside II:

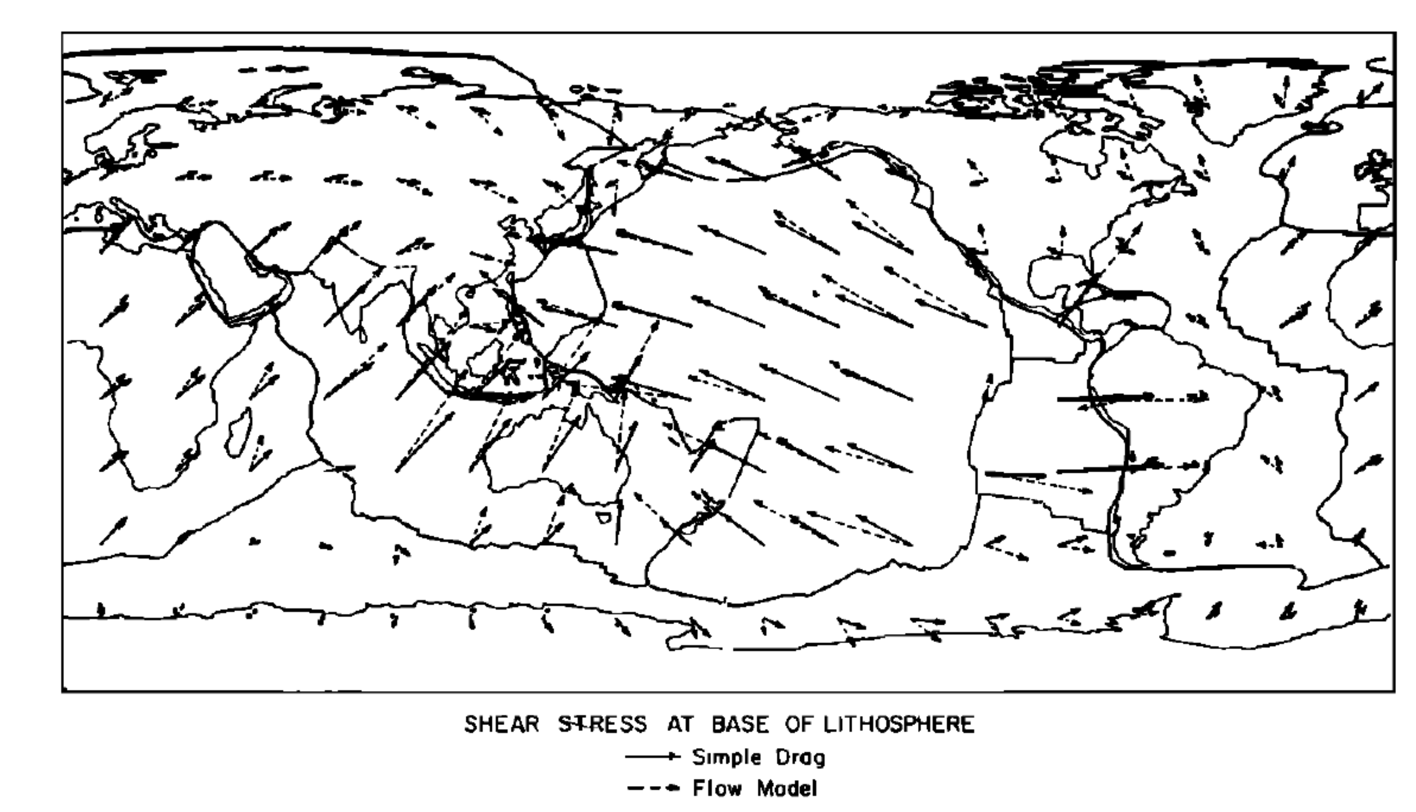
- Peclet# = ratio of diffusive to convective time scale, $Pe = t_{\text{diffusion}} / t_{\text{convection}}$
- $t_{\text{diff}} = a^2 / \kappa$, $t_{\text{conv}} = a / v_{\text{Stokes}}$, $\Delta\rho = \Delta T \alpha \rho_0$, then $Pe \rightarrow Ra$ (with a instead of L)

Density driven flow

$$v \propto \frac{\Delta\rho}{\eta}$$

$$\sigma \propto \eta\dot{\varepsilon} \propto \eta\frac{v}{a} \propto \frac{\Delta\rho}{a}$$

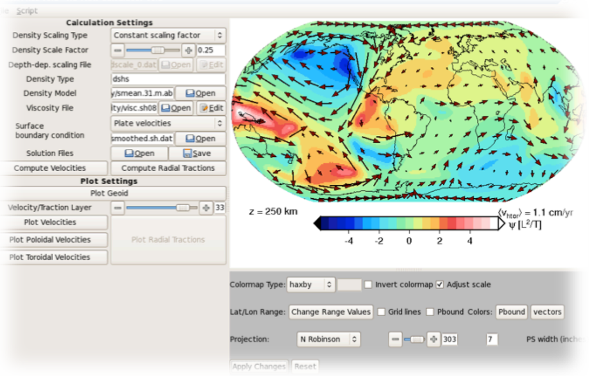
Plate motions and global mantle flow



Hager & O'Connell (1979)

Mantle circulation

- treat mantle and lithosphere as a fluid
- infinite Prandtl number (no inertia) approximation
  - Navier-Stokes turns into Stokes equation
- instantaneous solution for given density and boundary conditions
  - can solve in < 1 s for spherical Earth without lateral viscosity variations



HC of SEATREE GUI is part of UGESCE or CIDER VirtualBox distribution

force balance
(conservation of momentum)

normalized temperature

$$\frac{\partial \sigma_{ij}}{\partial x_j} = -Ra\tilde{T}\delta_{ir}$$

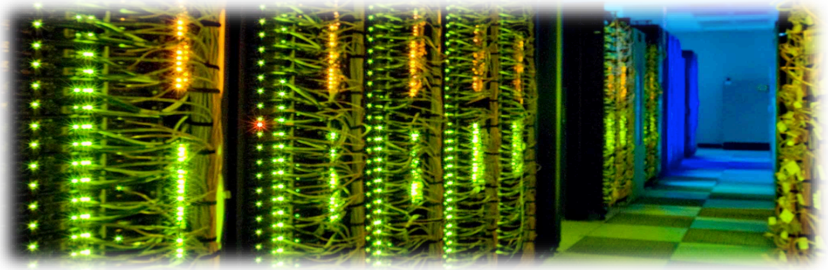
thermal buoyancy

constitutive equation
(rheology)
and conservation of mass

$$\sigma_{ij} = -p\delta_{ij} + 2\eta\dot{\varepsilon}_{ij}$$

$$\frac{\partial v_i}{\partial x_i} = 0$$

Mantle circulation



- Thermo-chemical heterogeneity and complex rheologies make things interesting
- Finite element methods best suited for lateral viscosity variations (can solve all of this, in ~hours, at < km resolution without approximations), with ~512 CPUs

force balance
(conservation of momentum)

$$\frac{\partial \sigma_{ij}}{\partial x_j} = -Ra\tilde{T}\delta_{ir} + Ra_C\tilde{C}\delta_{ir}$$

chemical buoyancy

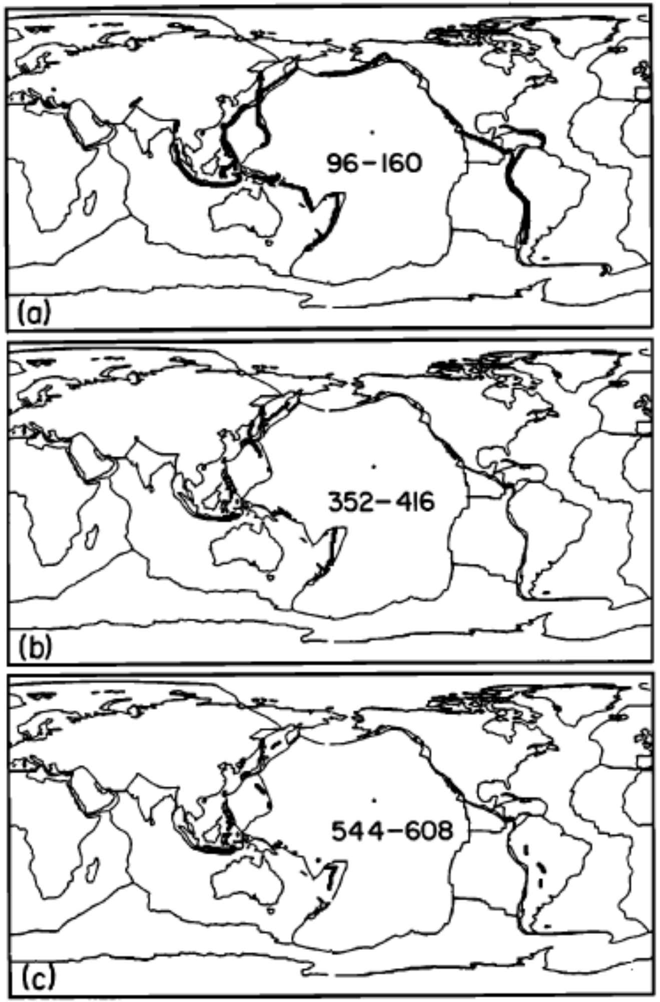
constitutive law
(rheology)

$$\sigma_{ij} = -p\delta_{ij} + 2\eta(\sigma, T, d, H_2O, \varepsilon)\dot{\varepsilon}_{ij}$$

non-linear rheology

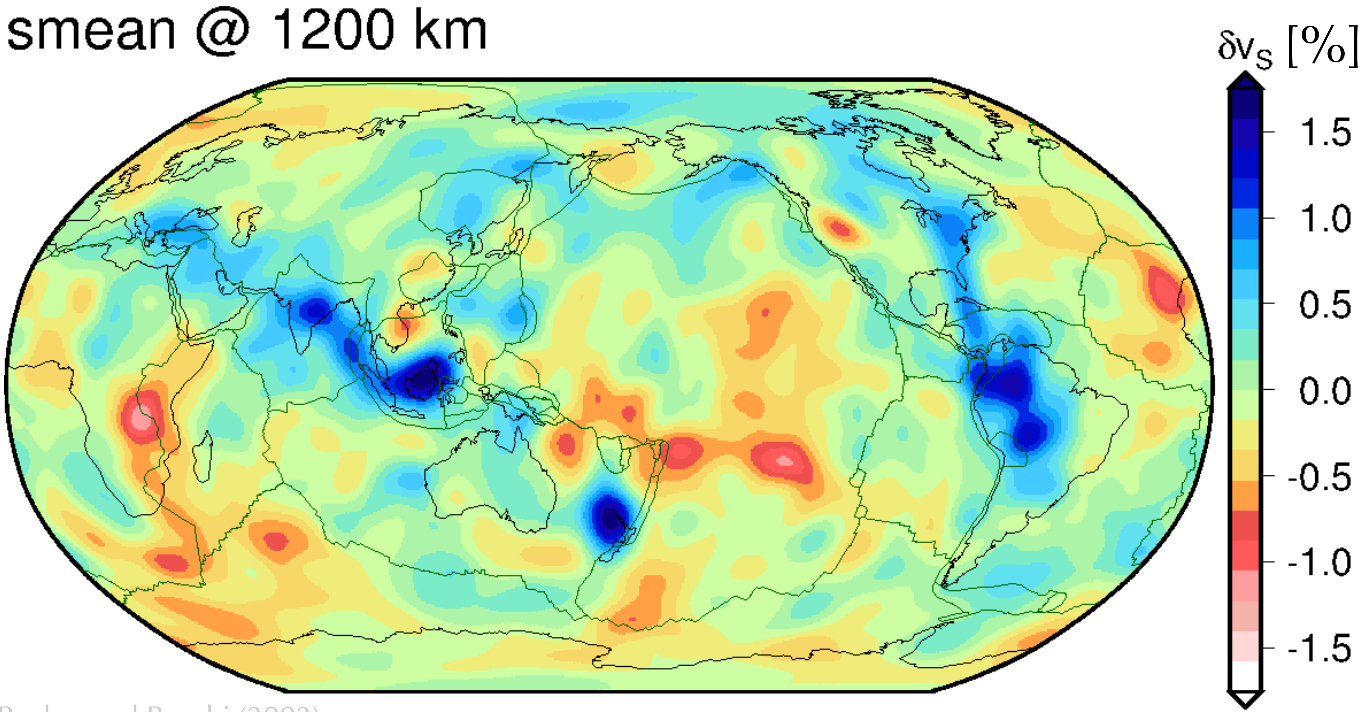
How do we know the density variations in the mantle?

- ➢ upper mantle slabs from Wadati-Benioff zones



Hager (1984)

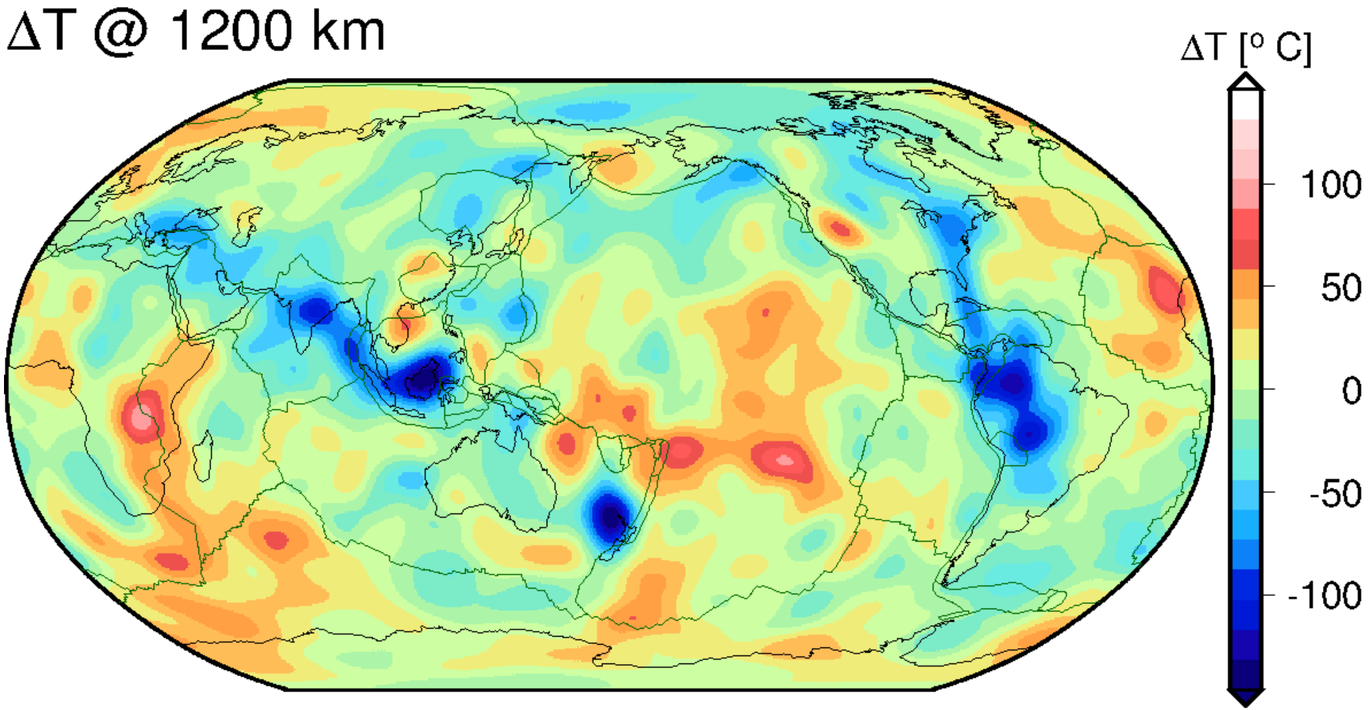
Seismic tomography also shows slabs



Becker and Boschi (2002)

- *S* wave models provide poor image of slabs in upper mantle
- *P* wave models poor outside subduction zones in upper mantle

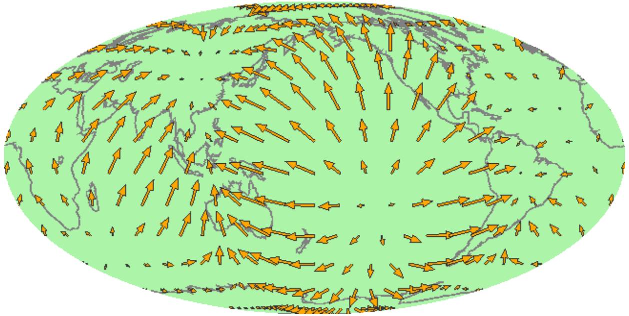
Besides cratons and piles: dln ρ/d ln v_S = 0.2



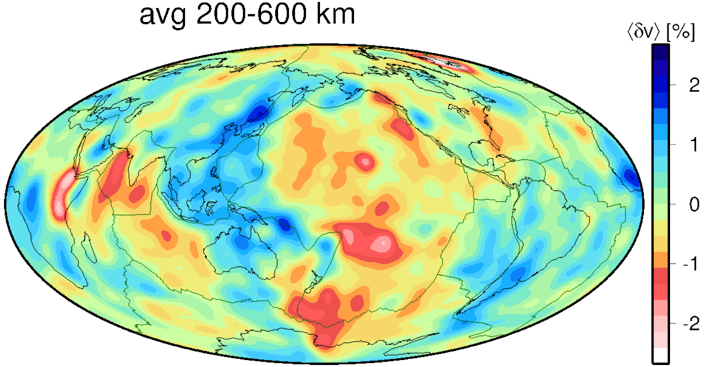
- Use mineral physics to convert velocity into temperature (density) anomalies

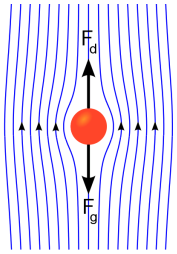
Tomography driven flow at surface

Flow model with free slip surface
(no lateral viscosity variations)



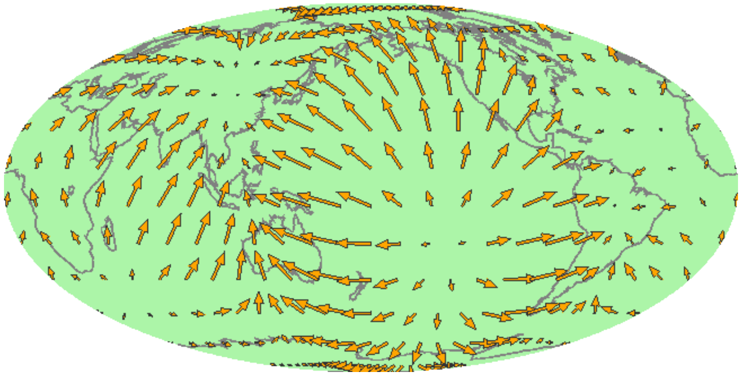
Upper mantle averaged tomography





Surface motions compared to plate motions

Flow model with free slip surface and no LVVS



Observed plate velocities in hot spot reference frame

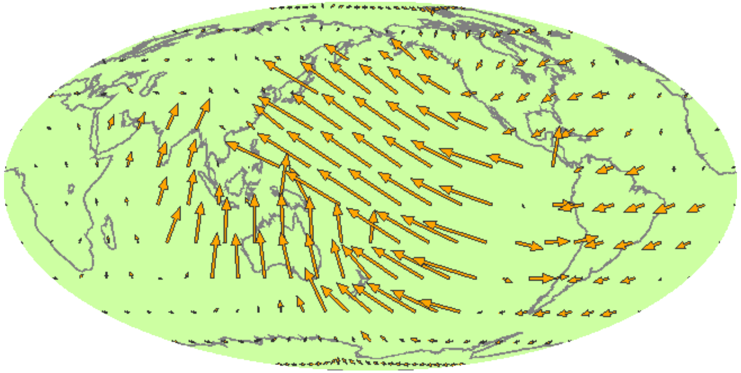
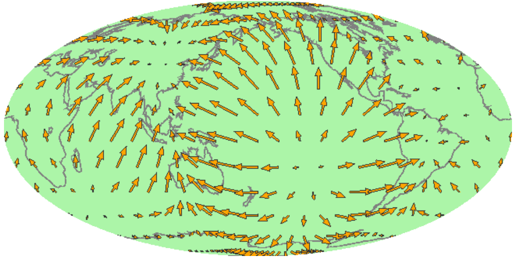
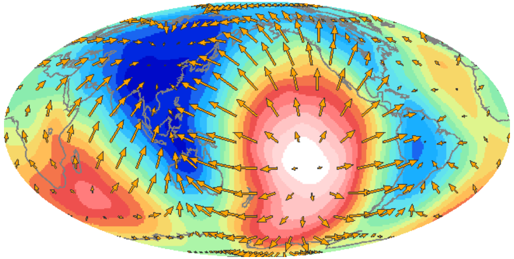


Plate motions require LVVs in lithosphere

Flow model with only radial viscosity variations

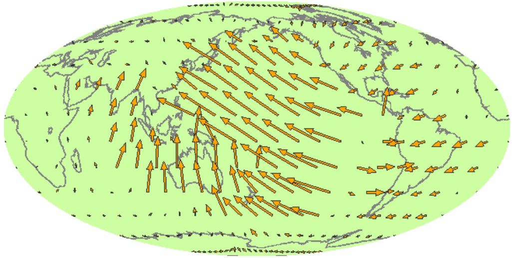
poloidal component



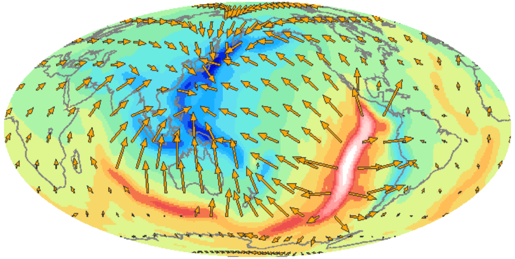


- No toroidal flow without lateral viscosity variations (no PT coupling)
- Strain-rates not very plate-like

Observed plate velocities in hot spot reference frame

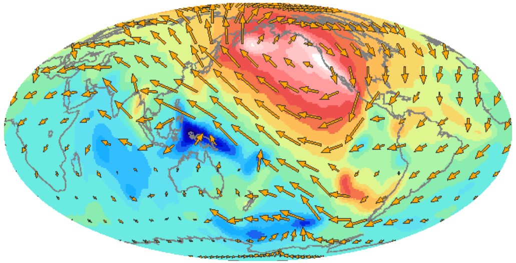


poloidal component



sources and sinks

toroidal component

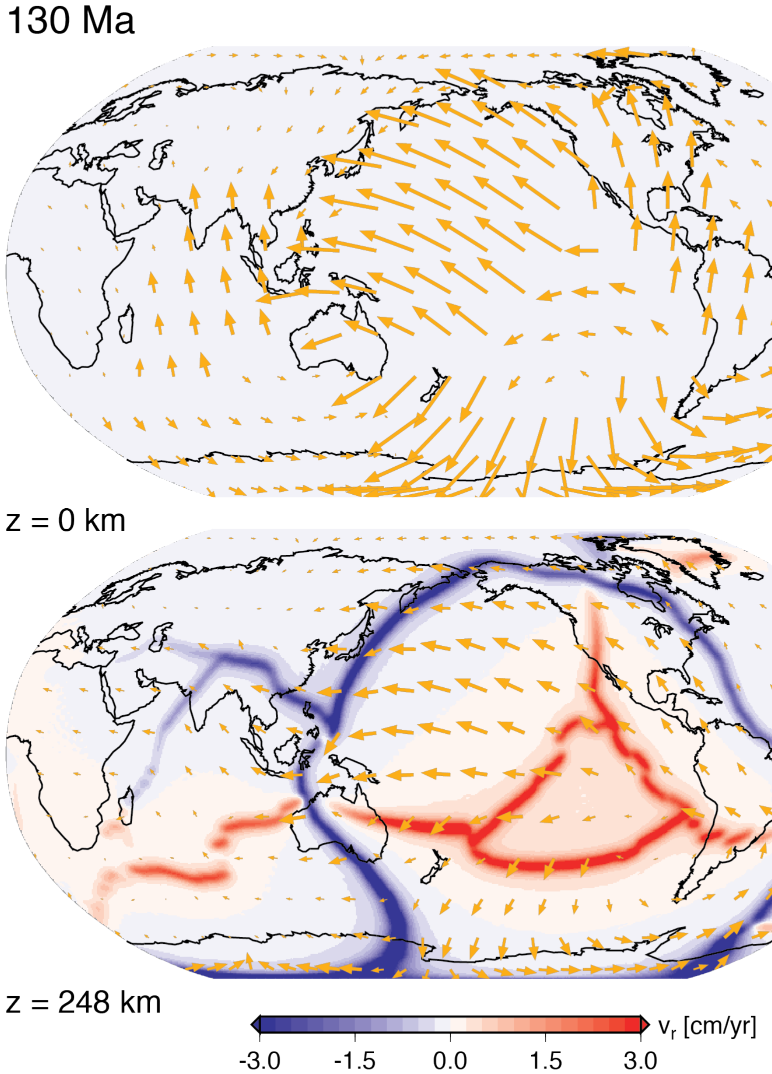


strike slip motion, spin

Ricard and Vigny (1989); O'Connell et al. (1991); Ricard et al. (1991); Ribe (1993); Forte & Peltier (1993); Thoraval & Richards (1997); Moucha et al. (2008); Ghosh et al. (2010)

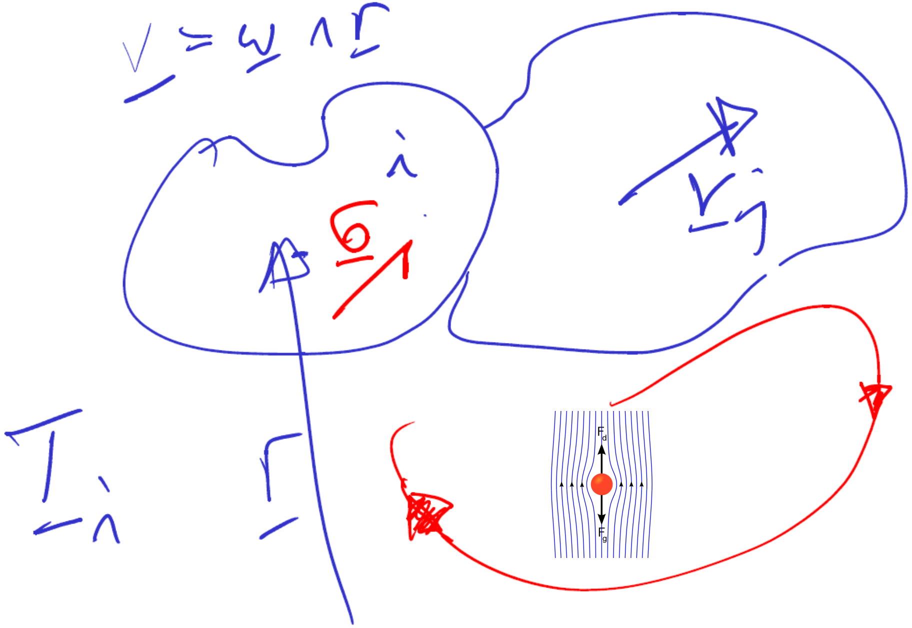
Plate-plate Interactions

- can compute interaction matrices for arbitrary plate geometries and viscosity distributions



cf. Hager and O'Connell (1981), Ricard and Vigny (1989), Forte (1993)

Solve for rigid plate motions given mantle tractions



$$\mathbf{T}_i = \int_{plate} dA\,\mathbf{r} \times \sigma_{flow}$$

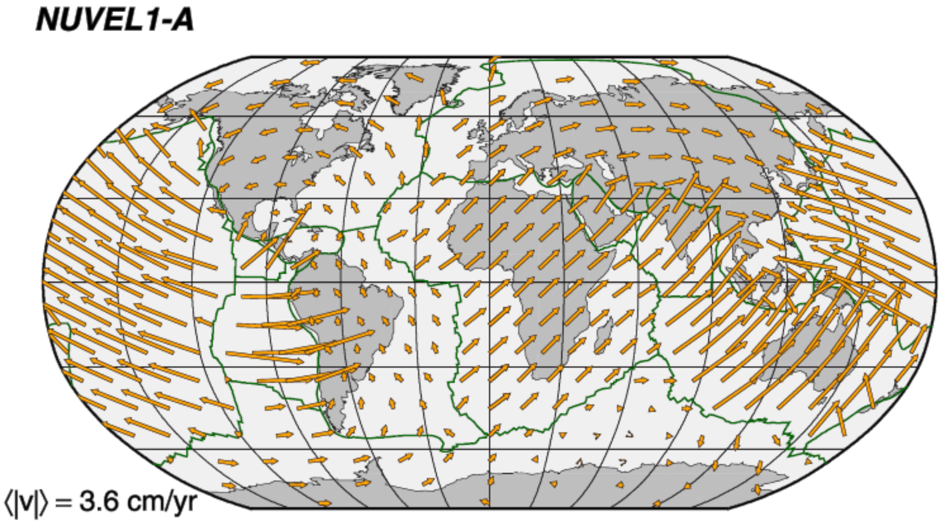
$$\mathbf{T}_{vd} = \mathbf{I}\omega = \sum^{M} T_i$$

Note: Can construct plate motion interaction matrix **I**, for any LVVs

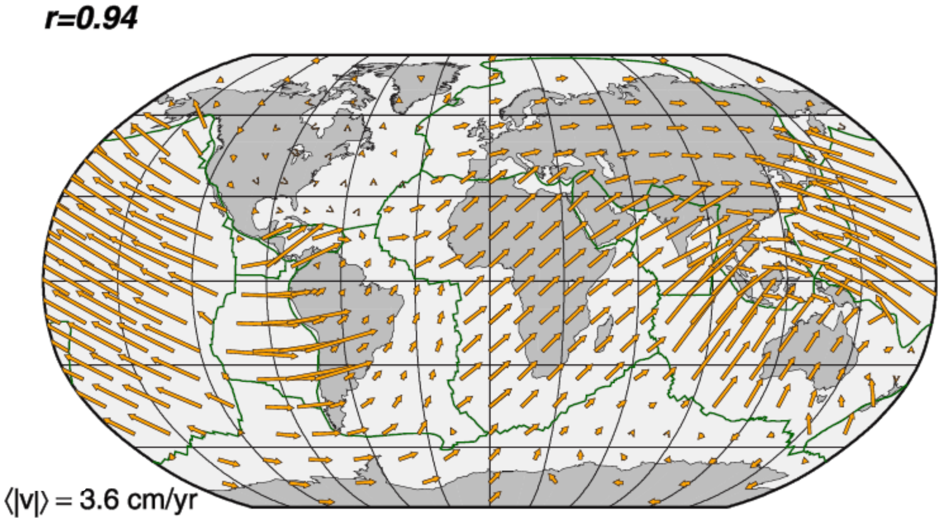
cf. Ricard and Vigny (1989); Forte (1993); Becker and O'Connell (2001)
Conrad and Lithgo-Bertelloni (2002): van Summeren et al. (2010)

Plate motion models ~work

plate motions



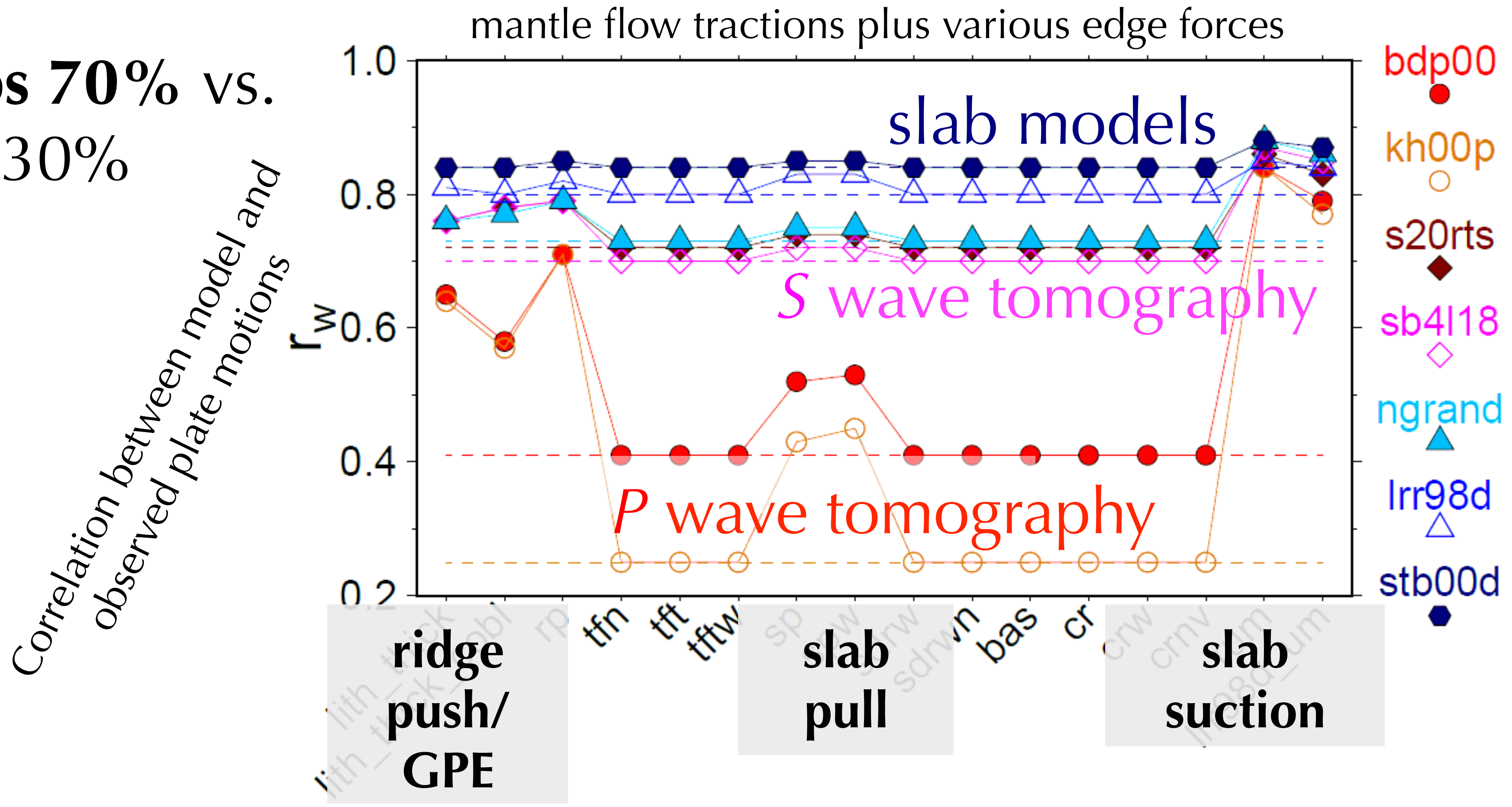
mantle flow model prediction



Faccenna et al. (2013)

e.g. Ricard and Vigny (1989); Lithgow-Bertelloni and Richards (1998); Becker and O'Connell (2001); Ghosh et al. (2010); Forte (2015)

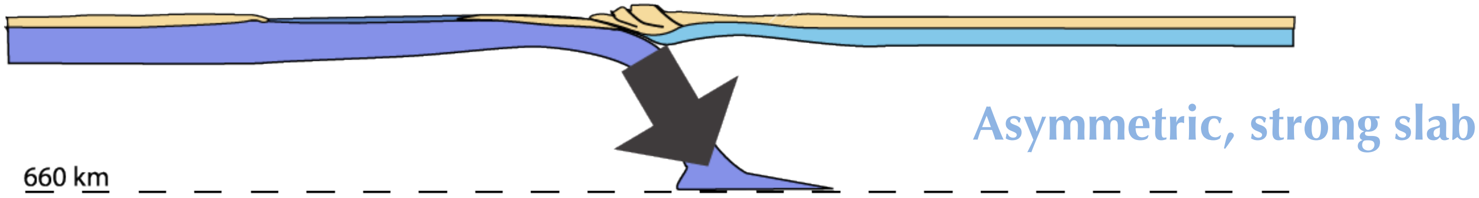
Slabs 70% vs.
rest 30%



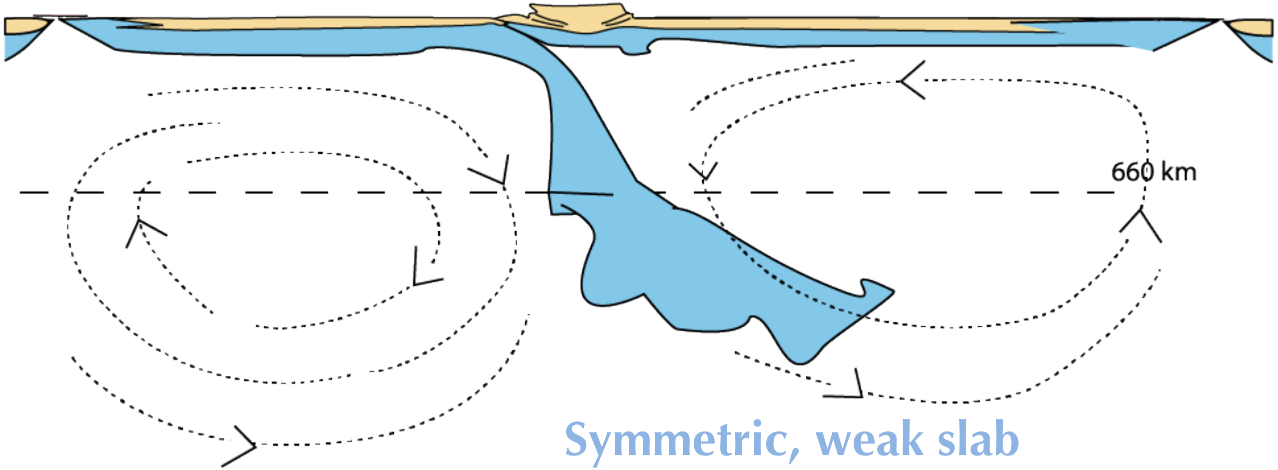
cf. Lithgow-Bertelloni and Richards (1998); Ghosh et al. (2010); Forte (2015)

Becker & O'Connell (2001)

Slab Pull

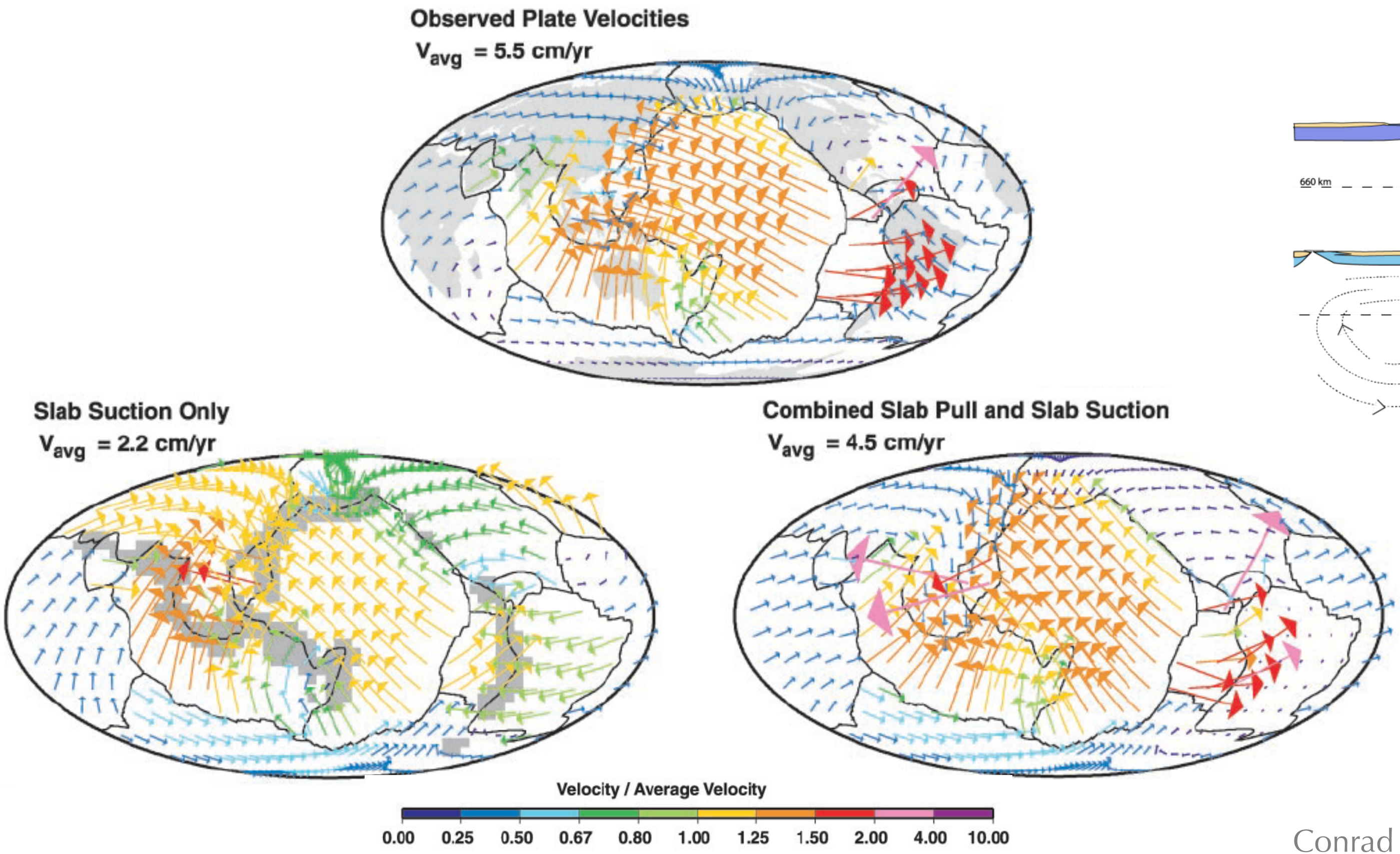


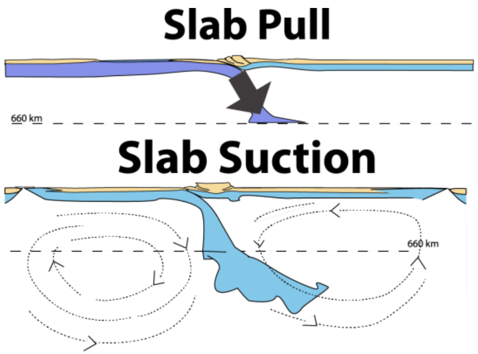
Slab Suction



cf. Conrad and Lithgow-Bertelloni (2002)

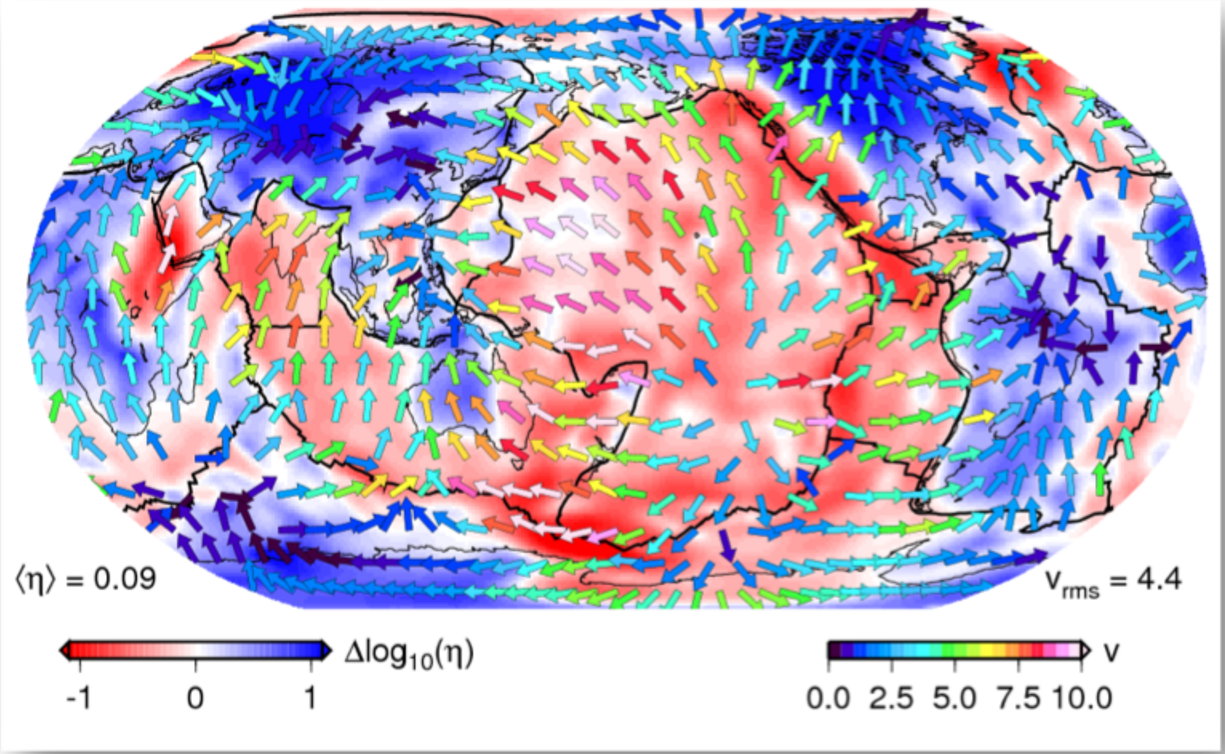
Plate speed vs. slab suction / slab pull





Conrad and Lithgow-Bertelloni (2002)

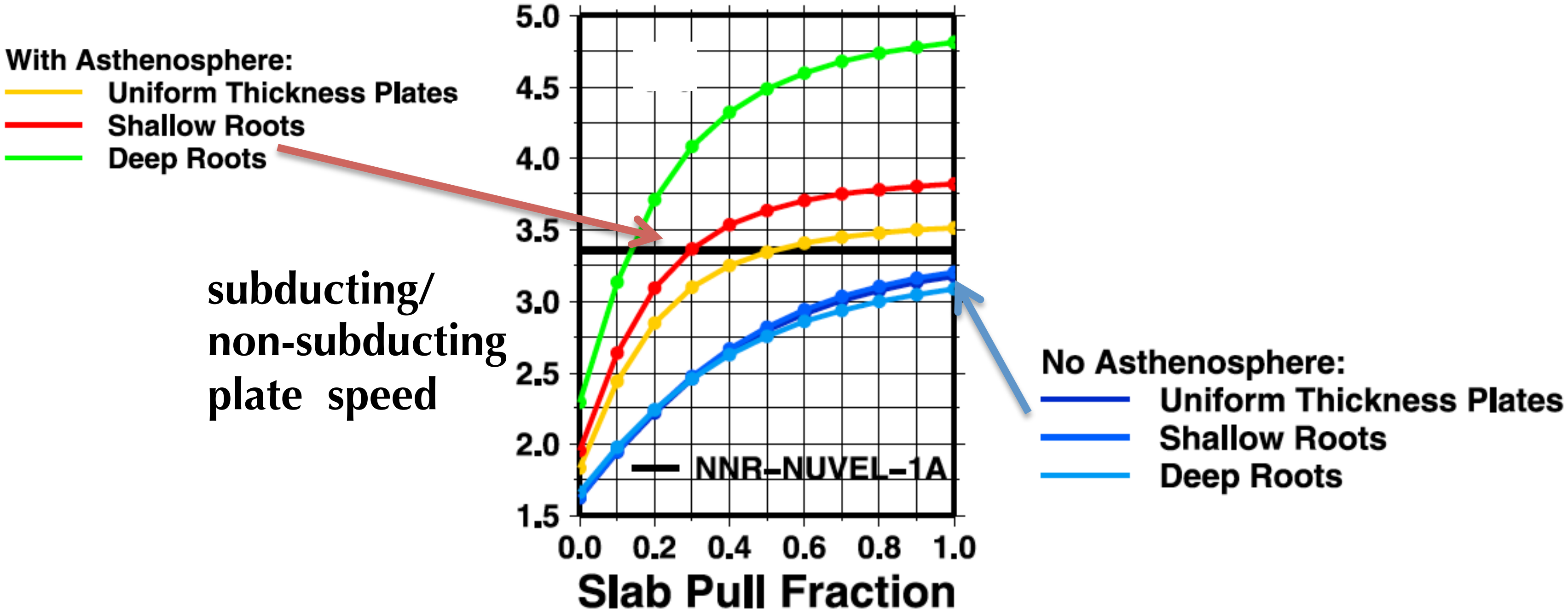
Plate speed vs. asthenospheric viscosity



cf. Ricard et al. (1993); Zhong (2000)

Becker (2006)

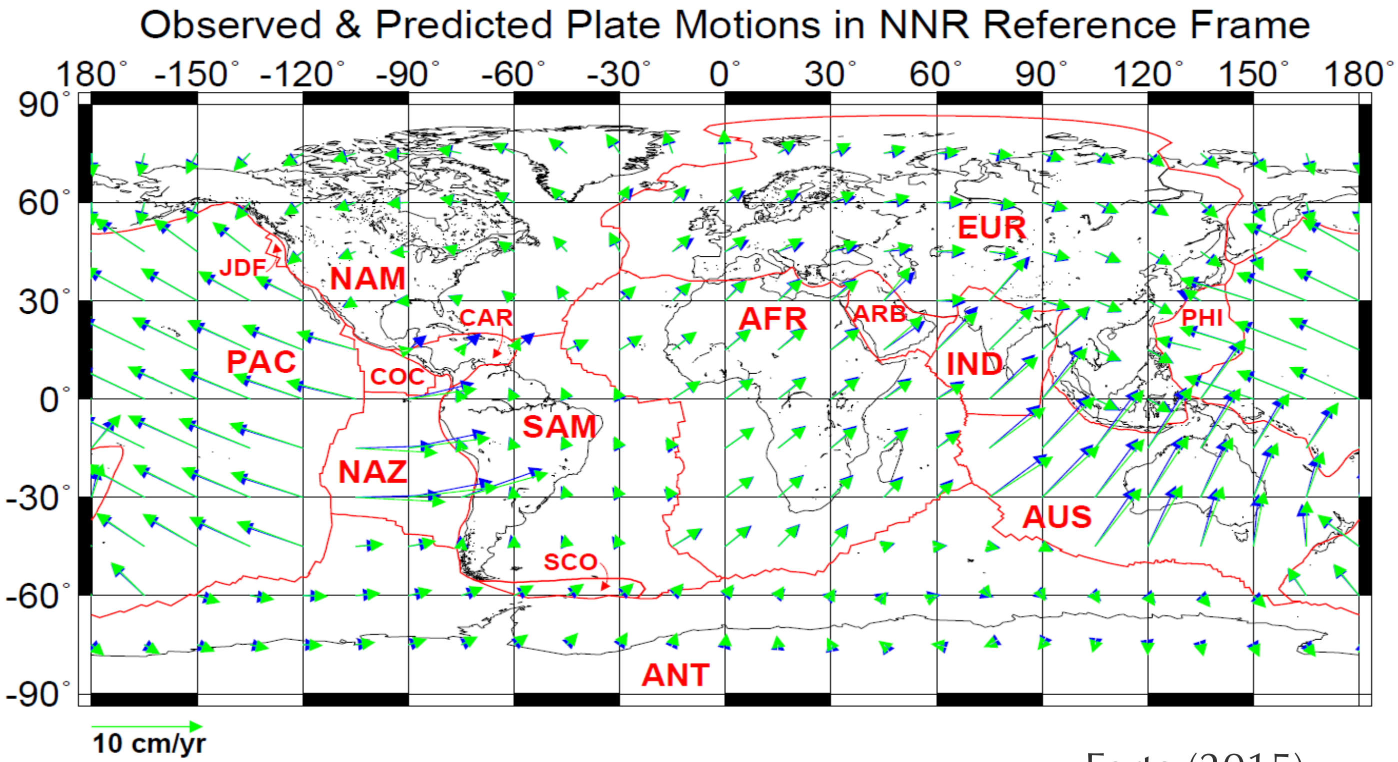
Asthenosphere vs. slab viscosity tradeoff



cf. Becker and O'Connell (2001); Conrad and Lithgow-Bertelloni (2002); Becker (2006)

van Summeren et al. (2012)

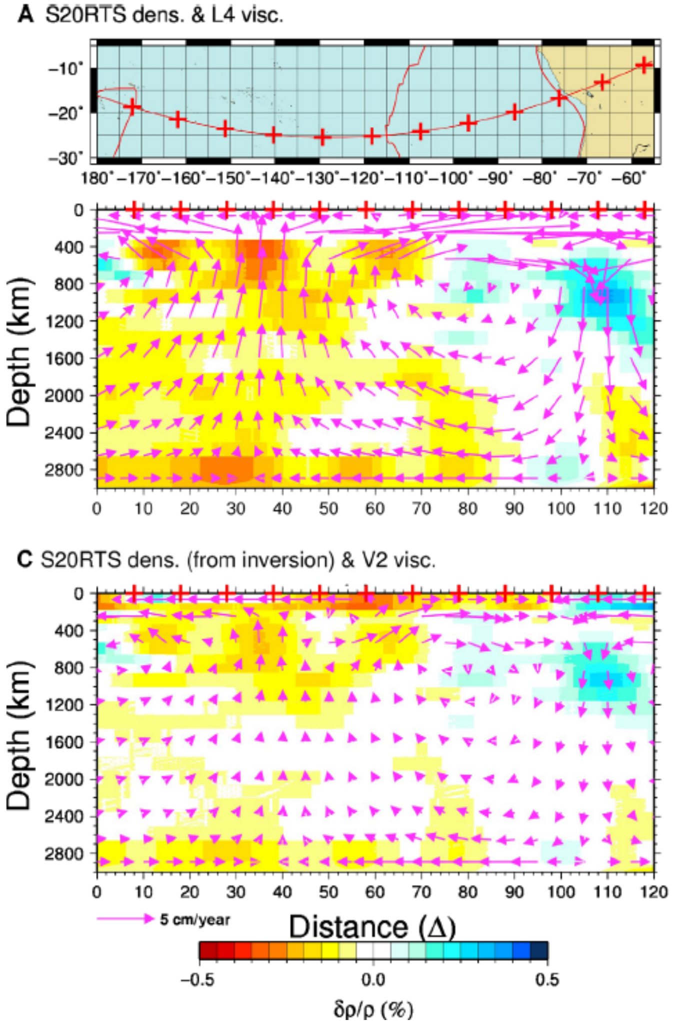
Some more uncertainties



Forte (2015)

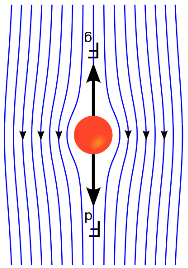
Importance of viscosity and density

(mineral physics, compositional anomalies)



simple tomography to density scaling, simple viscosity structure

joint tomography / dynamics inversion for density, complicated viscosity structure



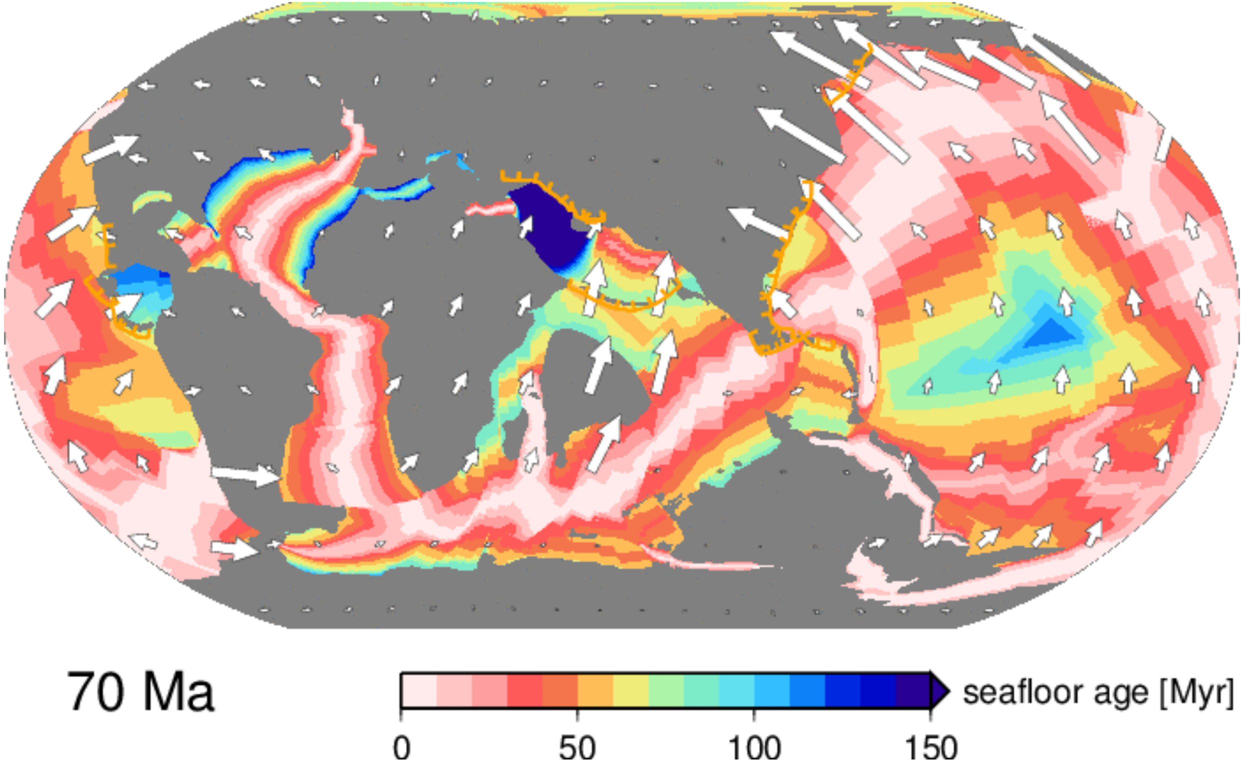
Rowley et al. (2016)

cf. Simmons et al. (2009)

Forte and Mitrovica (2004)

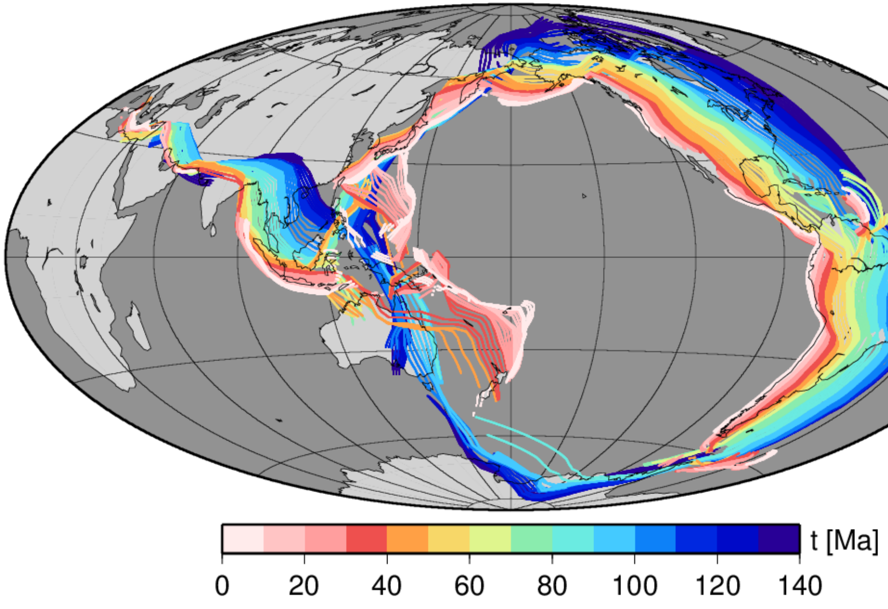
Forte (2015)

Global plate tectonics experiments in the past



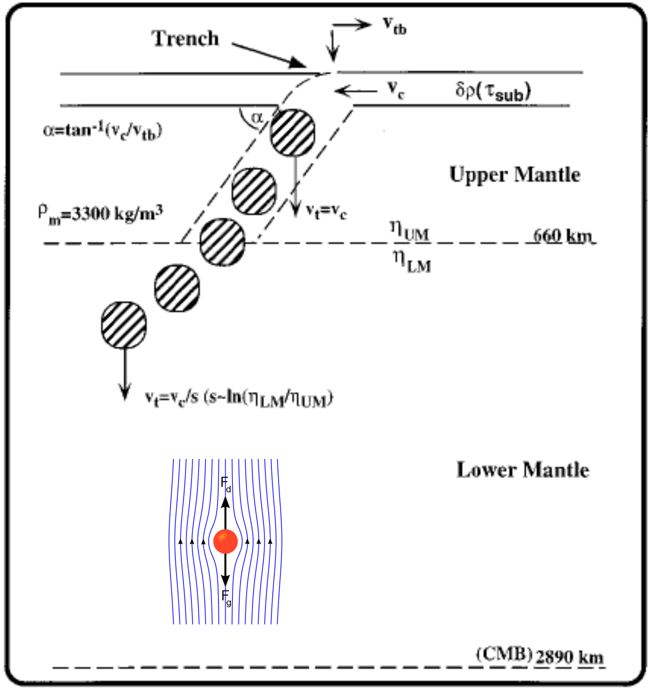
Mueller et al. (2016)

Stokeslets link subduction history and mantle viscosity to present-day structure

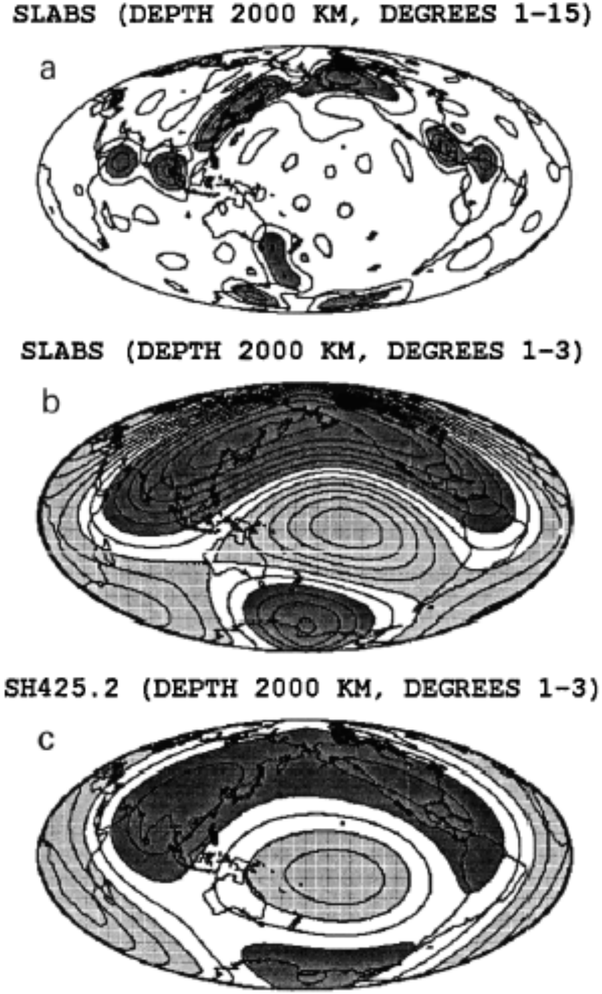


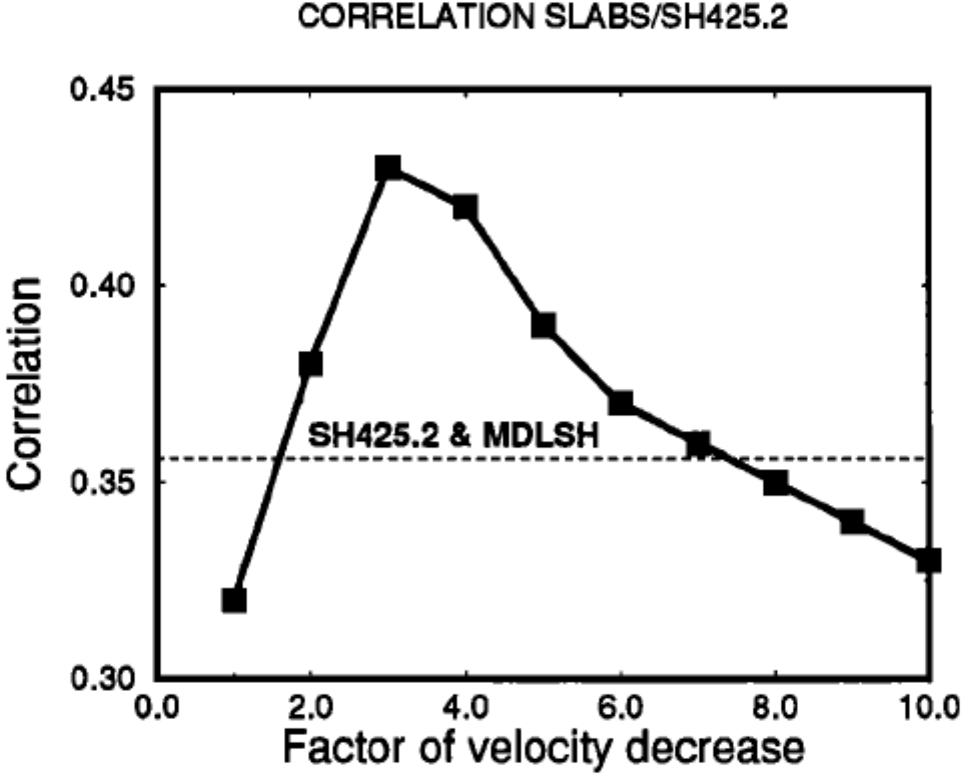
trench locations over time

Steinberger et al. (2010)



Ricard et al. (1993); Lithgow-Bertelloni et al. (1993, 1998)

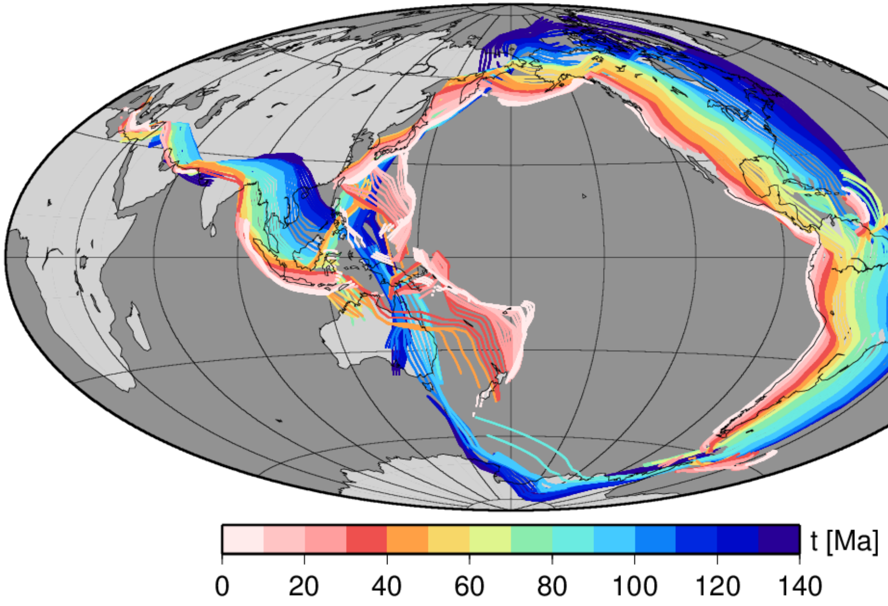


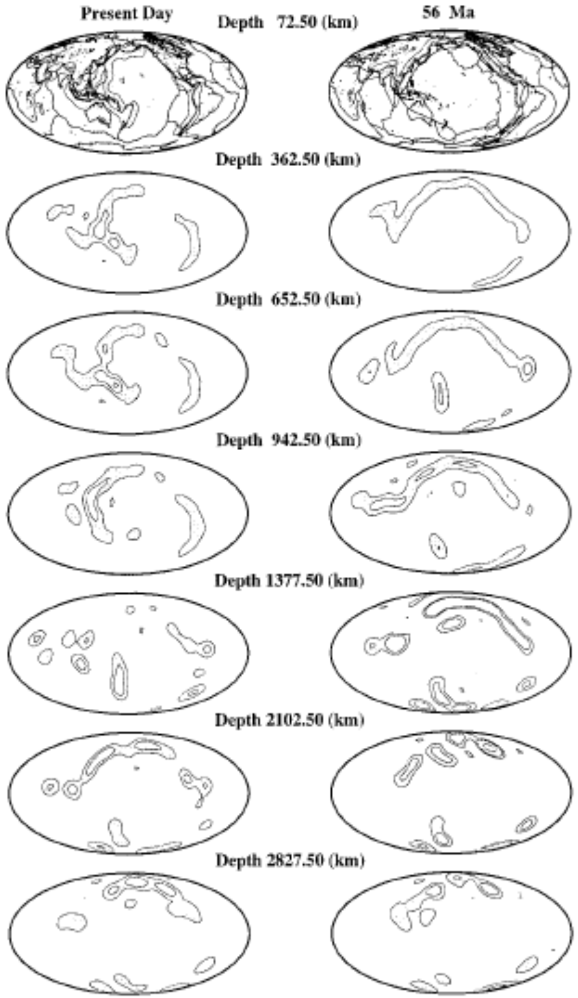


- constraint on upper/lower mantle viscosity increase

Ricard et al. (1993)

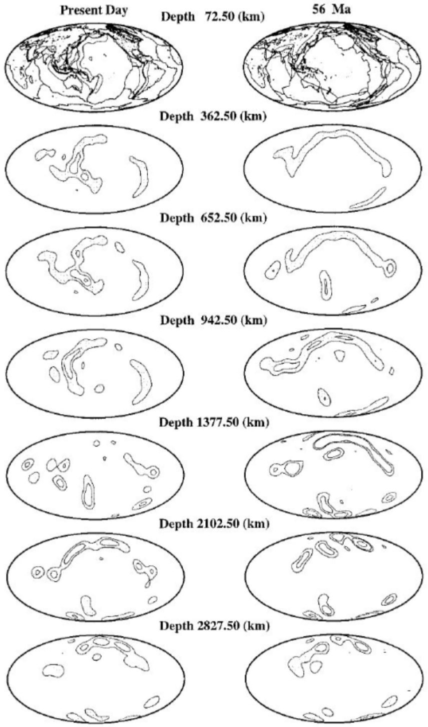
Mantle structure as *f*(*t*) from subduction

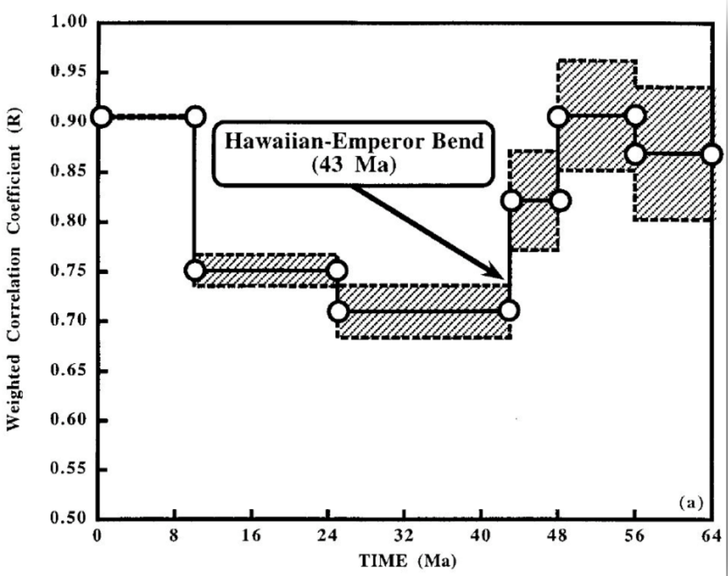




Ricard et al. (1993); Lithgow-Bertelloni & Richards (1998);
Steinberger (2000); Spasojevich et al. (2009); Steinberger and Torsvik (2010)
van der Meer (2010); Steinberger et al. (2014); Bower et al. (2015)

Time-dependent match to plate motions based on slablets

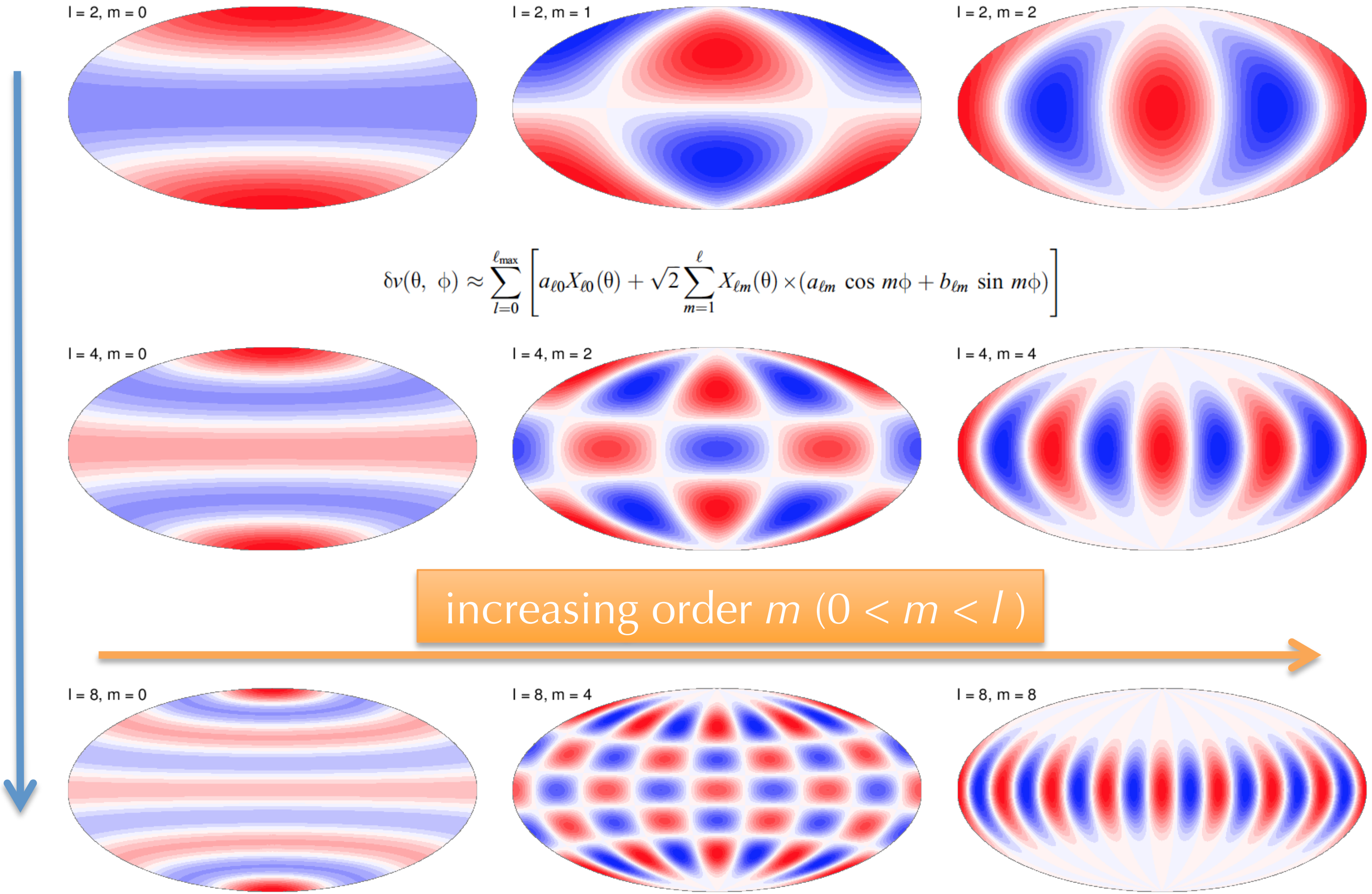




Lithgow-Bertelloni and Richards (1998)

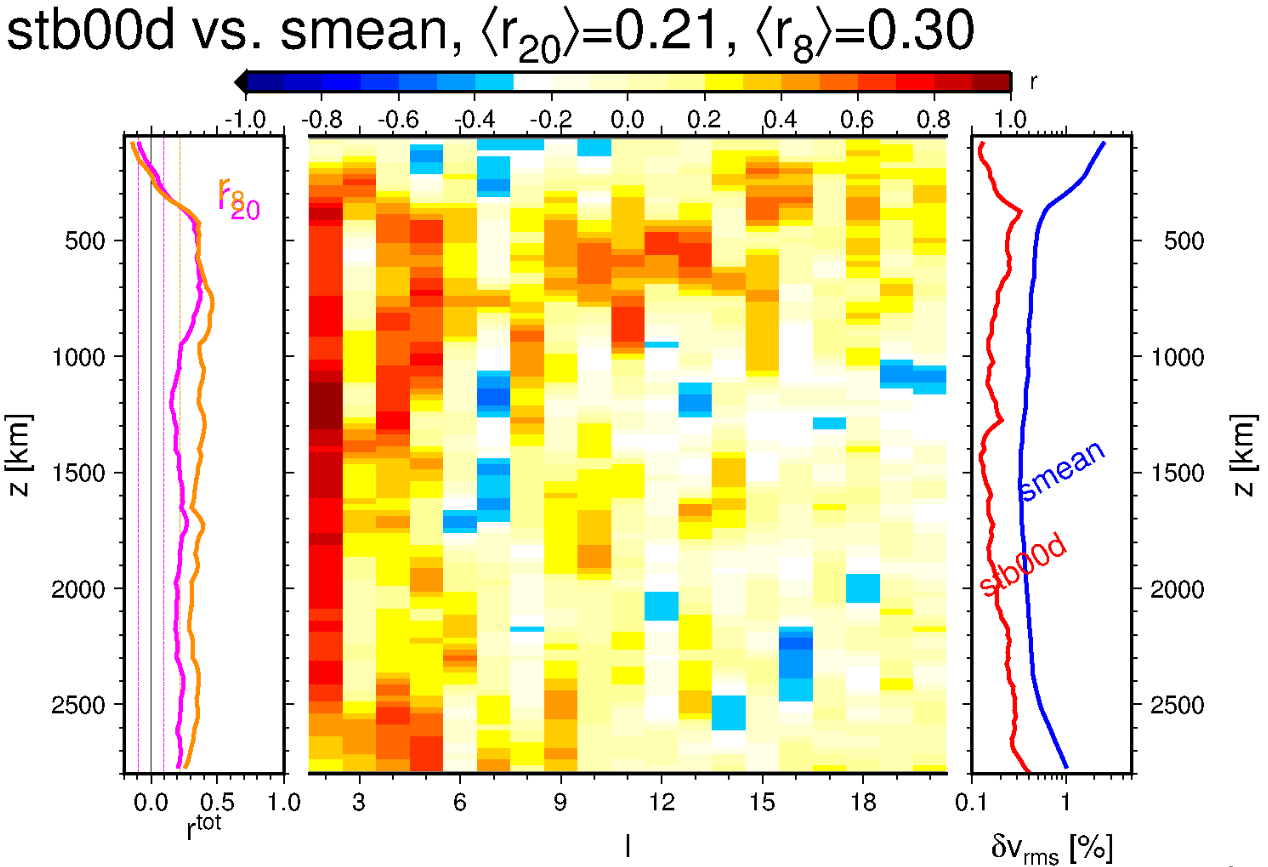
Spherical harmonics for analysis of global fields

increasing degree *l* (1/wavelength)



$$\delta v(\theta,\ \phi) \approx \sum_{l=0}^{\ell_{\max}} \left[a_{\ell 0} X_{\ell 0}(\theta) + \sqrt{2} \sum_{m=1}^{\ell} X_{\ell m}(\theta) \times (a_{\ell m}\ \cos m\phi + b_{\ell m}\ \sin m\phi) \right]$$

Correlation of global slab model with tomography (does not work that well…)

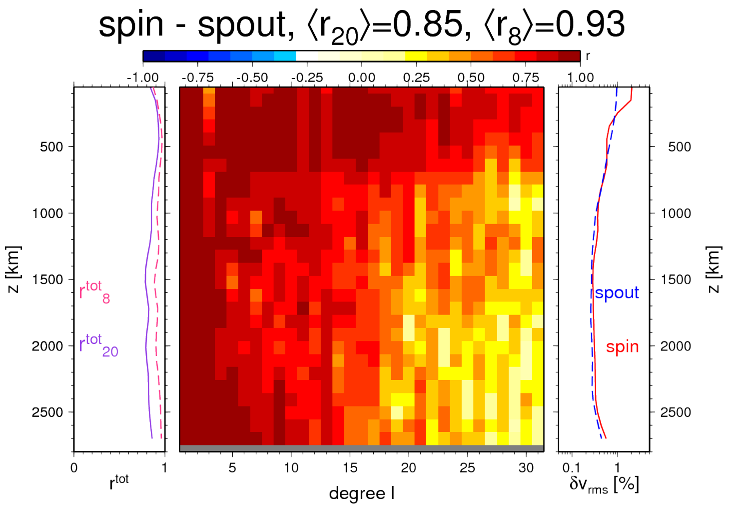


Becker & Boschi (2002)

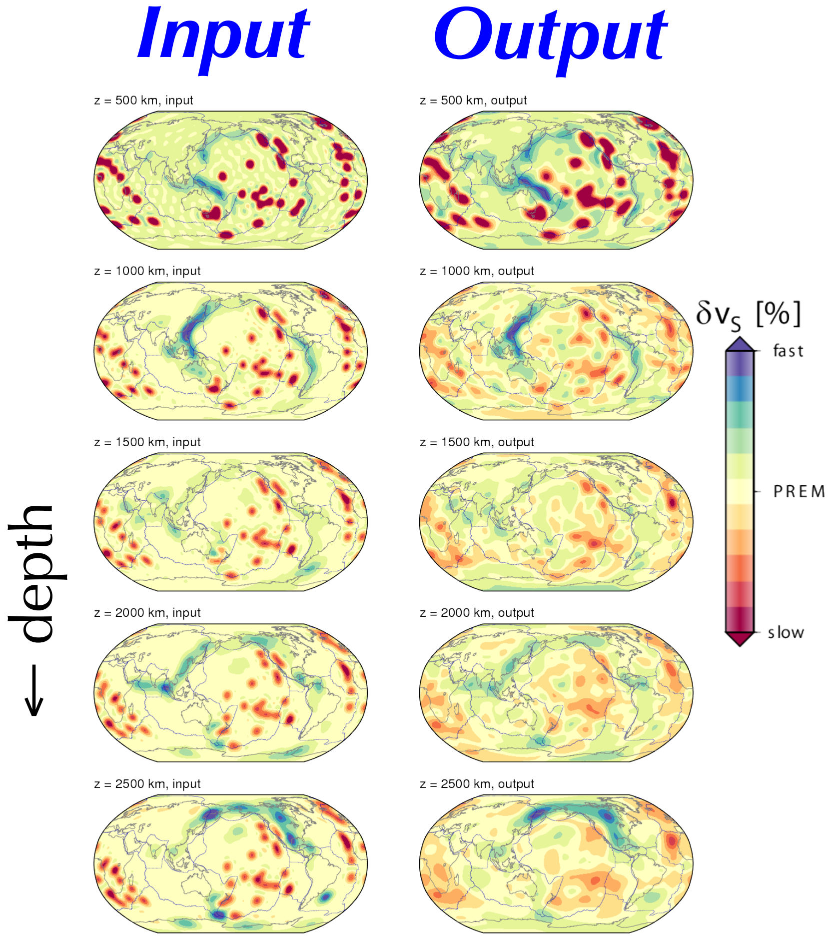
Lithgow-Bertelloni & Richards (1998); Steinberger (2000); Bunge & Grand (2000); Spasojevic & Gurnis (2009)

Seeing the slab I

✔

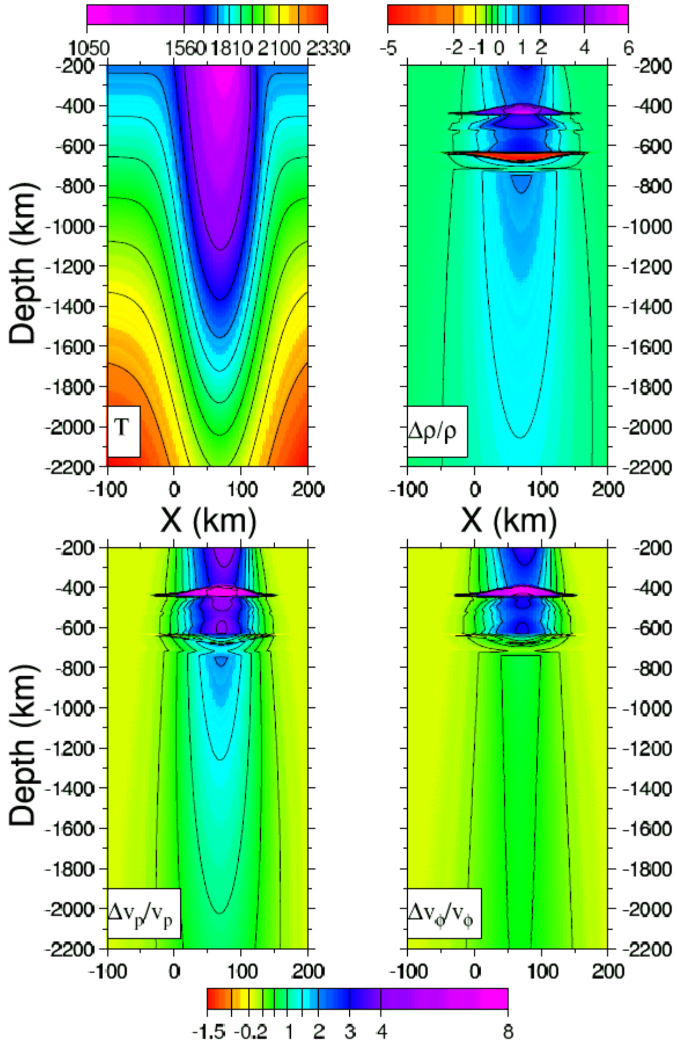


Note: can resolve structure up to degree l_{max} ~15 in wave theoretical framework



Seeing the slab II

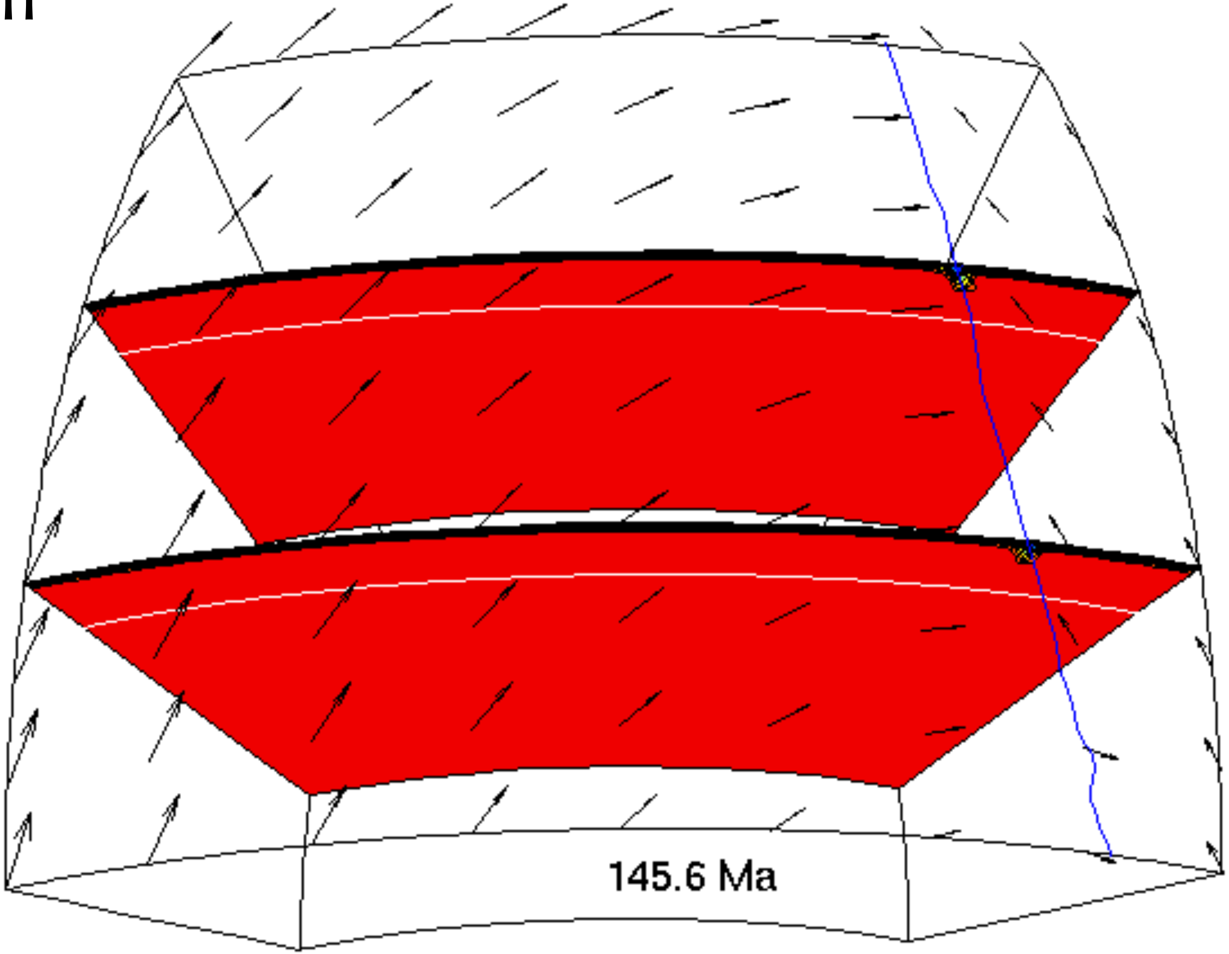
?



Ricard et al. (2005)

Seeing the slab III

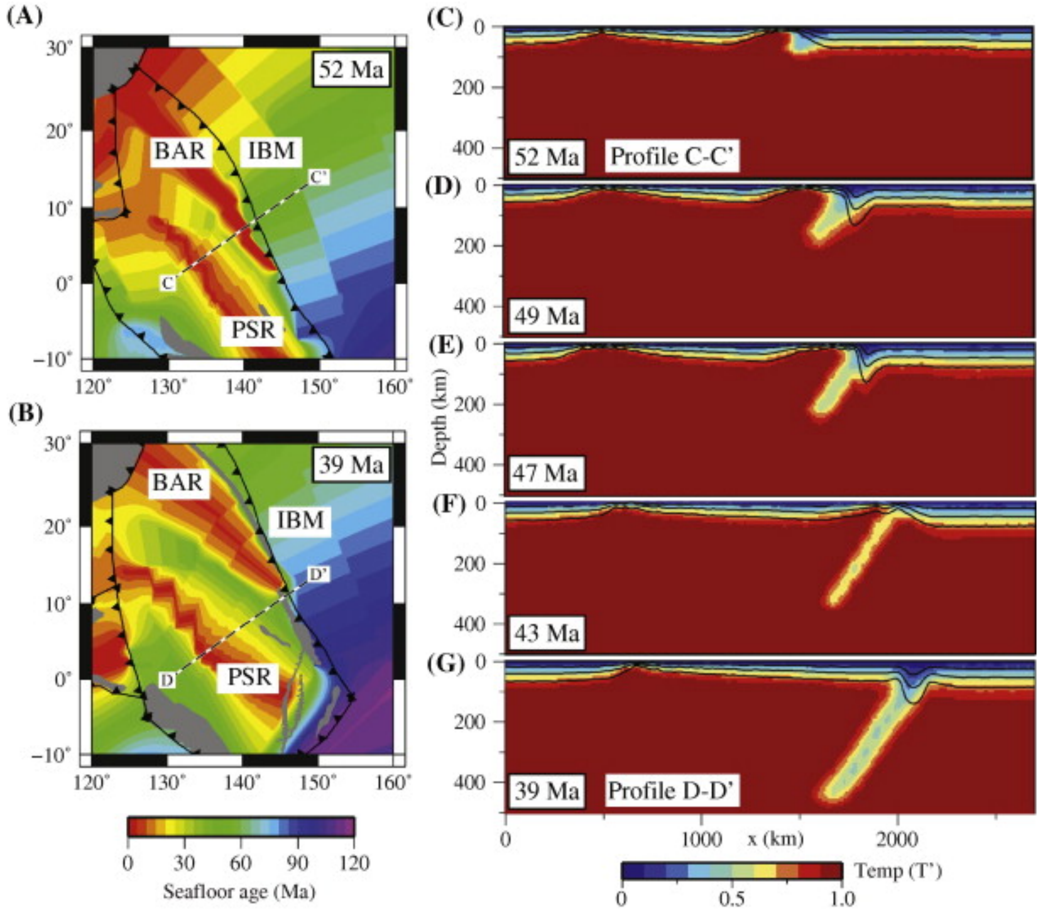
?



Tan et al. (2001)

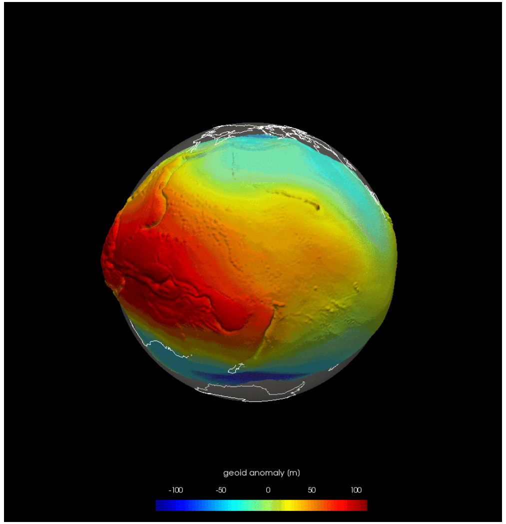
Slab models do not quite explain mantle structure, because of…

uncertainties about
- plate reconstructions
- slab and mantle rheology
- mineral physics and composition
    - mass flux through 660
- active upwellings and thermo-chemical piles

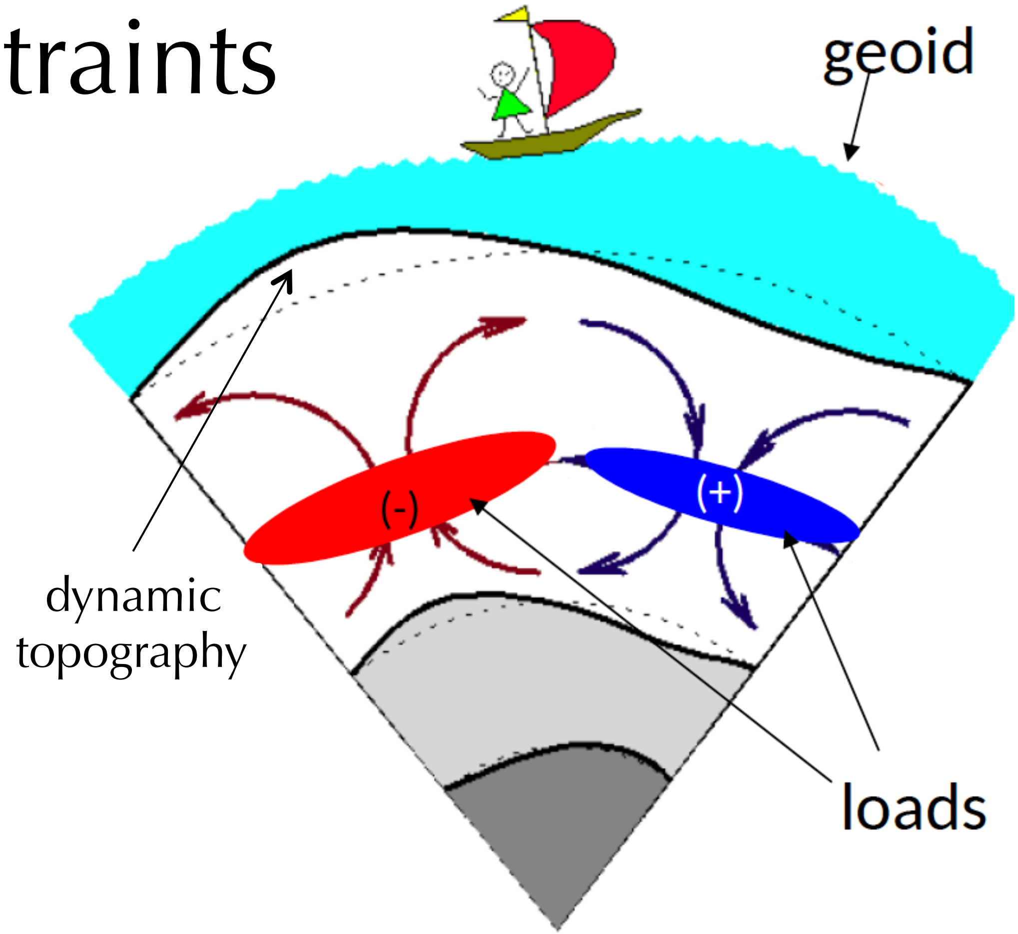


Bower et al. (2015)

Other constraints on slabs



vertically exaggerated EGM360 geoid



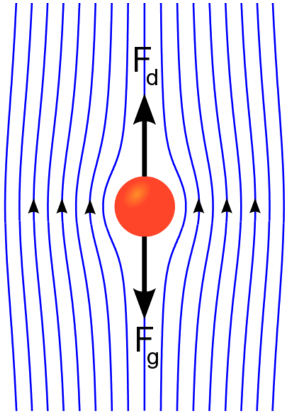
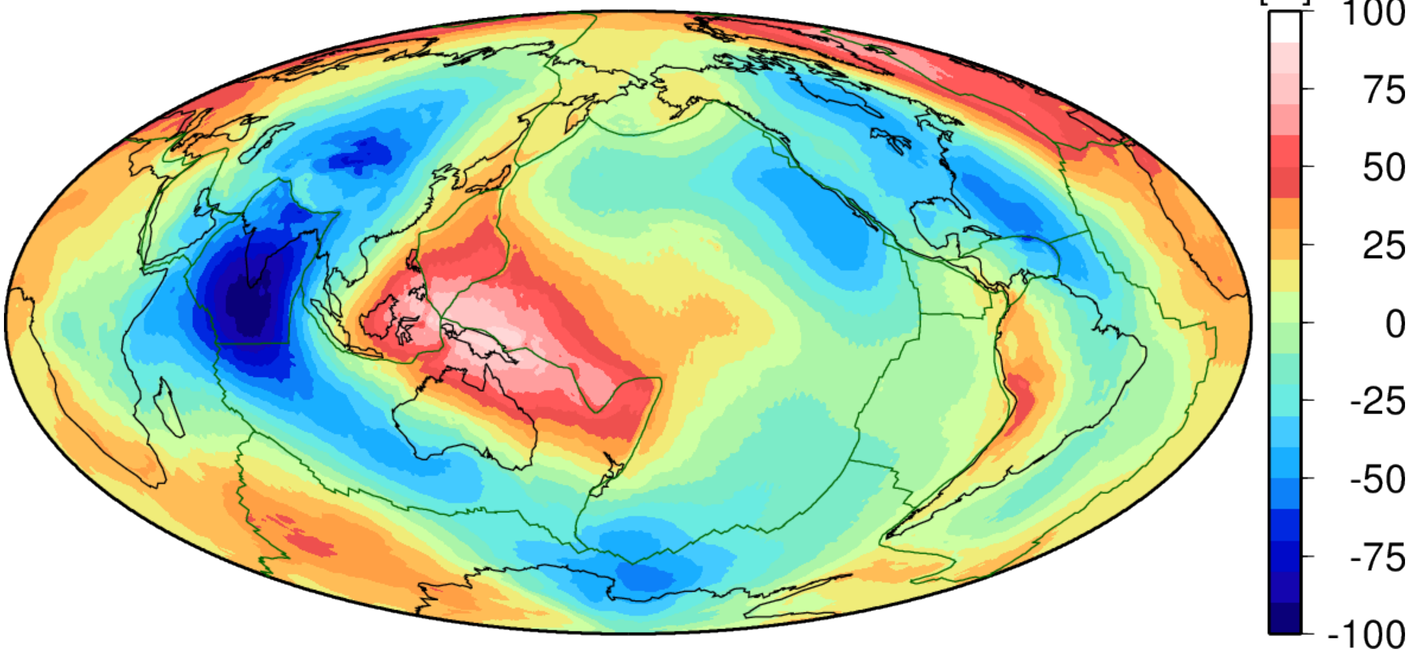


Figure from Y. Ricard

Geoid anomalies

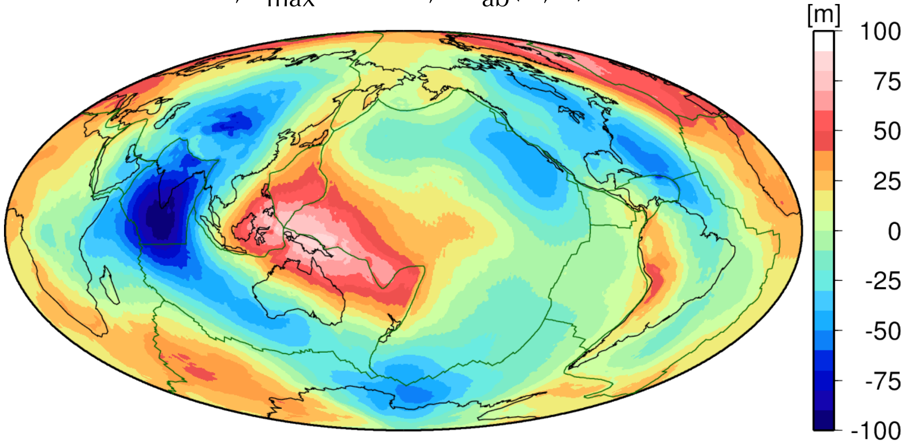
ITG-GRACE, $l_{max} = 180$; non-elliptical ($G_{ab}(l = 2, m = 0) \leftarrow 0$)



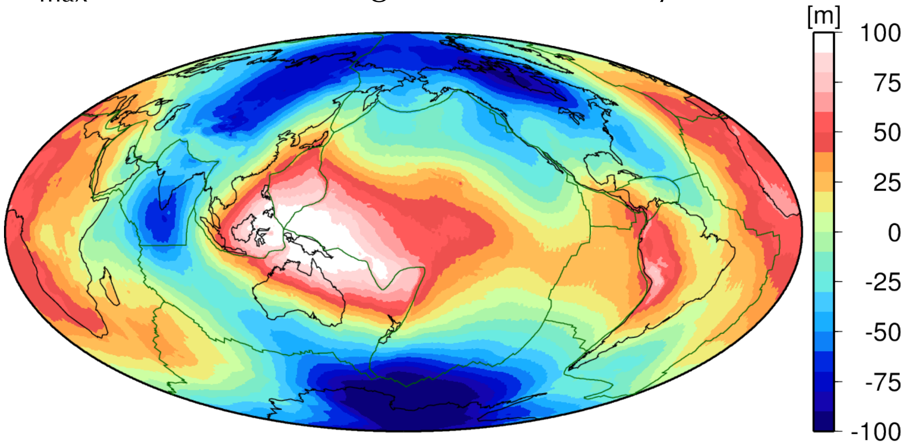
scale is saturated

Geoid anomalies

ITG-GRACE, l_{max} = 180; $G_{ab}(2,0) = 0$



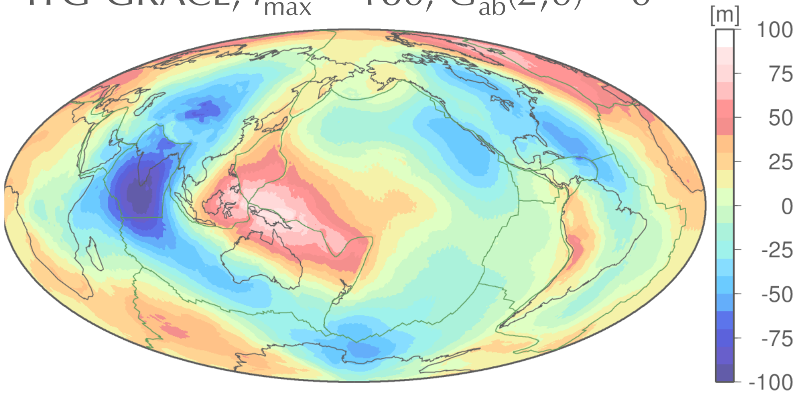
l_{max} = 180 – Nakiboglu (1982) non-hydrostatic



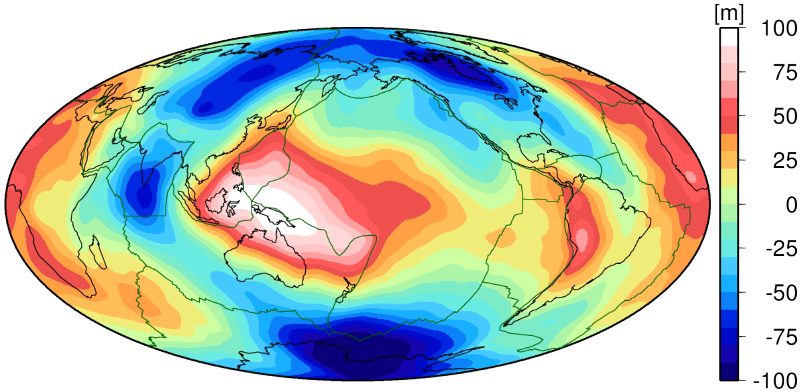
scales are saturated

Geoid anomalies

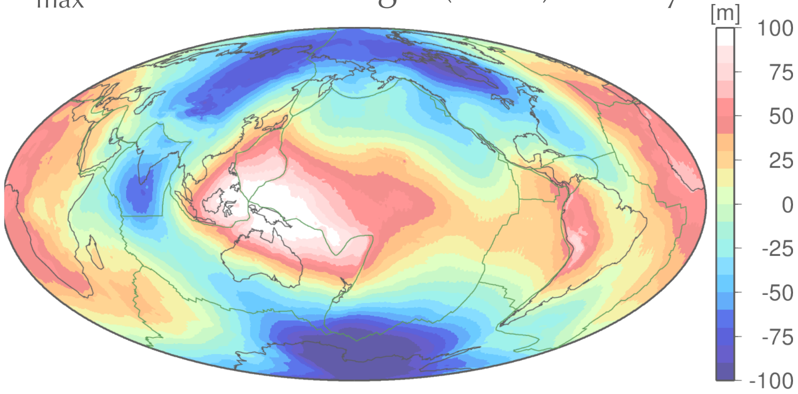
ITG-GRACE, l_{max} = 180; $G_{ab}(2,0) = 0$



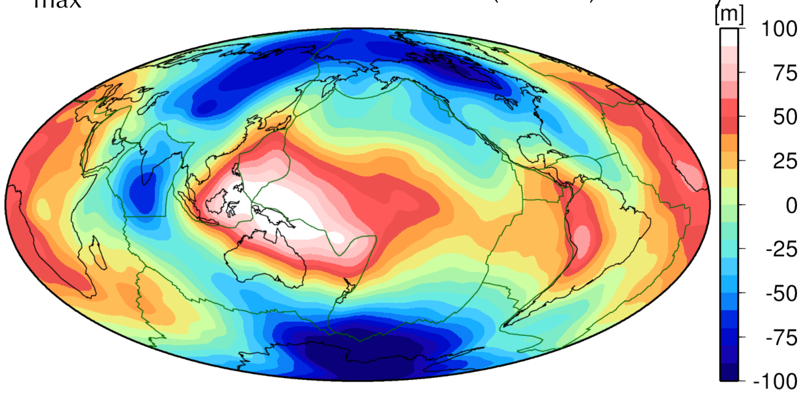
l_{max} = 31 – Nakiboglu (1982) non-hydrostatic



l_{max} = 180 – Nakiboglu (1982) non-hydrostatic

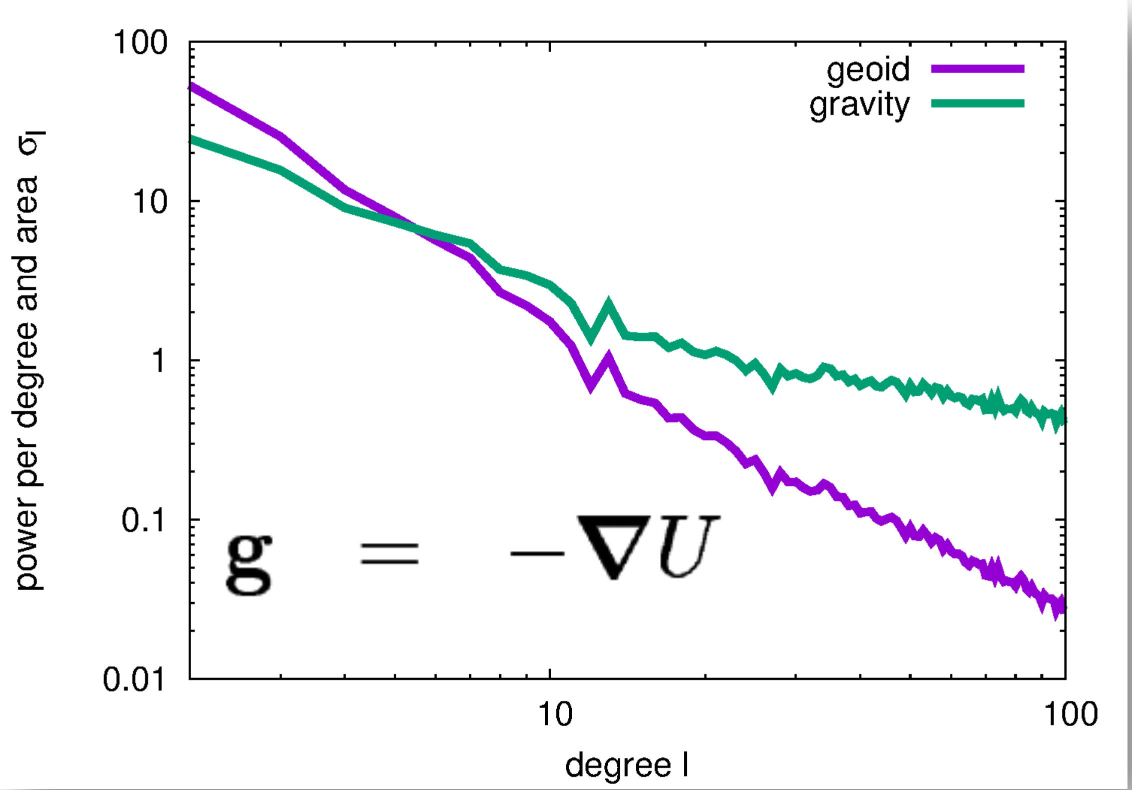


l_{max} = 31 – Chambat et al. (2010) non-hydrostatic



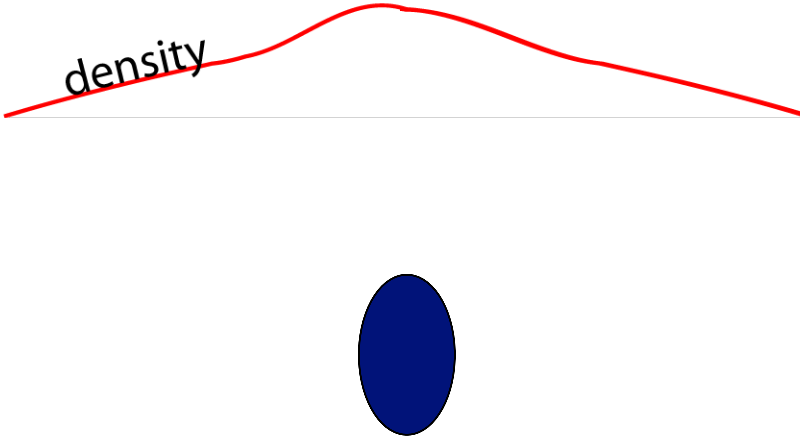
scales are saturated

Potential field constraints: Bias in wavelength dependence of model fit



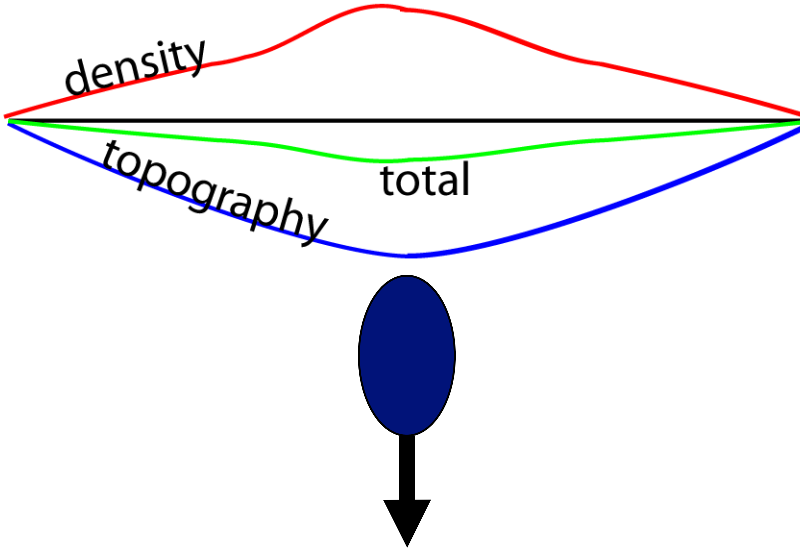
$$\mathbf{g} = -\nabla U$$

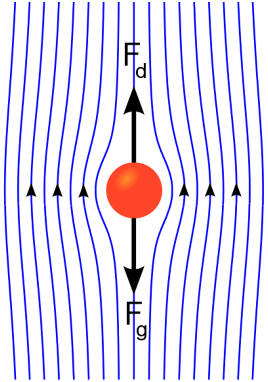
Let's fit the geoid: Static effect of dense anomaly



sketch from M. Billen's MYRES talk
cf. Hager (1984); Richards & Hager (1984); Ricard (1984)

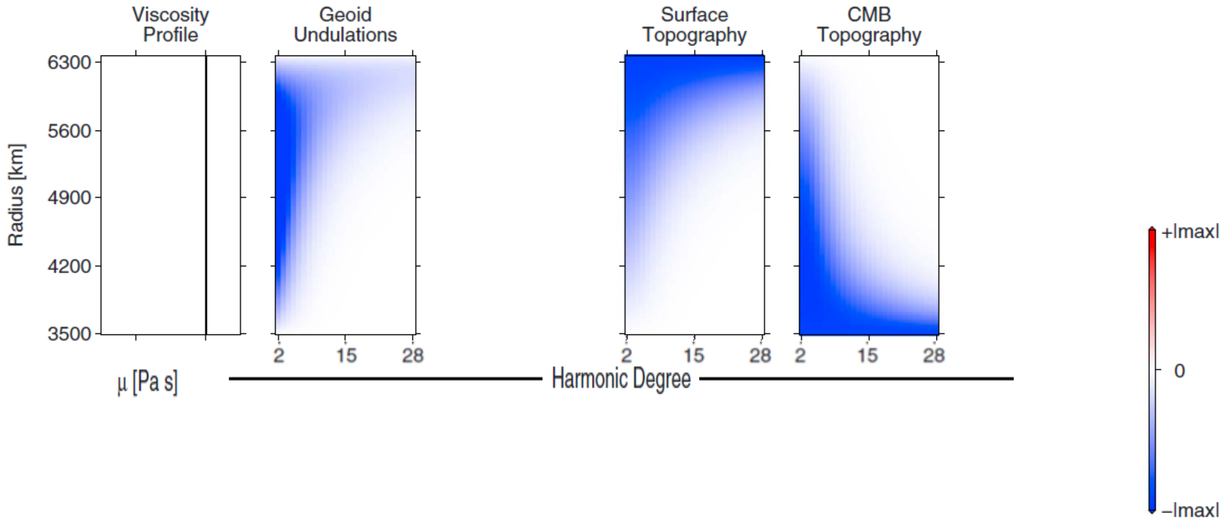
Combined static and dynamic effect of a slablet

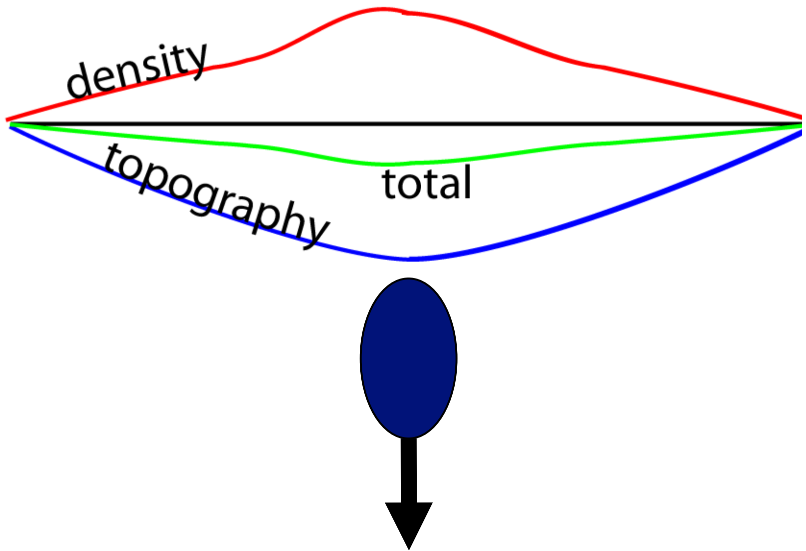




sketch from M. Billen's MYRES talk
cf. Hager (1984); Richards & Hager (1984); Ricard (1984)

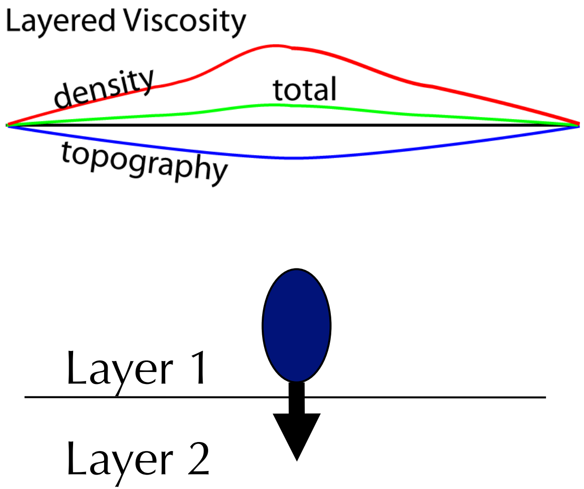
response to density anomalies as $f(z, l)$

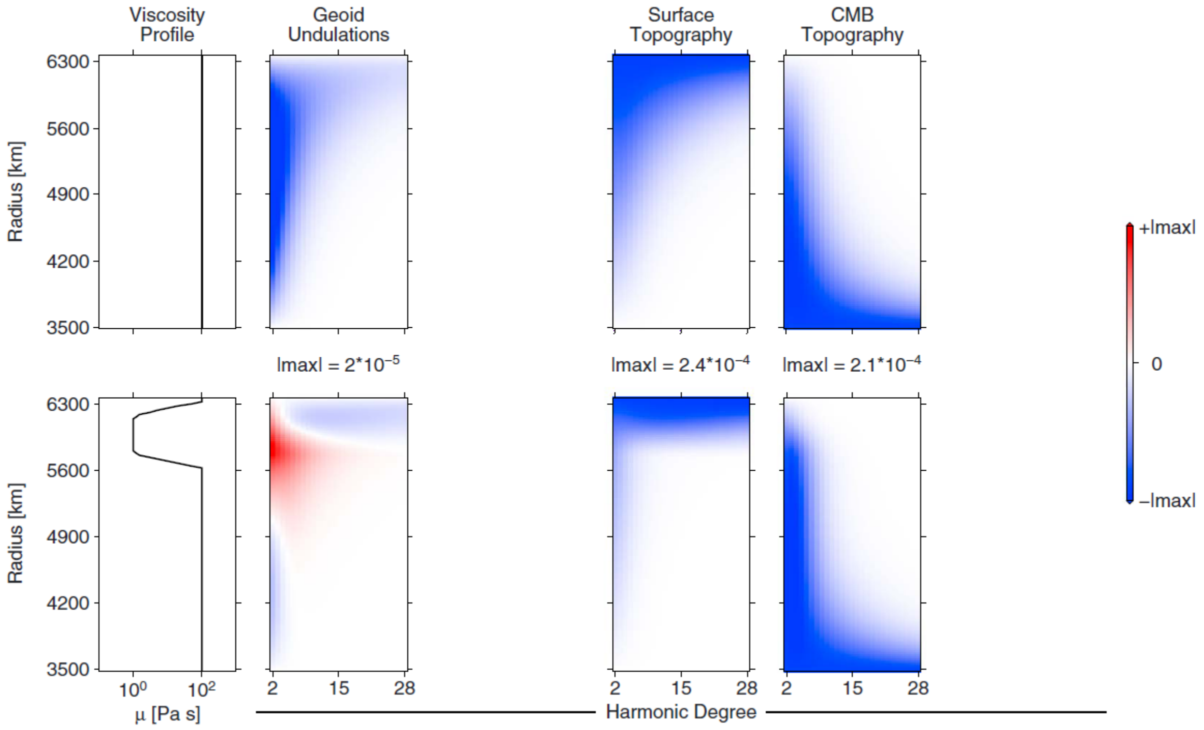




Colli et al (2016), sketch from M. Billen
cf. Richards & Hager (1984); Ricard (1984)

Kernels for layered viscosity mantle





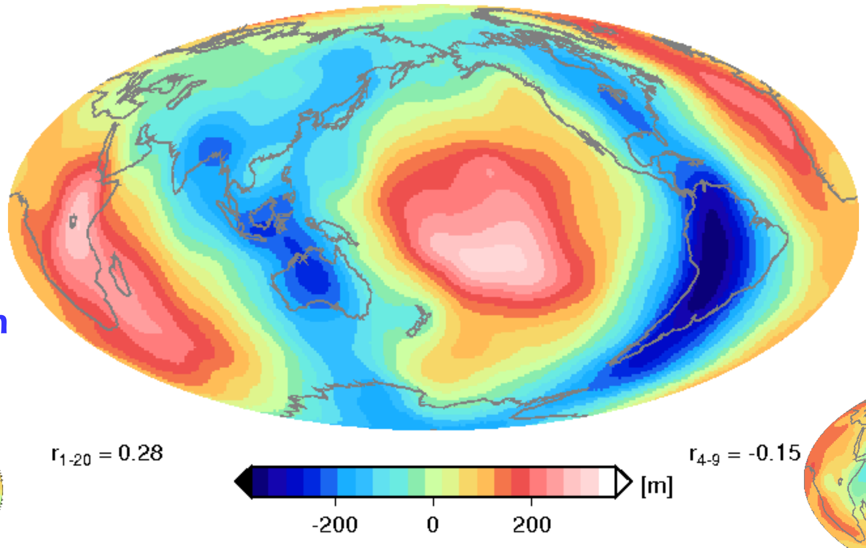
Colli et al (2016), sketch from M. Billen; cf. Richards & Hager (1984); Ricard (1984)

Geoid for tomography driven flow

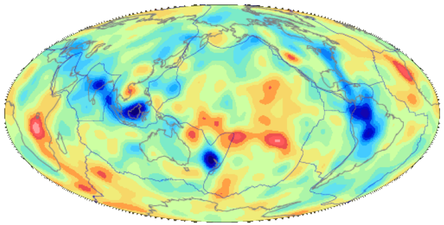
- Isoviscous – free slip surface boundary condition

constant
$d \ln \rho / d \ln v_S$

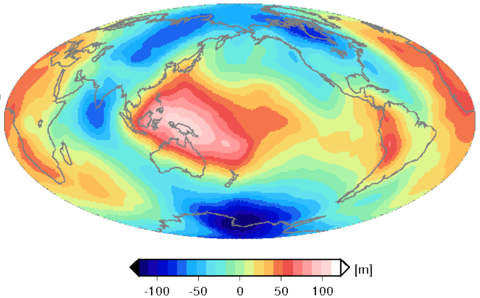
geoid prediction



tomography @ 1200 km



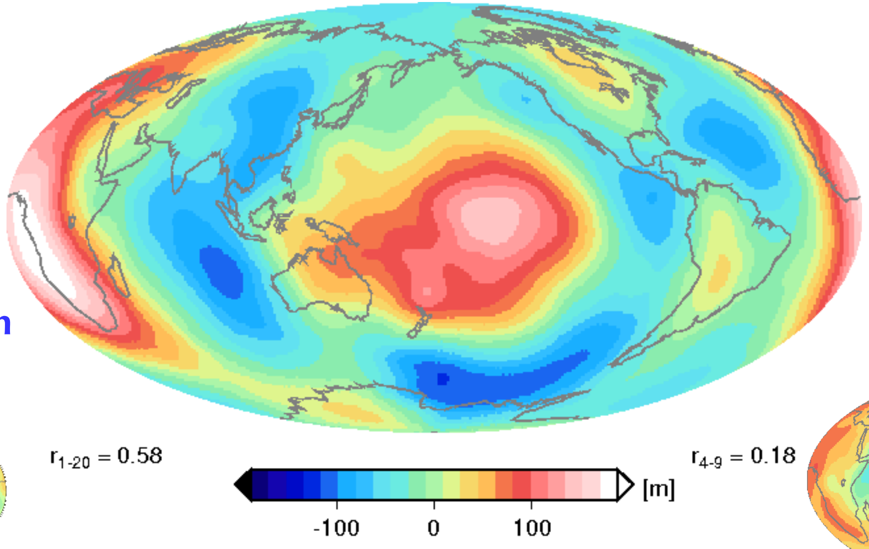
observed geoid



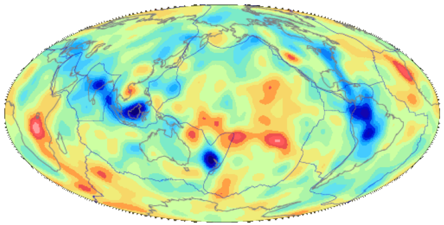
Geoid for tomography driven flow

- Lower mantle viscosity increase

geoid prediction



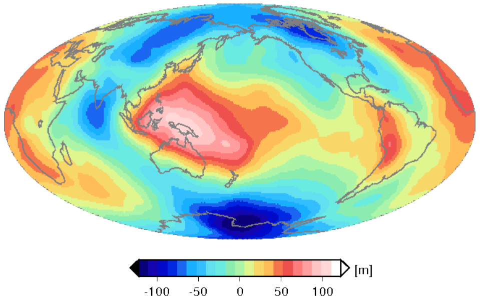
tomography @ 1200 km



$r_{1\text{-}20} = 0.58$

$r_{4\text{-}9} = 0.18$

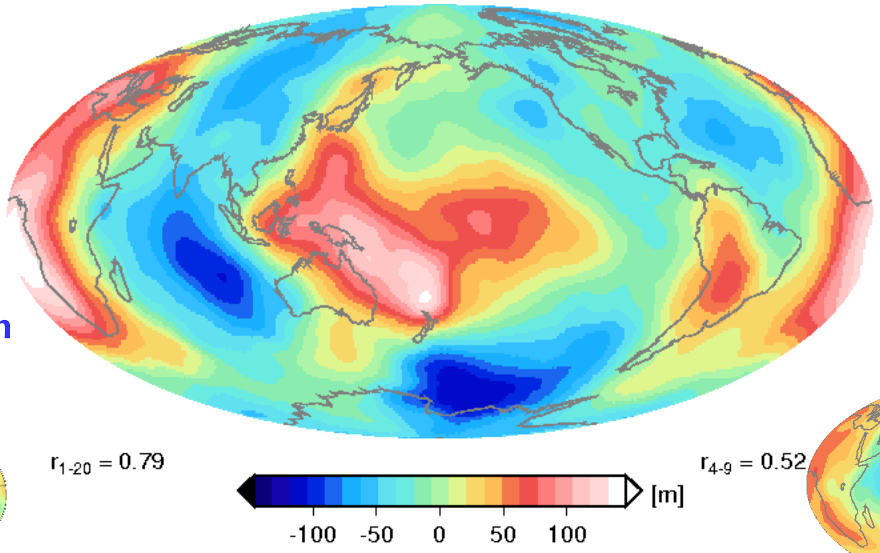
observed geoid



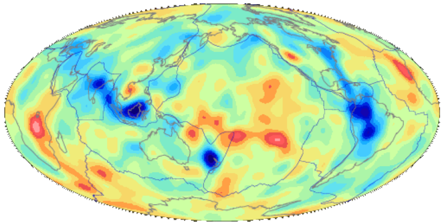
Geoid for tomography driven flow

- Four layer model

geoid prediction



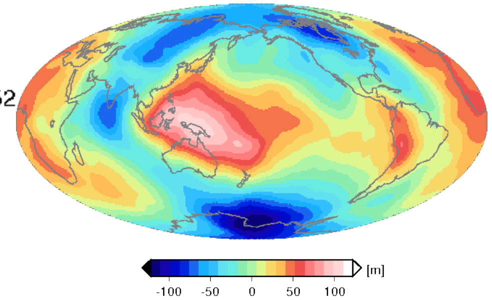
tomography @ 1200 km



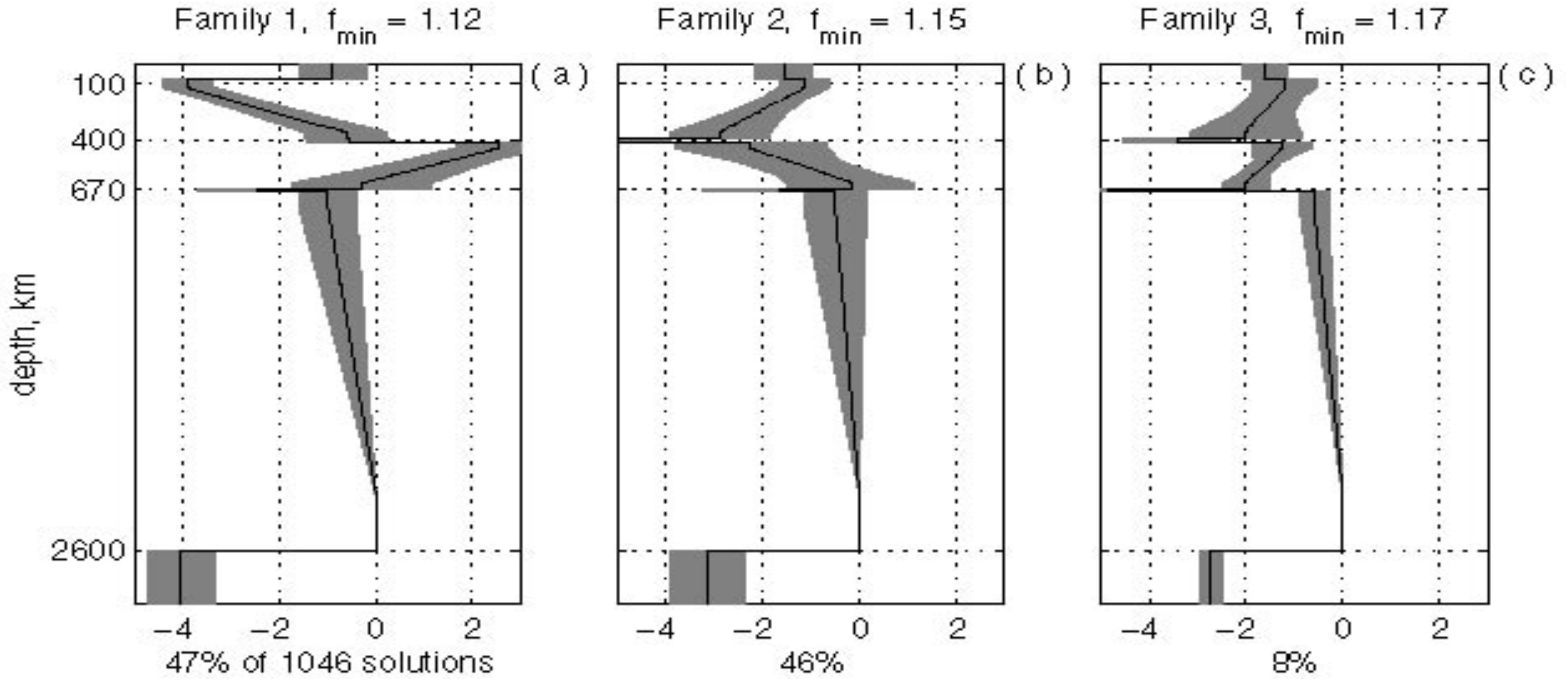
$r_{1\text{-}20} = 0.79$

$r_{4\text{-}9} = 0.52$

observed geoid



Viscosity inversions are non-unique
(Monte Carlo approach, based on geoid and surface dynamic topography)

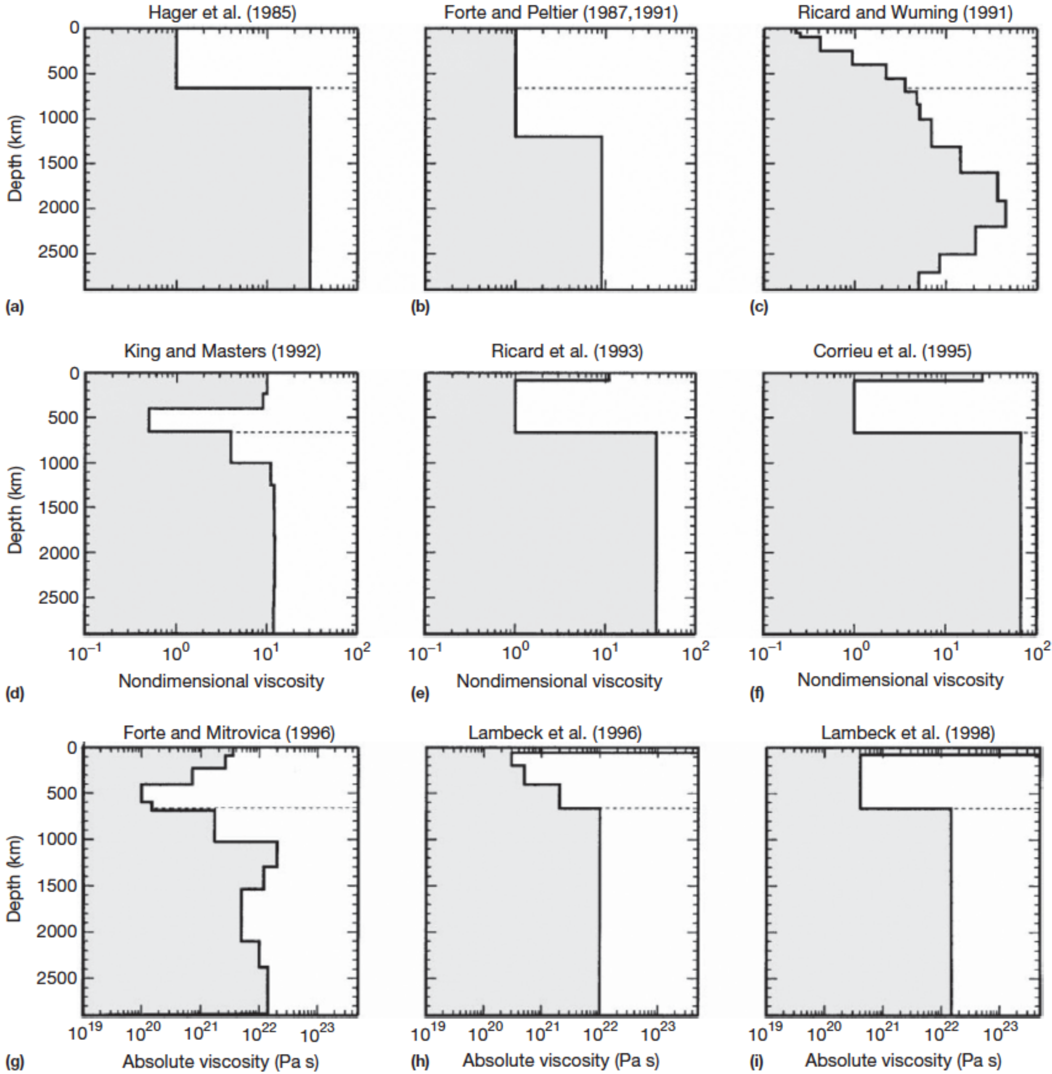


Panasyuk & Hager (2000)

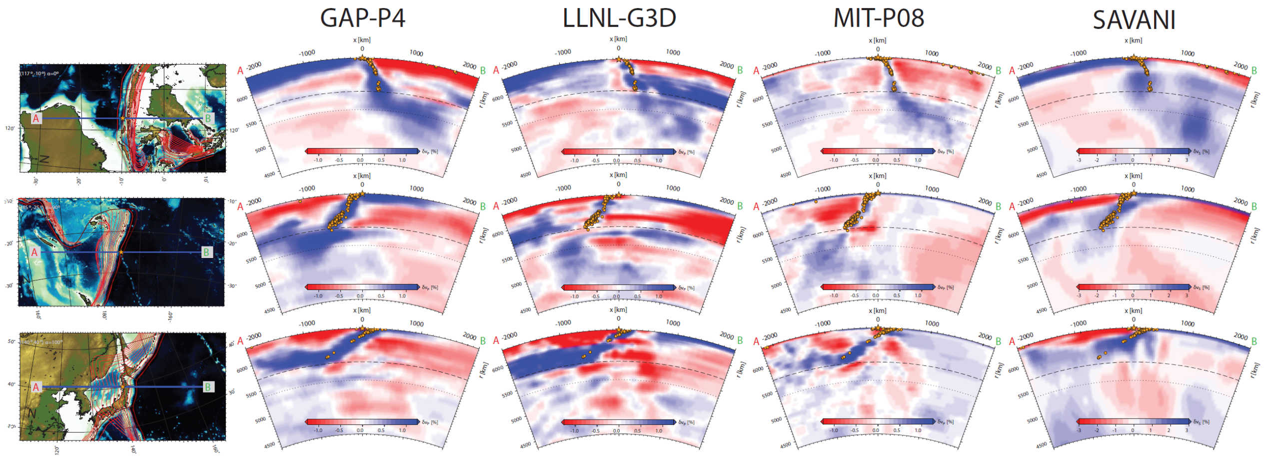
Geoid vs. GIA inversions

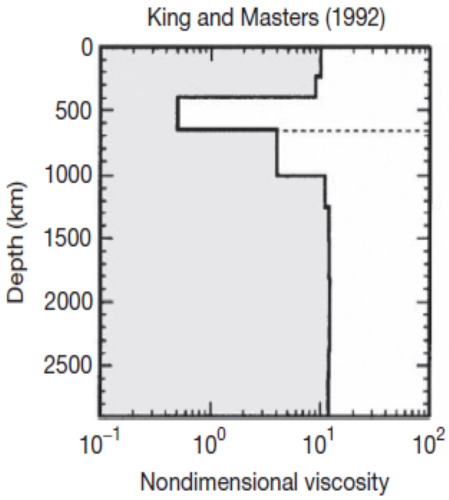
➢ still need to reconcile ice load model viscosities

Forte (2015)



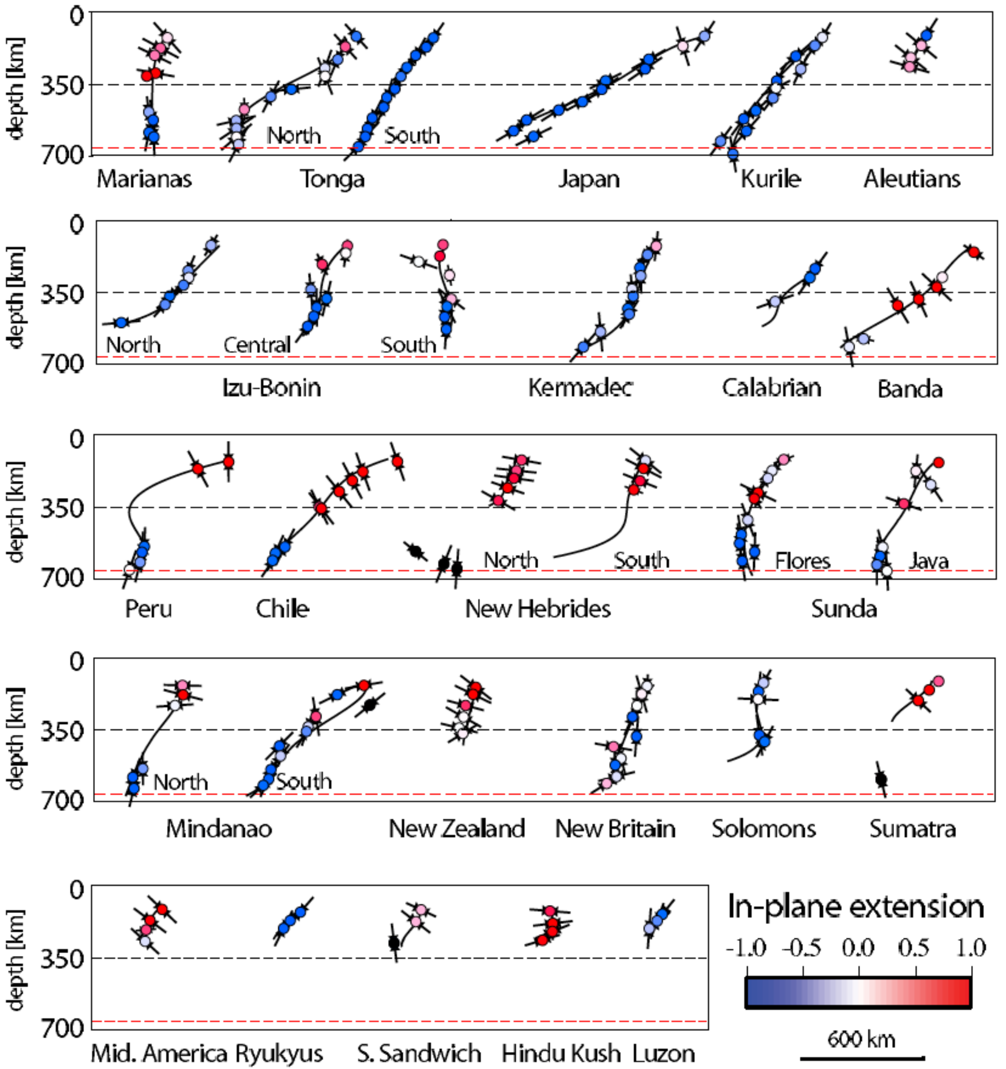
Slab ponding diversity and viscosity stratification in transition zone





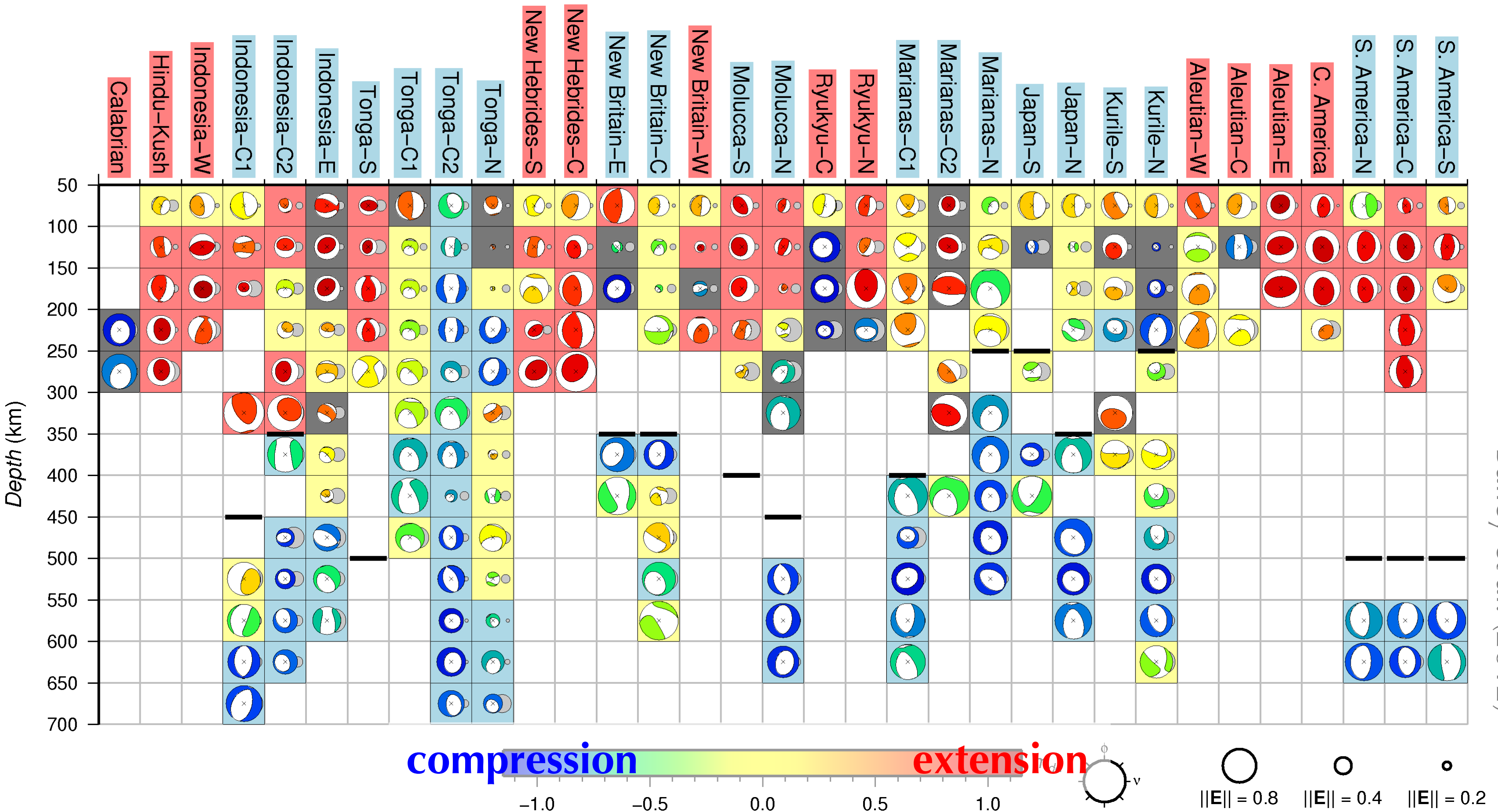
cf. Fukao and Obayashi (2013)
King and Masters (1992) Rudolph et al. (2016)

Earthquake constraints for slab and mantle viscosity



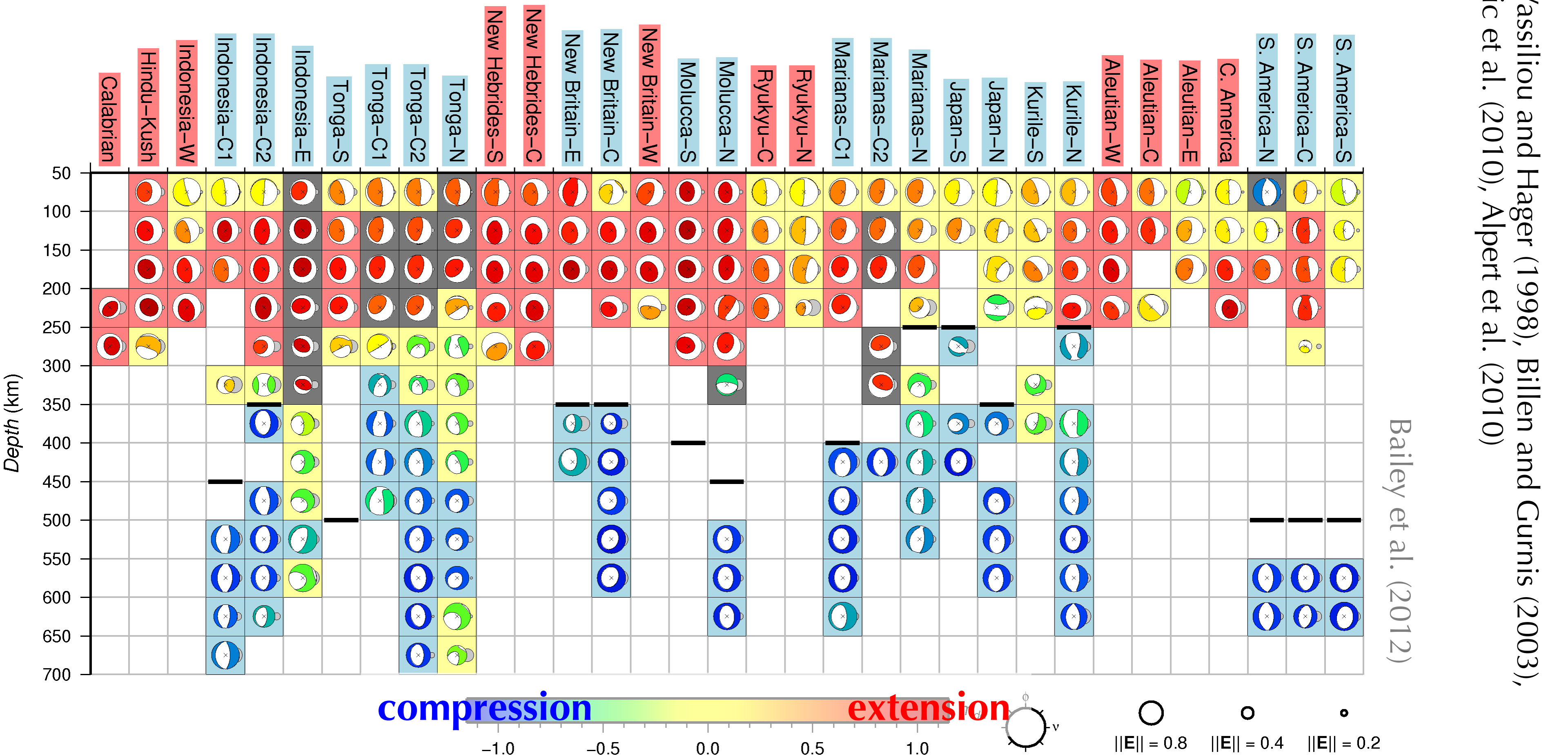
Alpert et al. (2010)
cf. Isacks and Molnar (1971)

Summed gCMTs (in-slab projection)

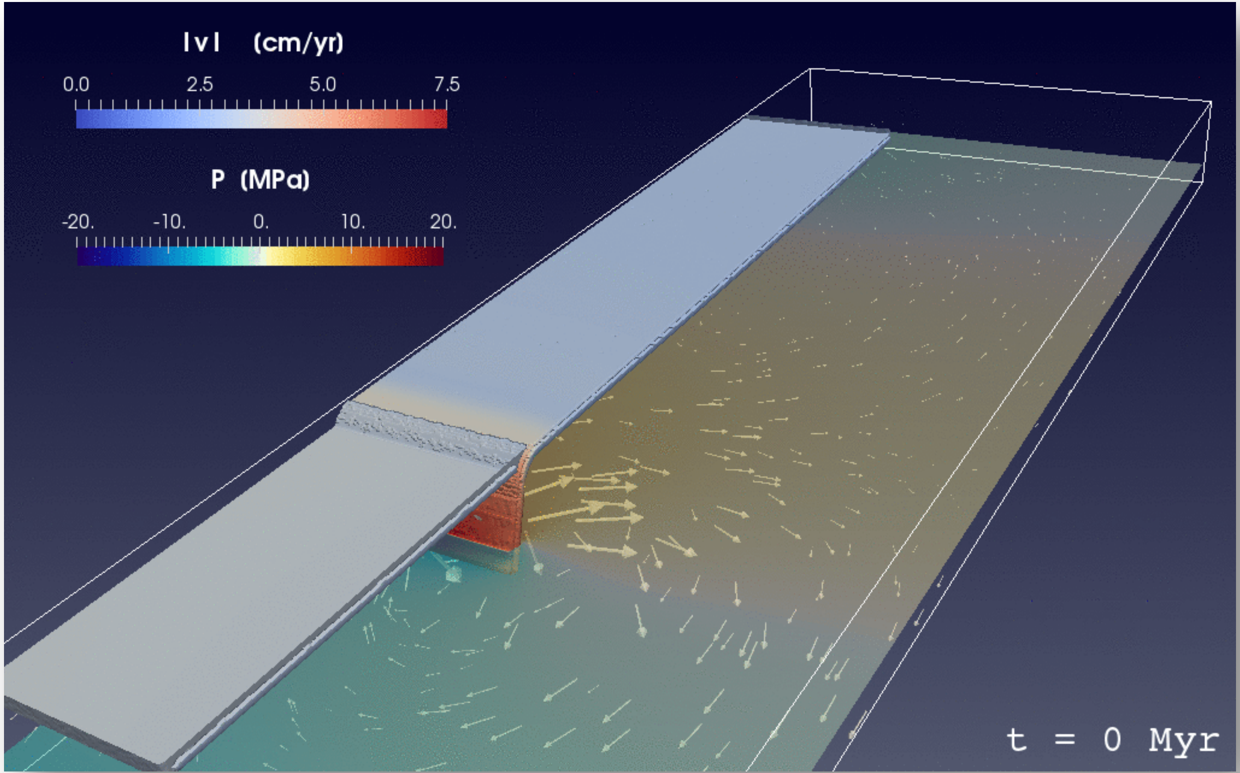


Bailey et al. (2012)

Predictions from global flow model with viscosity increase



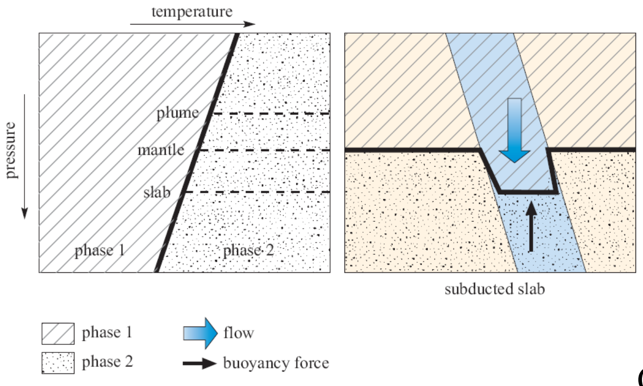
Regional subduction dynamics
(let's do our own experiments)

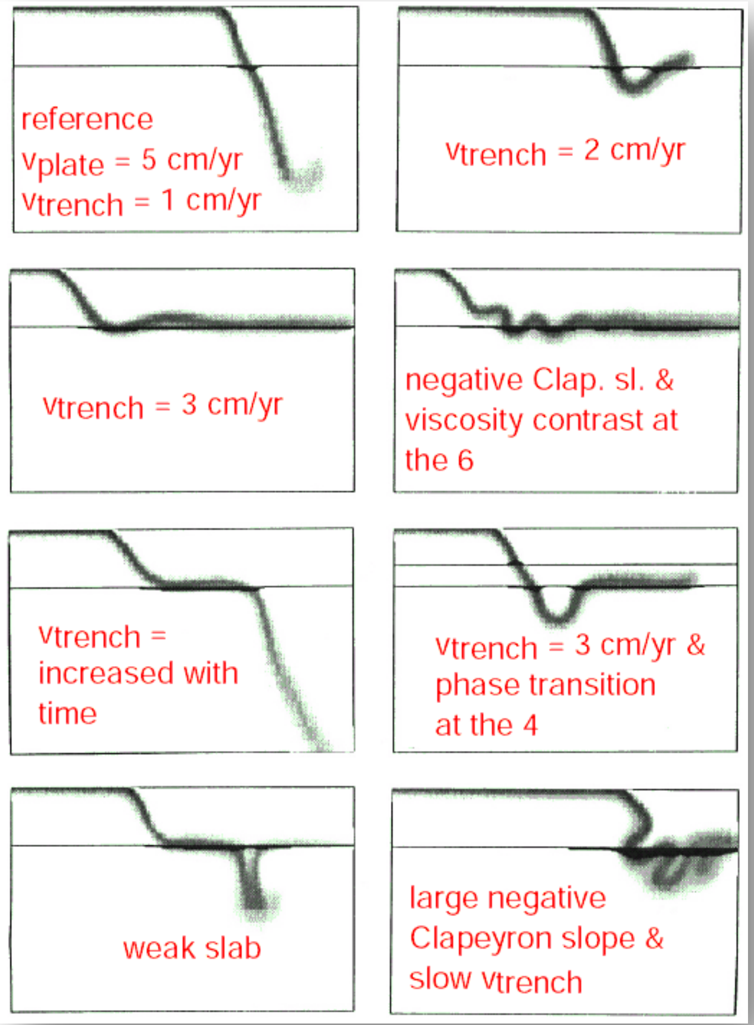


Holt et al. (2017)

Trench rollback and slab penetration

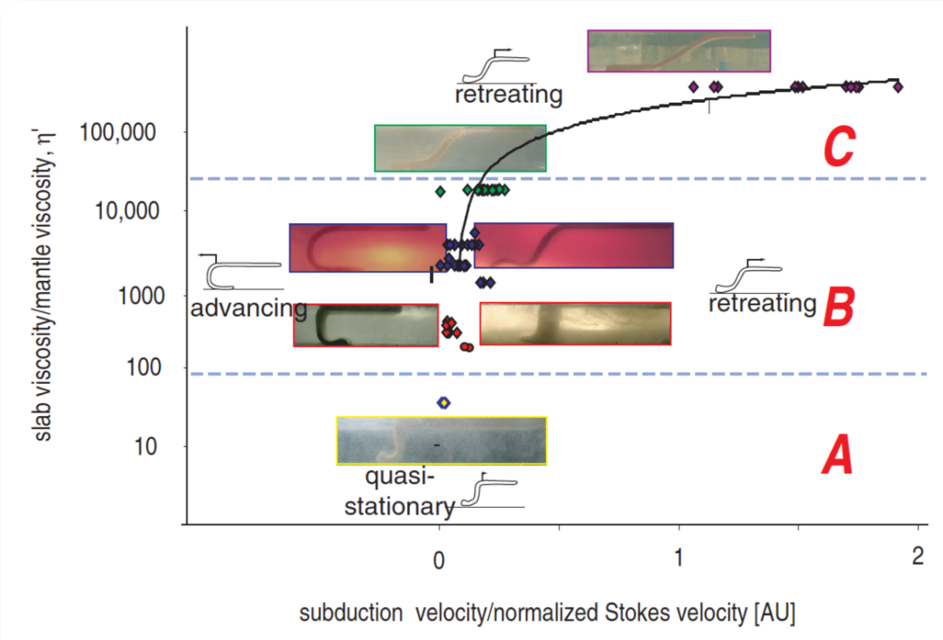
- kinematic (prescribed velocities) model varying plate/trench motion partitioning and importance of phase transition (v_{trench} vs. v_{Stokes})
- $\Delta\rho$ due to deeper phase transition for negative Clapeyron slope

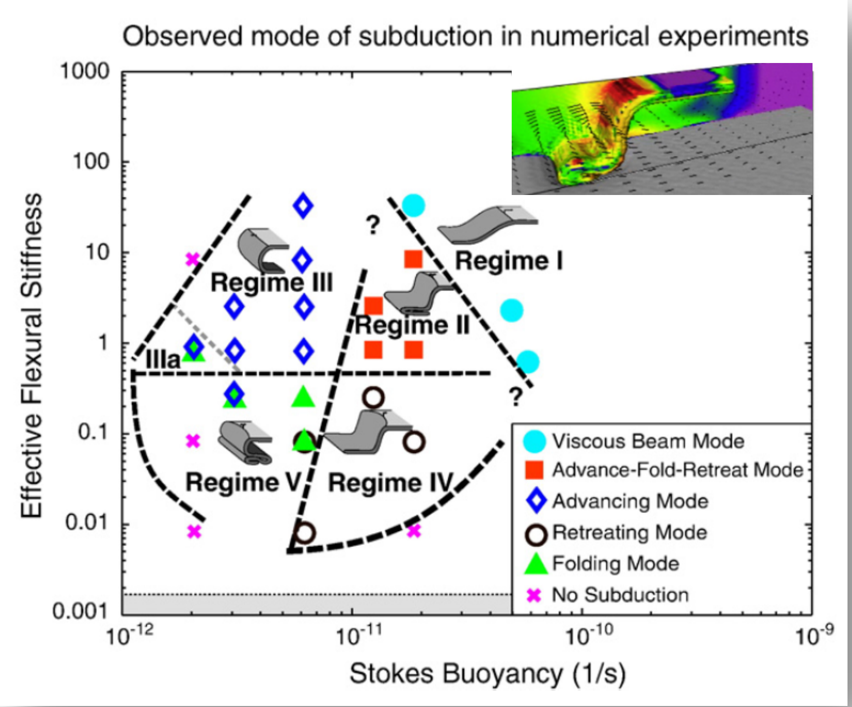




Christensen (1996)

Rollback dynamics phase diagrams



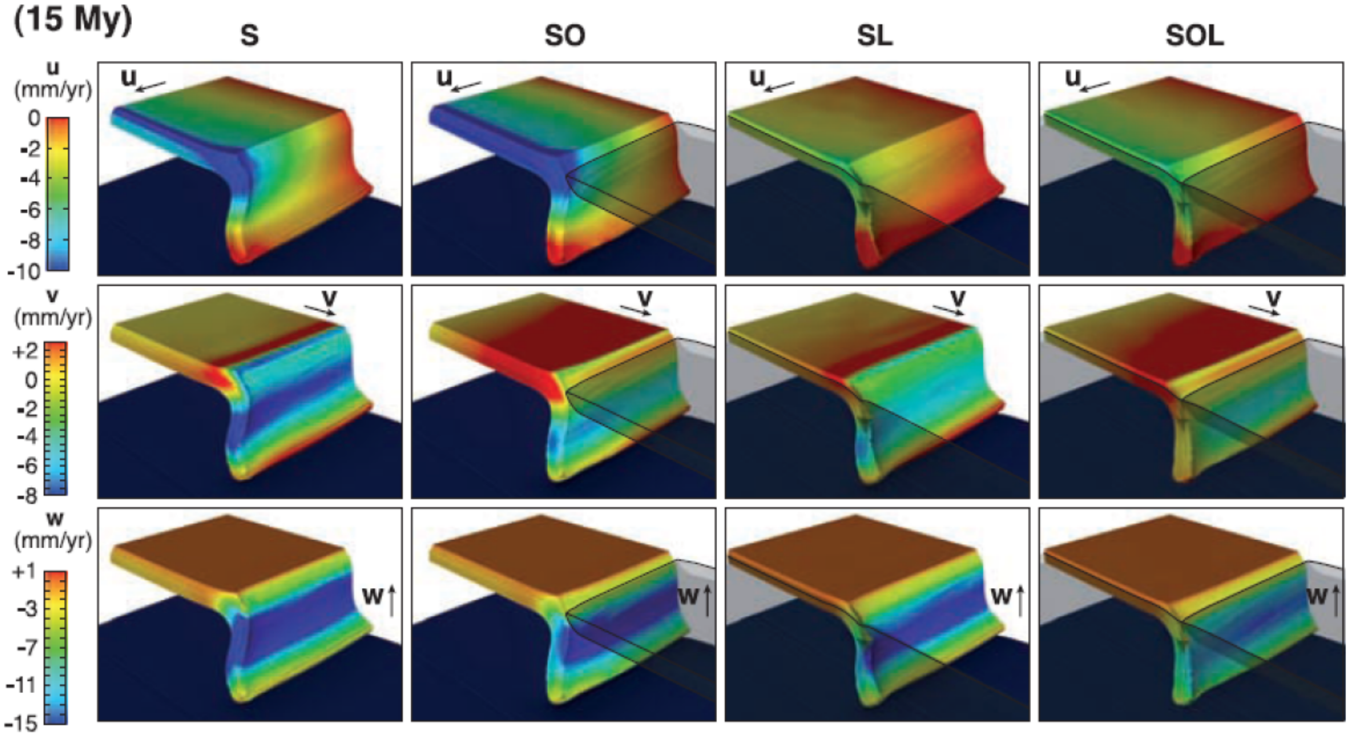


Funiciello et al. (2007)

Stegman et al. (2010)

cf. Ribe (2010)

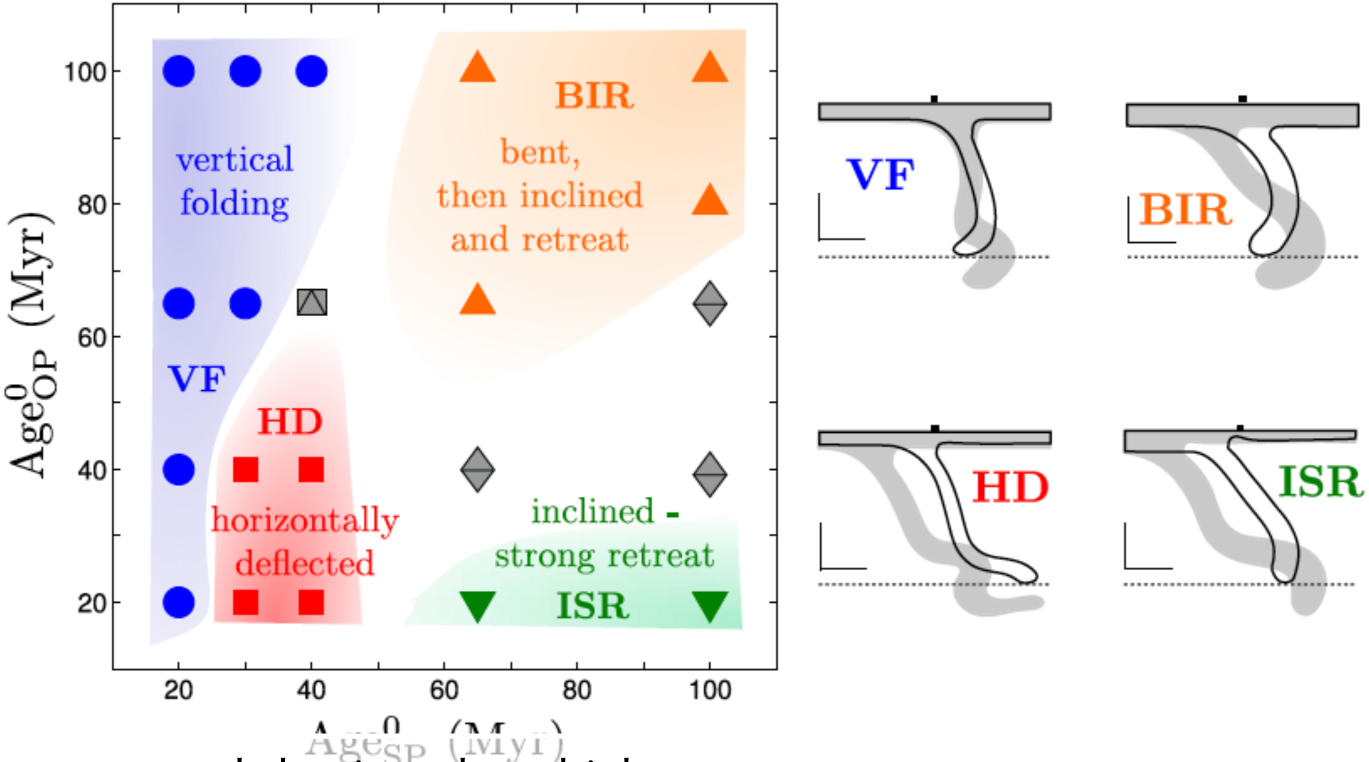
Annoyances I: The overriding plate



Yamato et al. (2009)

New regime diagrams for trench motions and ponding

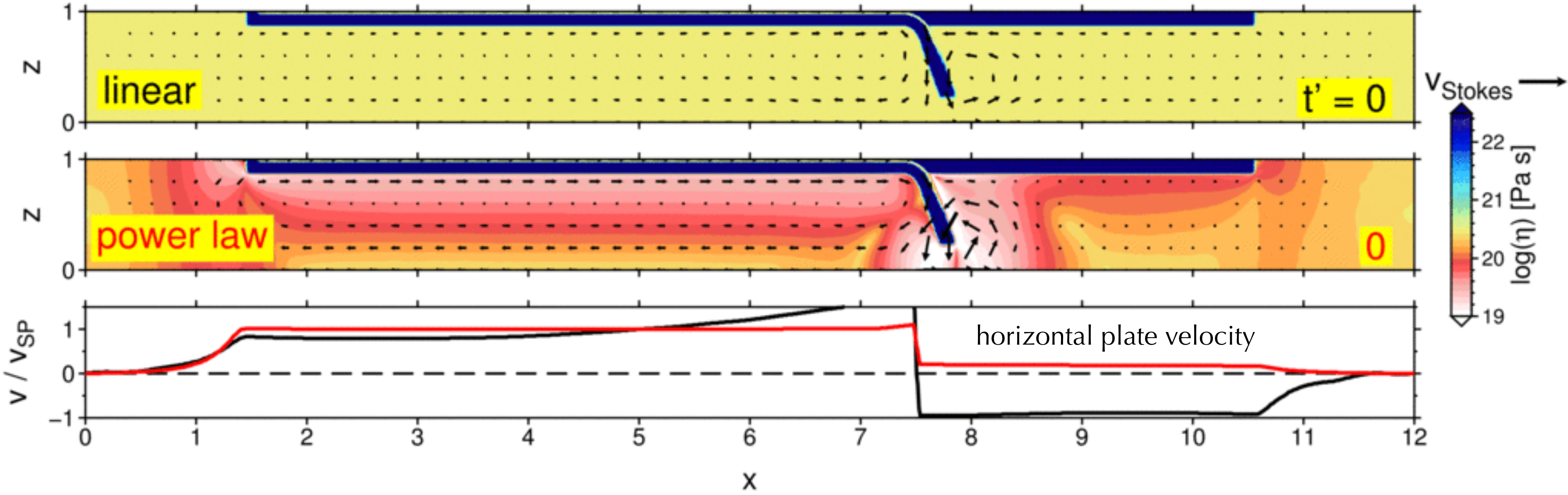
~overriding plate thickness



~subducting plate thickness

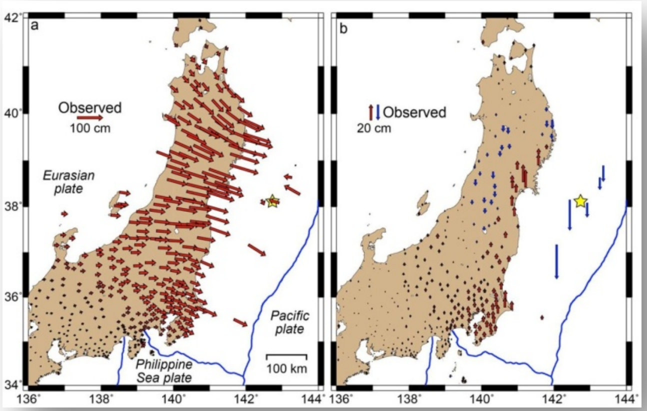
Garel et al. (2014)

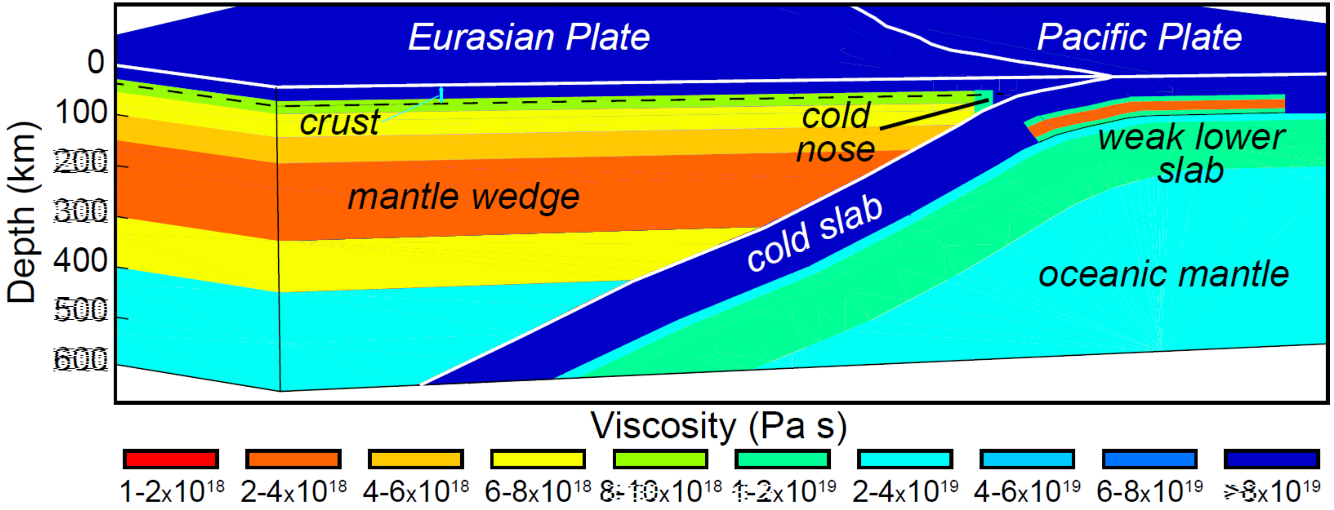
Annoyance II:
Trench motions for nonlinear mantle rheology



Holt and Becker (2017); cf. Billen and Hirth (2003), Jadamec and Billen (2012)

Large-scale rock mechanics experiment: Infer slab and mantle rheology from post-seismics (Tohoku-oki 2011 M9)

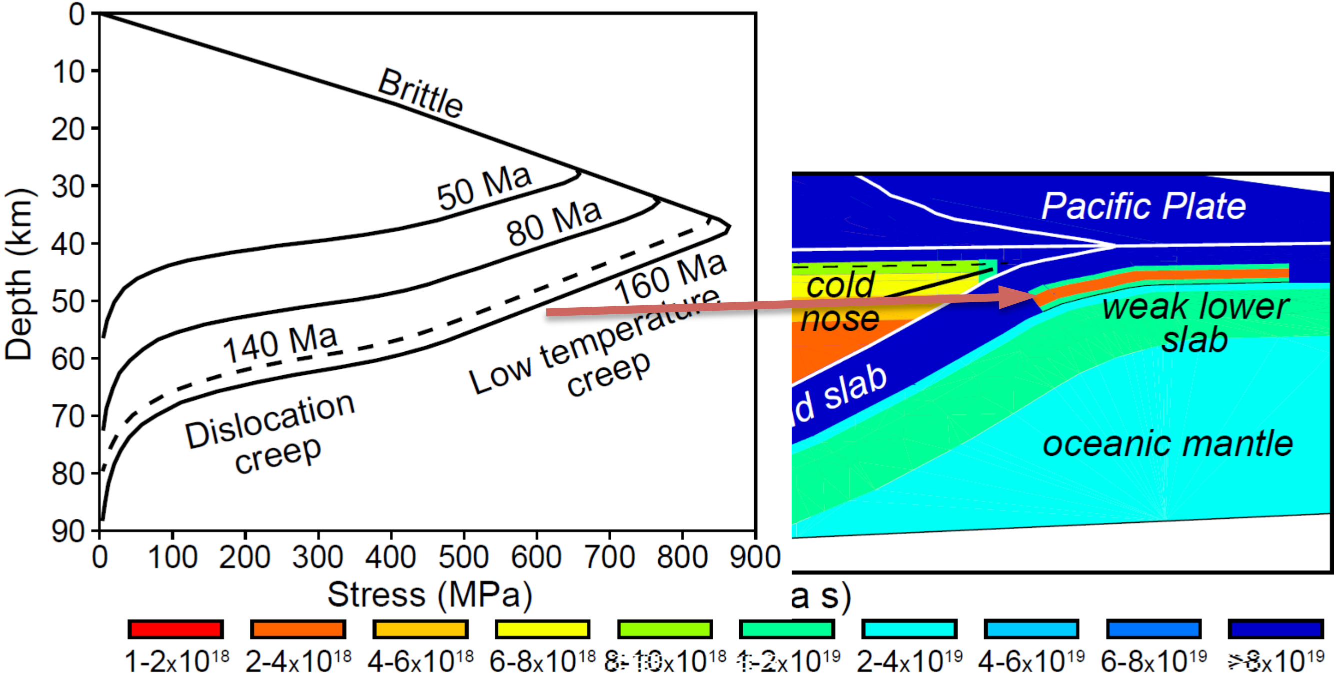




Freed et al. (2016), cf. Wu et al. (2015)

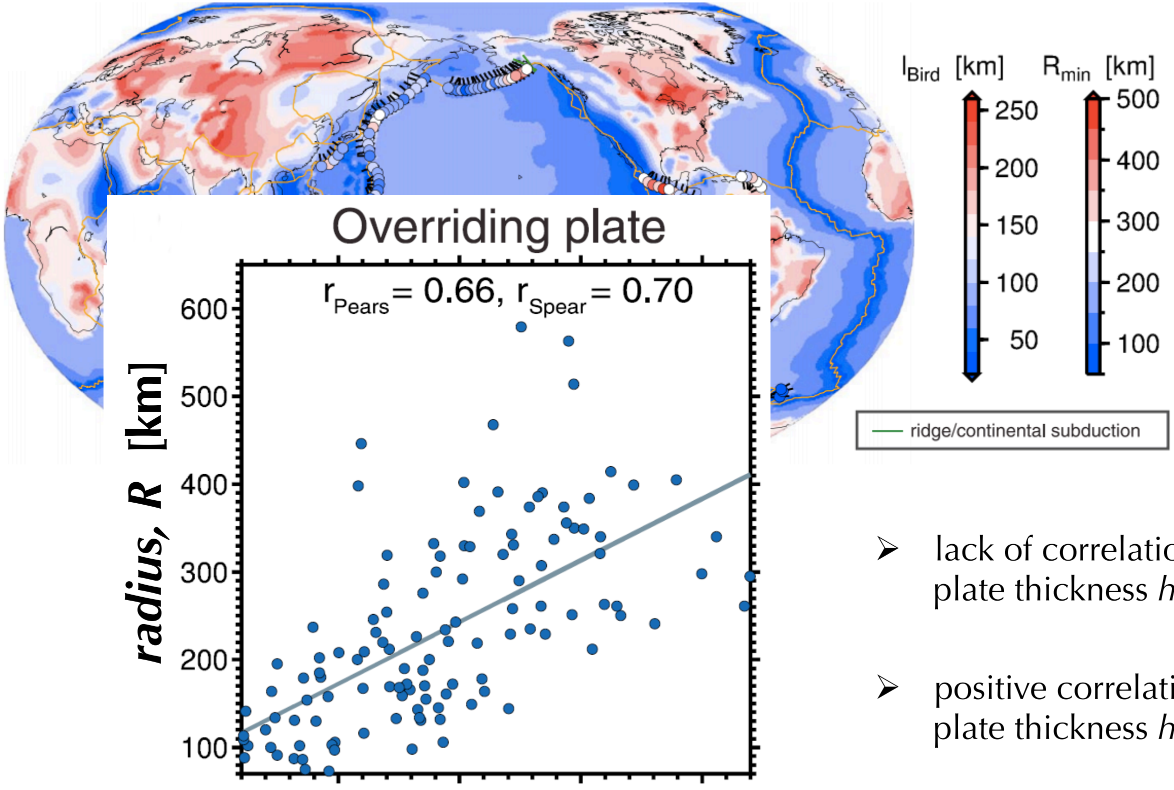
Plastic slab I: Weakening of oceanic plate by Peierls creep?

Buffett and Becker (2012)



Freed et al. (2016)

Plastic slab II: Overriding plate thickness controls bending radius for plastic, not for viscous plate – Earth behaves like that



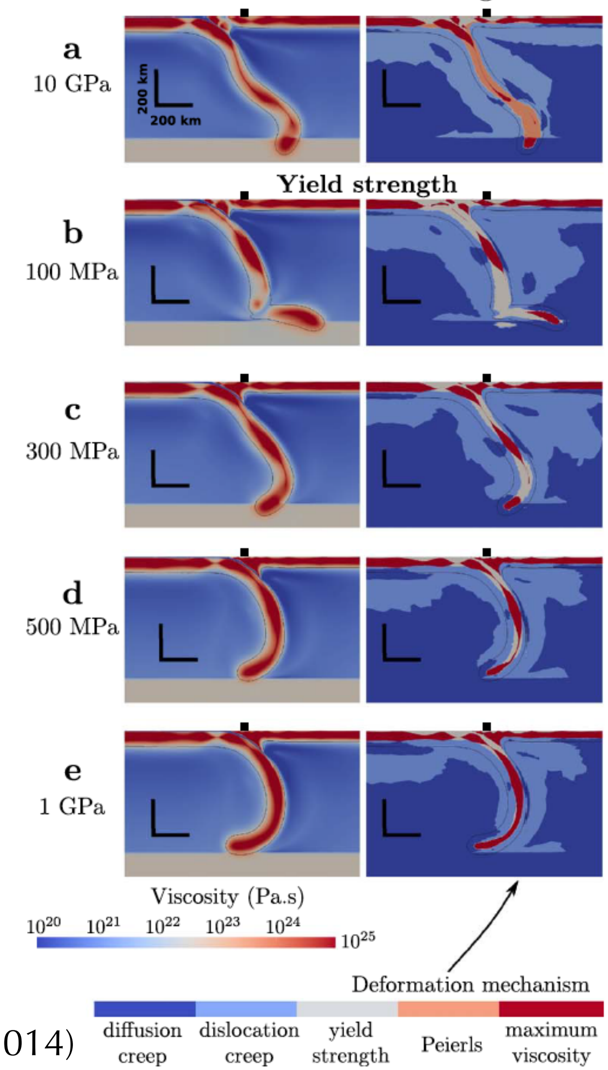
***overriding plate thickness, h_{OP}* [km]**

- lack of correlation between subducting plate thickness h_{SP} and radius R
- positive correlation between overriding plate thickness h_{OP} and radius R

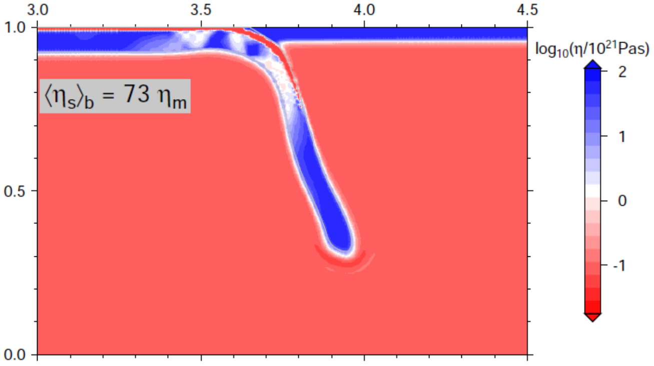
Holt et al. (2015), cf. Buffett and Becker (2012)

Annoyance III: Subduction with plastic rheology

- significant oceanic plate viscosity reduction, perhaps $\eta_{slab} \sim 100\ \eta_{upper\ mantle}$

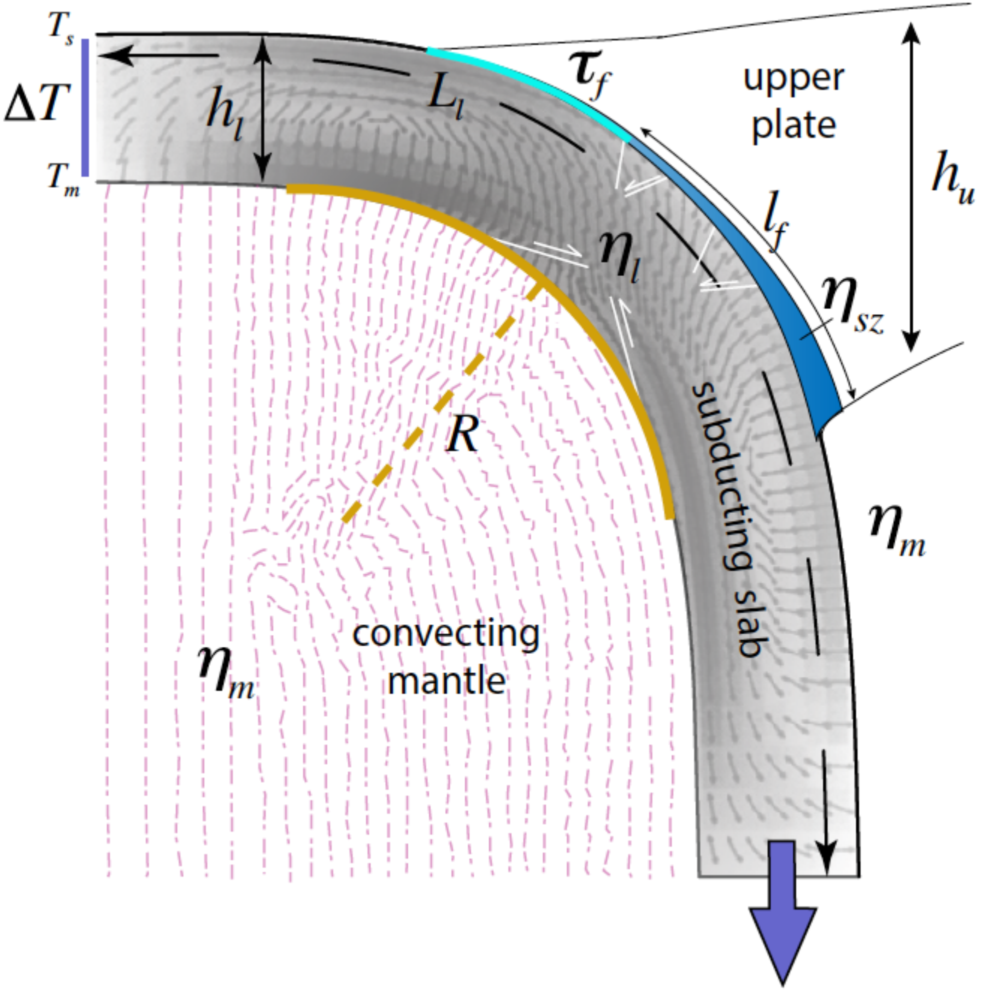


Garel et al. (2014)



Holt et al. (2015)

Work balance: viscous dissipation vs. potential energy release



slab sinking due to thermal density contrasts

shear resistance along slab interface

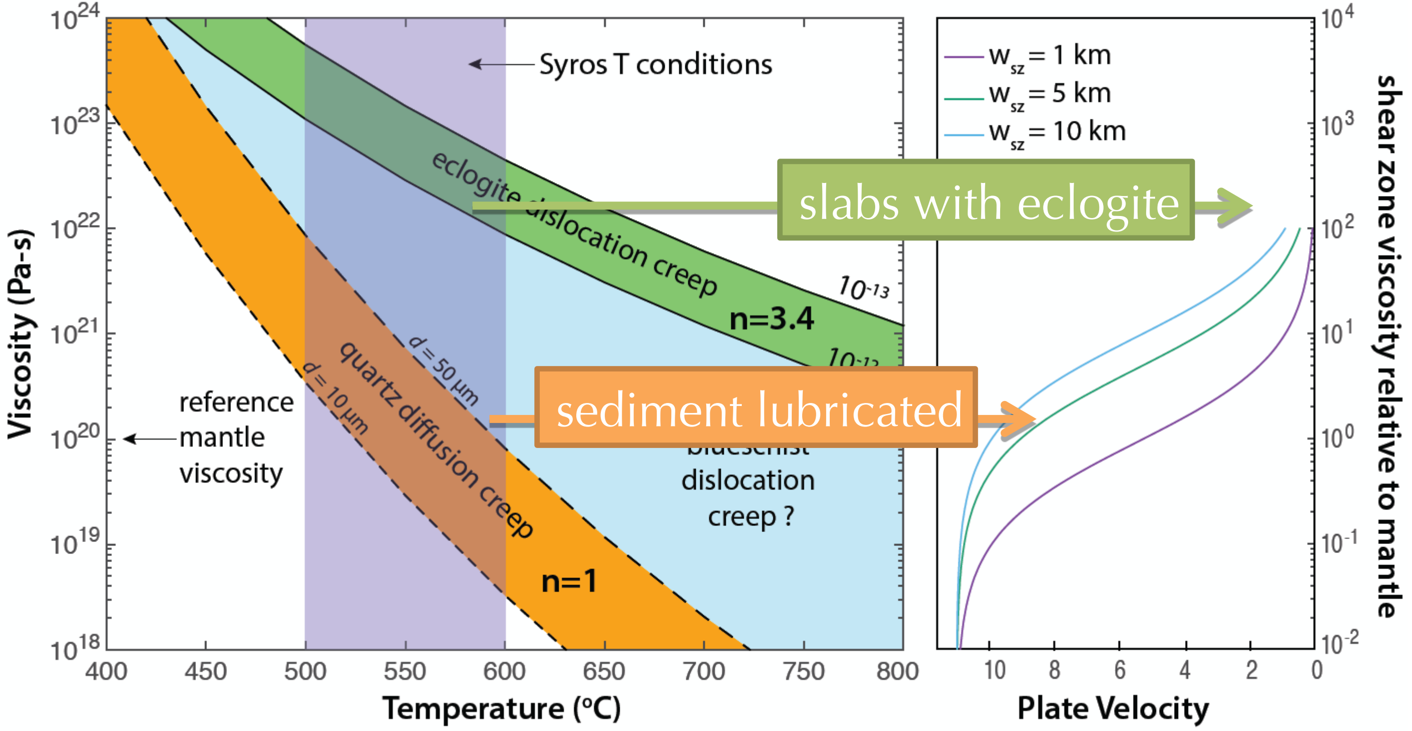
$$V_p = \frac{C_s \rho g \alpha \Delta T l_s h_s - C_f \tau_f l_f}{3\eta_m (A + C_m) + C_l \eta_l (h_l / R)^3}$$

dissipation into convecting mantle

dissipation into slab due to bending

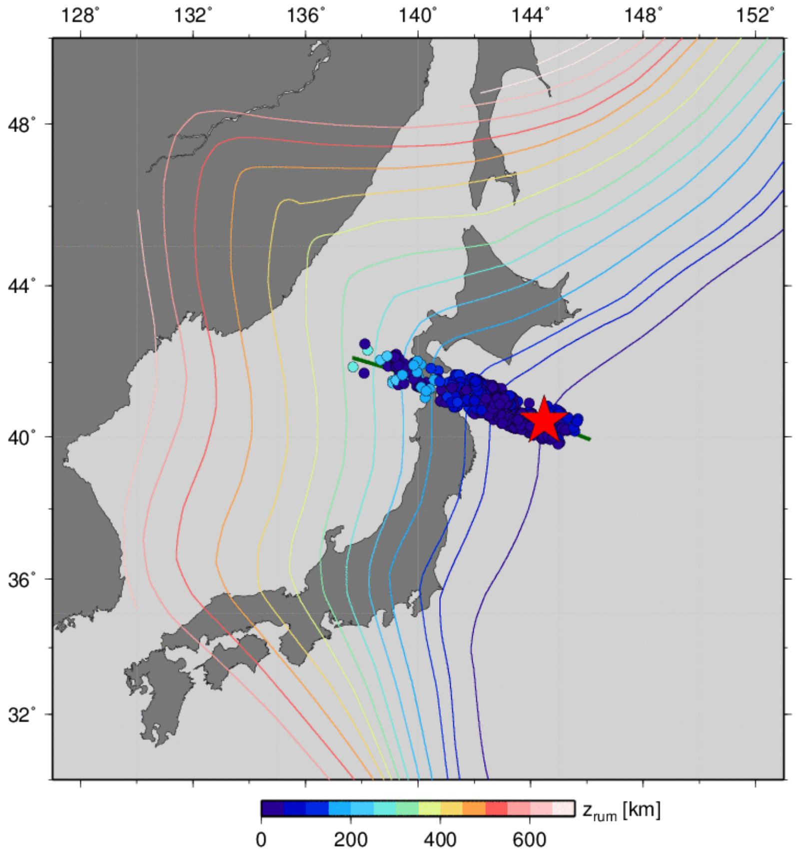
modified from Conrad and Hager (1999)

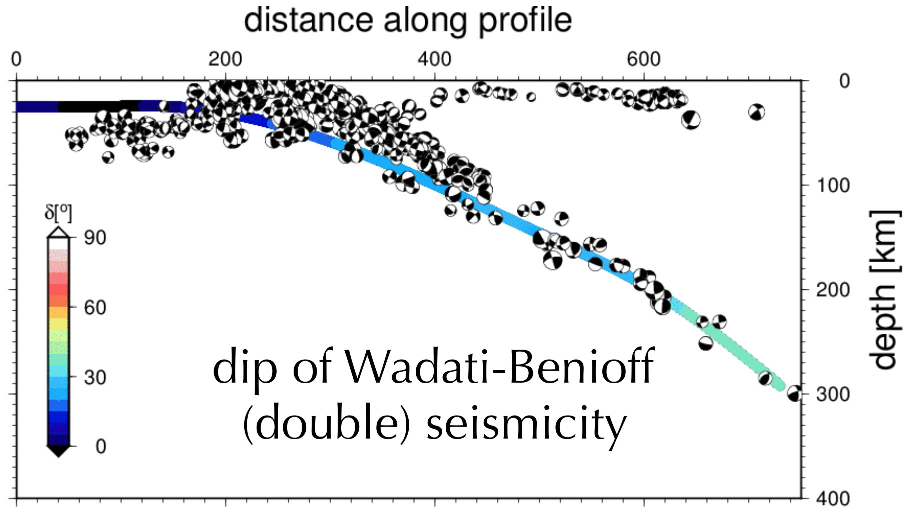
Annoyance IV: Interface (i.e. geology) control on plate velocities (continental erosion, long term cycles)?

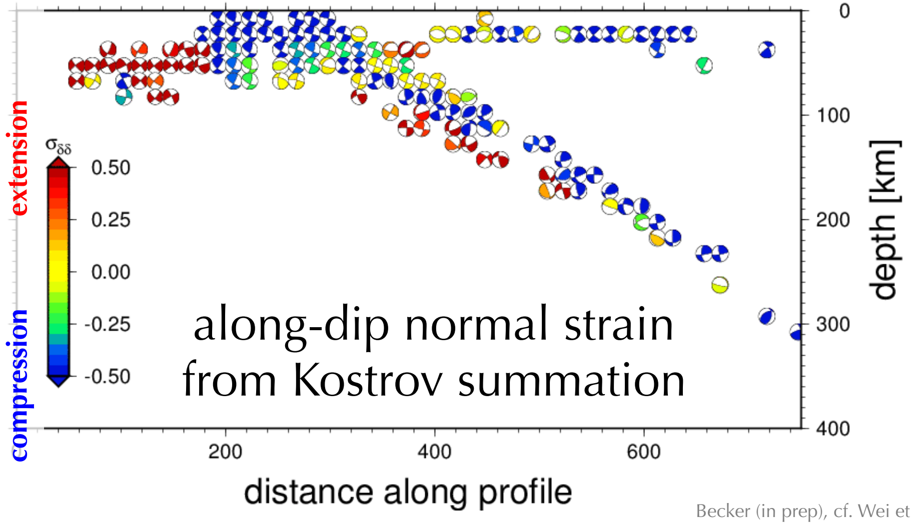


Behr and Becker (in prep.), cf. Buffett and Becker (2012)

Regional CMTs (F-Net)

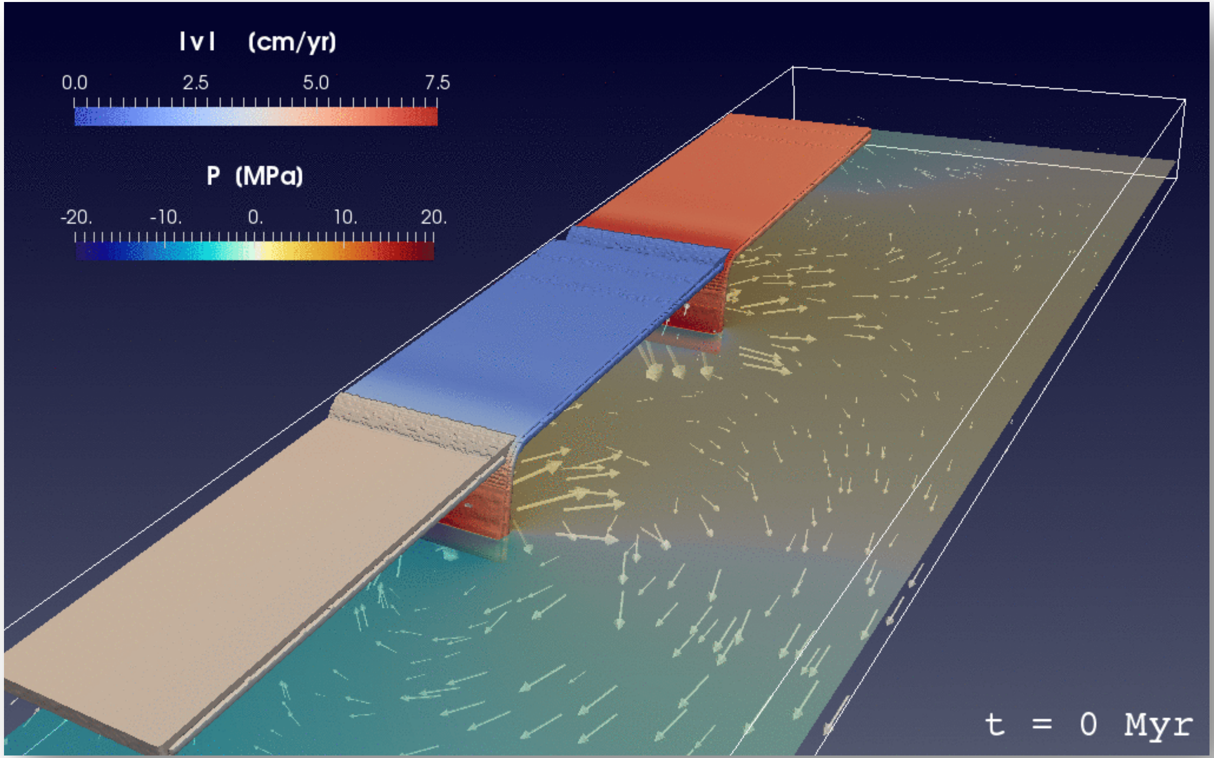






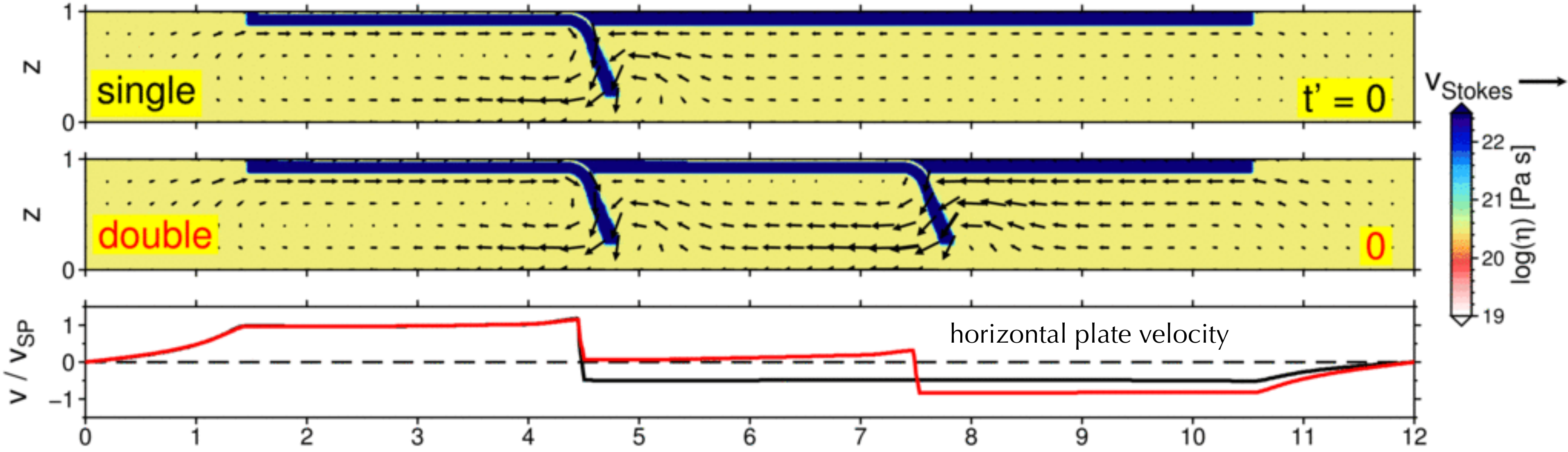
Becker (in prep), cf. Wei et el. (2017)

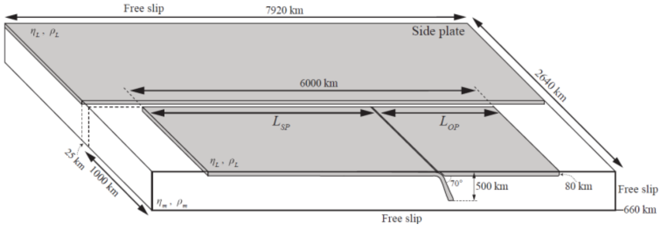
Slab – slab interactions



Holt et al. (2017)

Trench motions for slab – slab interactions



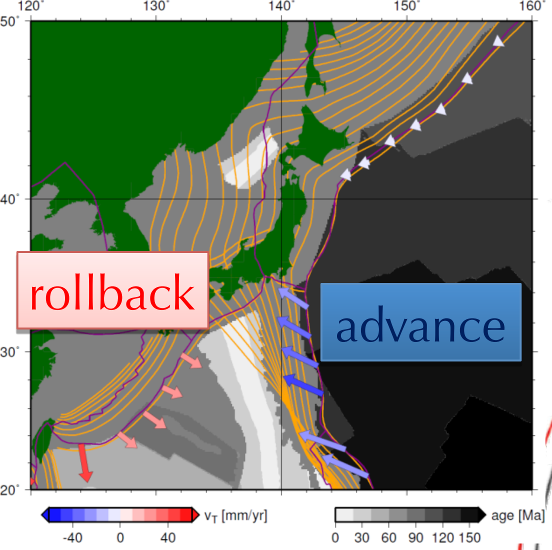


1 + 1 ~ 2

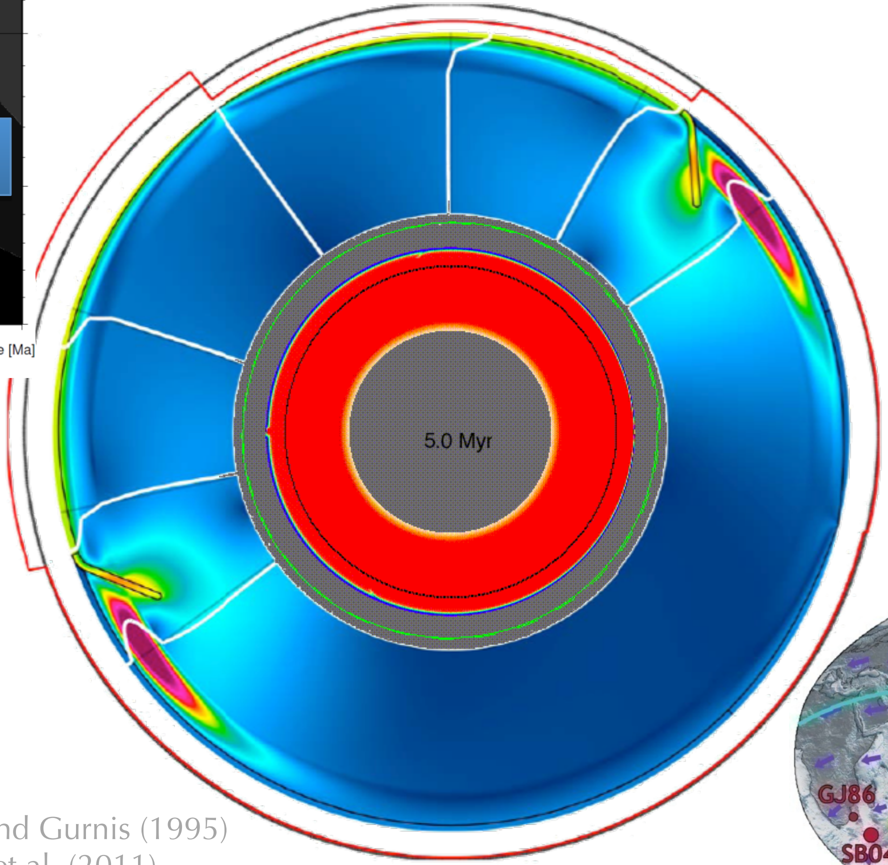
Holt et al. (2017)

cf. Cizcova and Bina (2015); Jagoutz et al. (2015); Faccenna et al. (submitted)

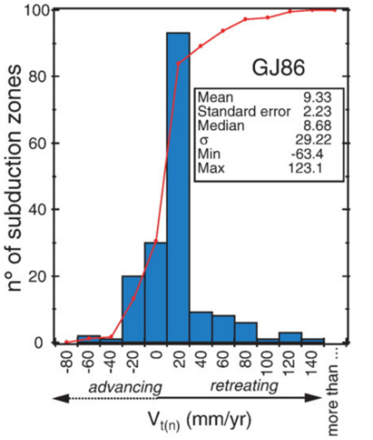
Global interactions:
Trench motions and reference frames



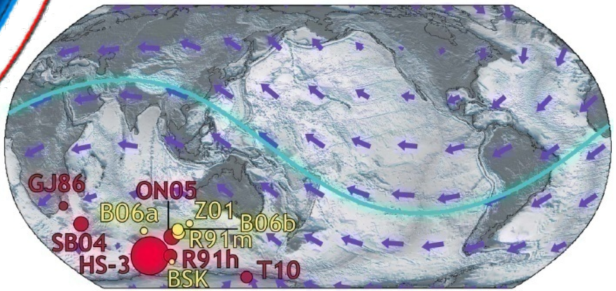
Becker et al. (2015)



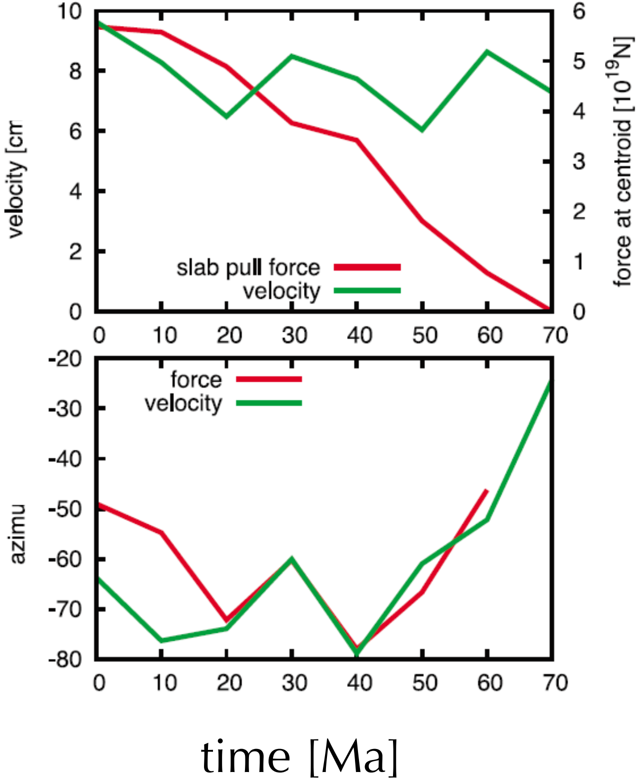
Zhong and Gurnis (1995)
Gerault et al. (2011)

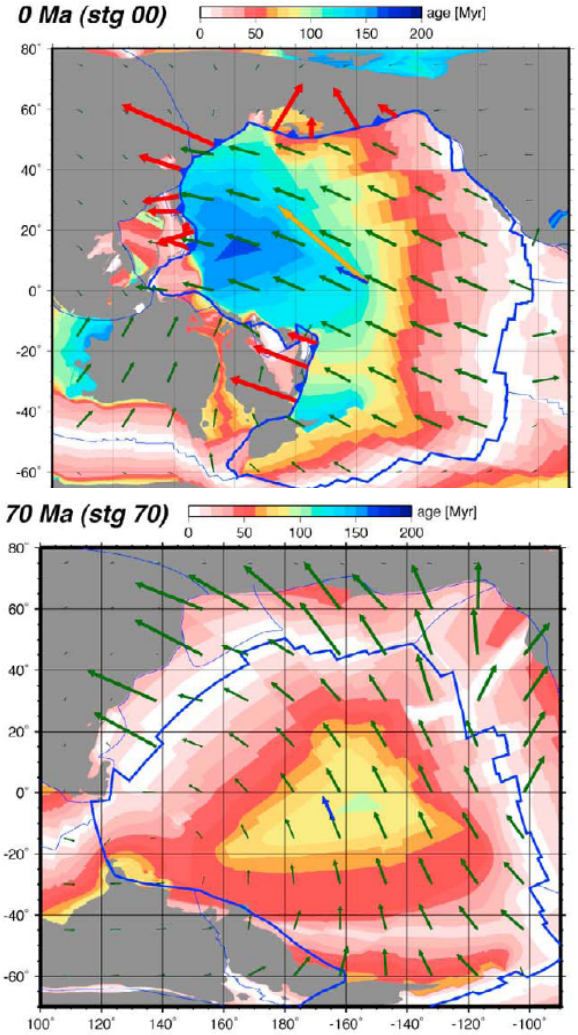


Funiciello et al. (2008)



Upper mantle slabs are not the whole story…

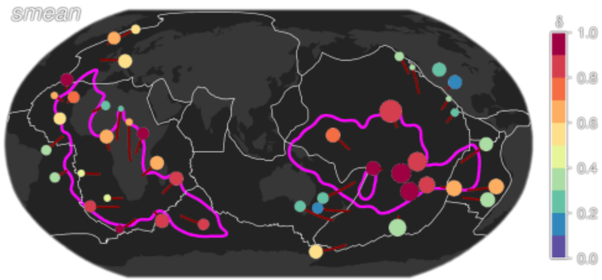




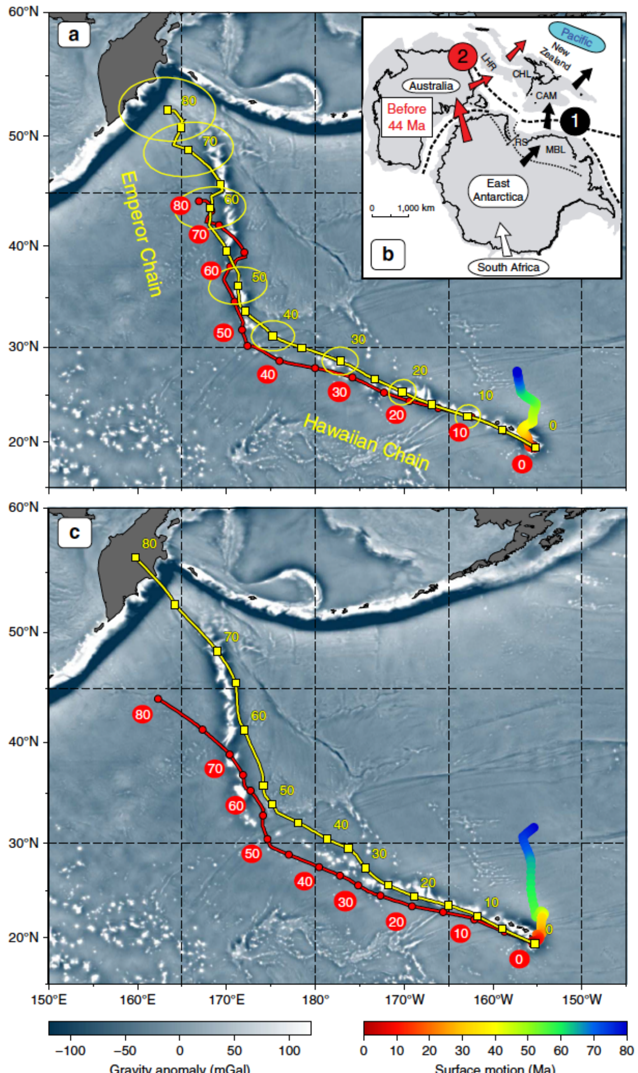
Faccenna et al. (2011)
cf. Gordon

How about plumes?

- ➢ Did the plumes or the plates move to cause hotspot track bends?
- ➢ Can we predict plume conduits?

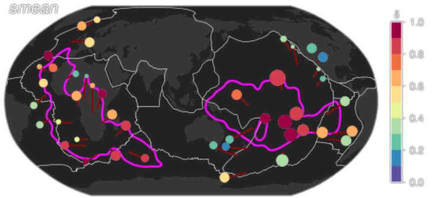


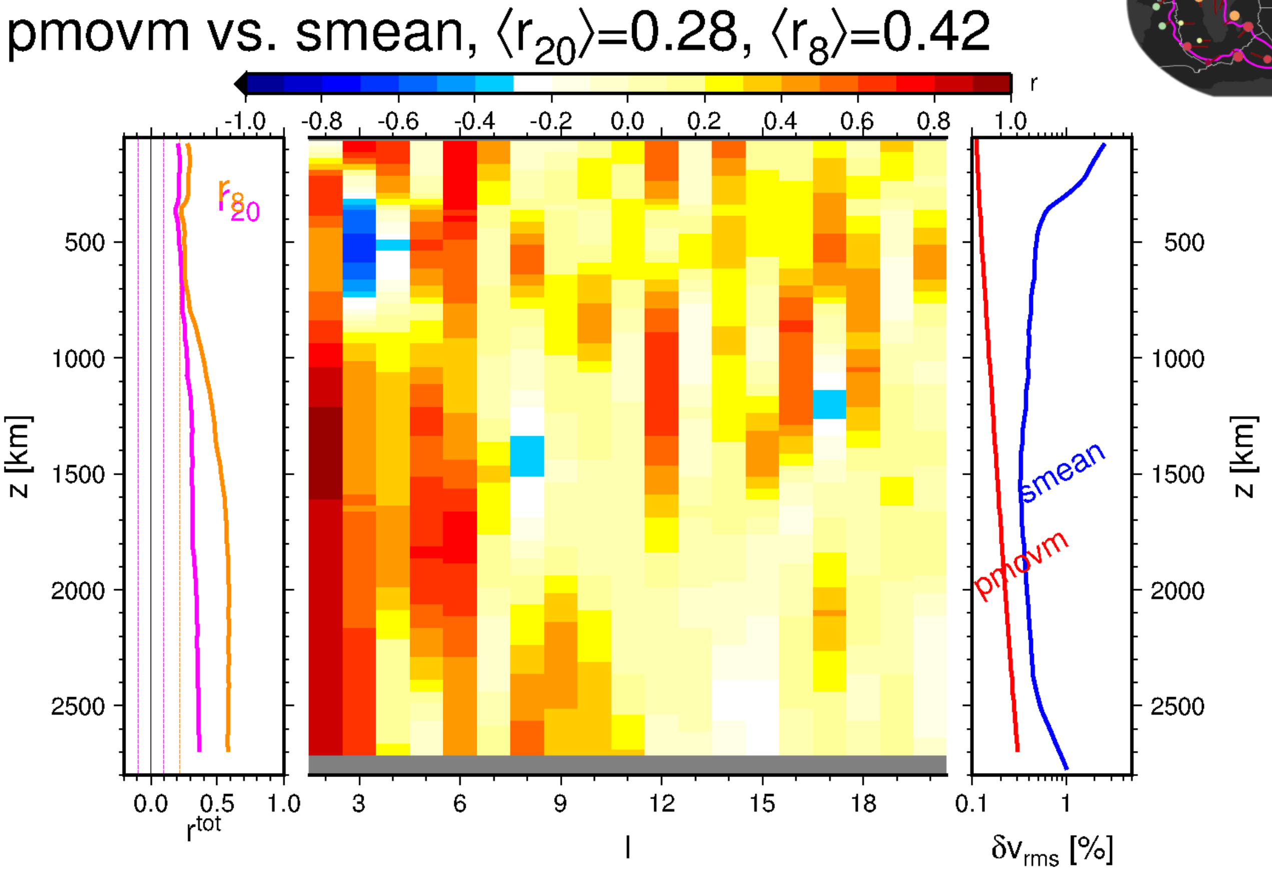
Torsvik et al. (2017)



cf. Steinberger (2000); Tarduno et al. (2009); Hassan et al. (2016)

Advected plumes vs. tomography

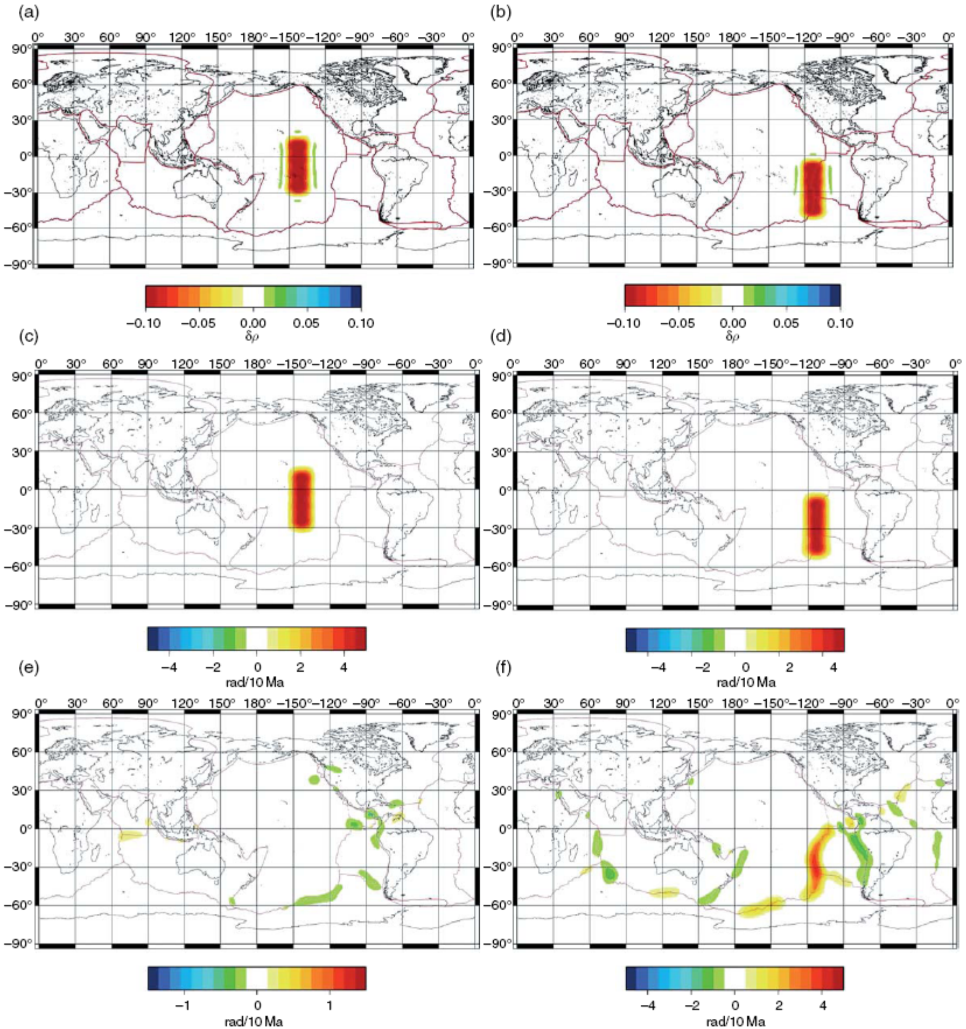




- correlation with *moving* plume conduits ~better than with slabs (r_8 ~ 0.5 for slabs and plumes)

Boschi et al. (2007, 2008)

Plumes as plate driving forces



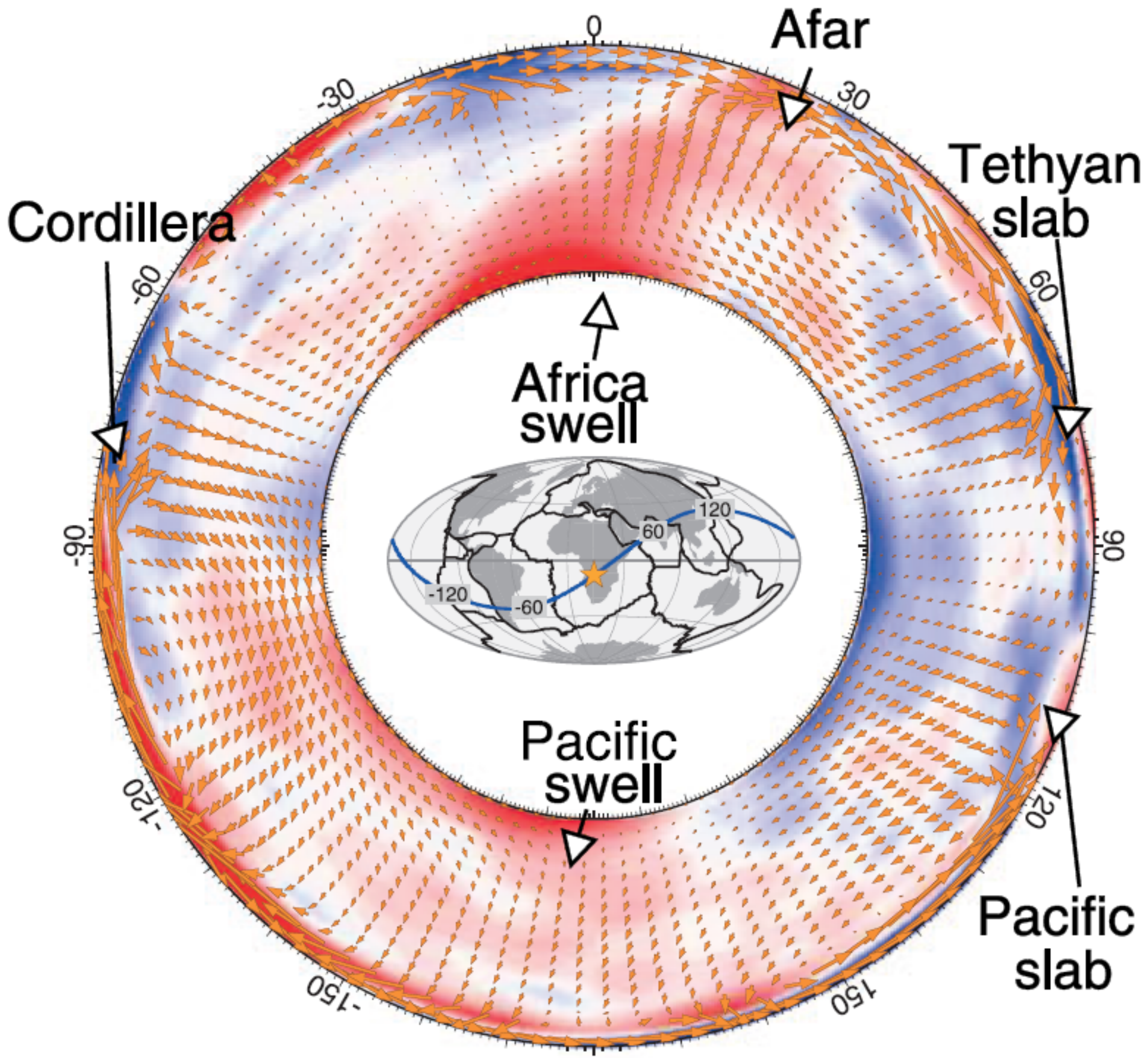
Two density sources

Free-slip solution (poloidal only)

Plate solution (poloidal only)

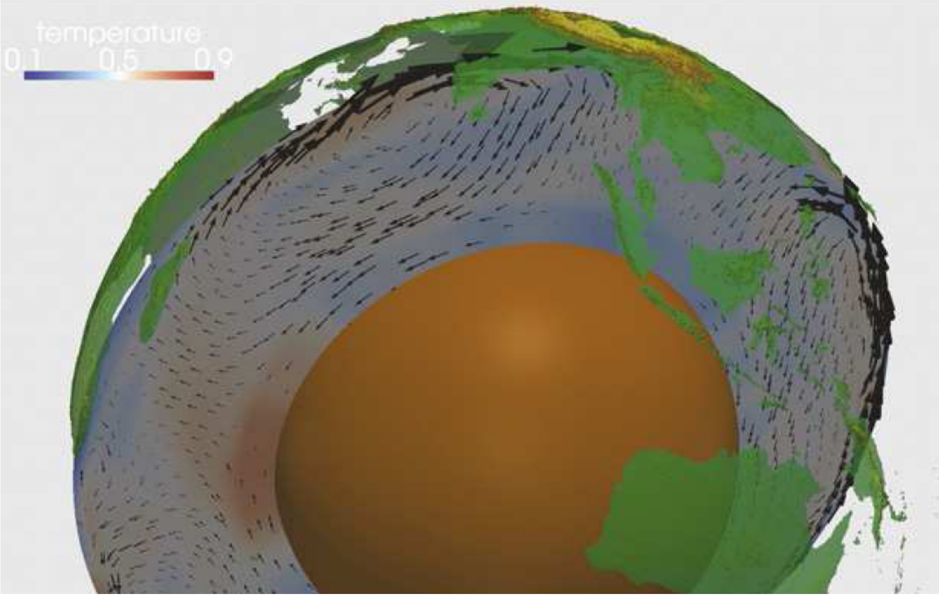
Forte (2015)

Mantle conveyor belts

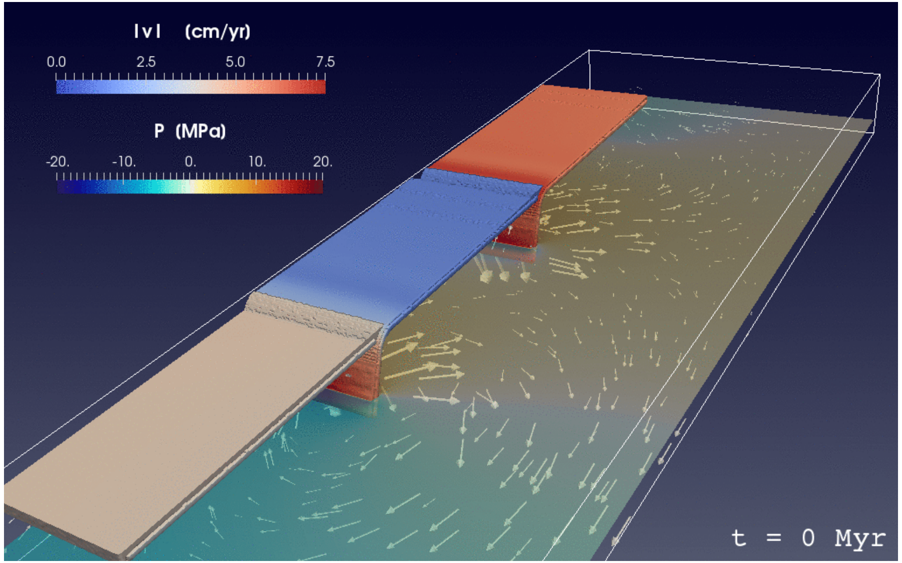


Faccenna et al. (2013)

India’s motion at present:
Mantle conveyor belt,
broad-scale upwelling push?



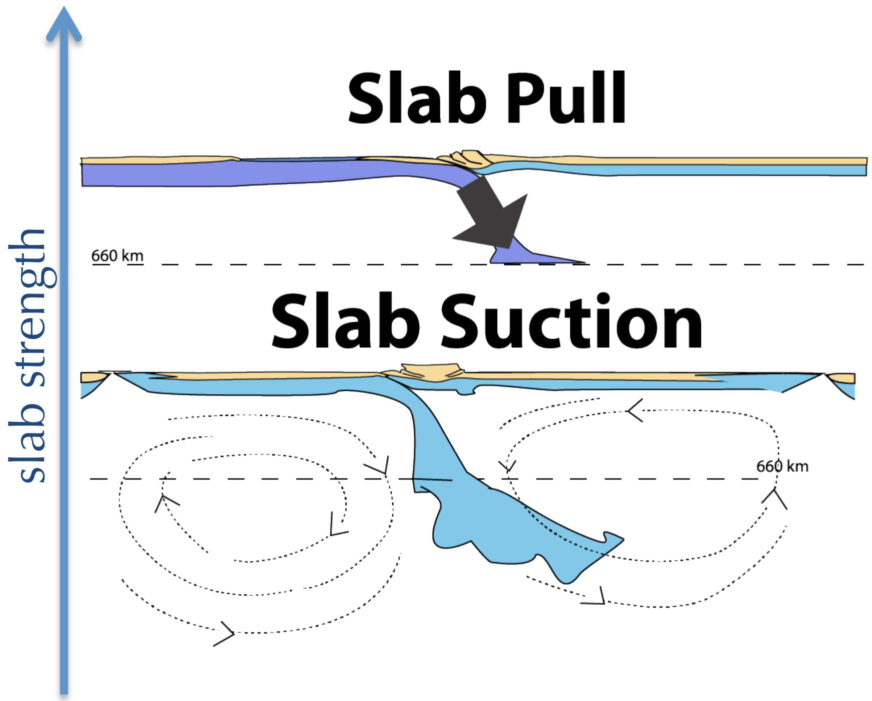
Becker and Faccenna (2011)

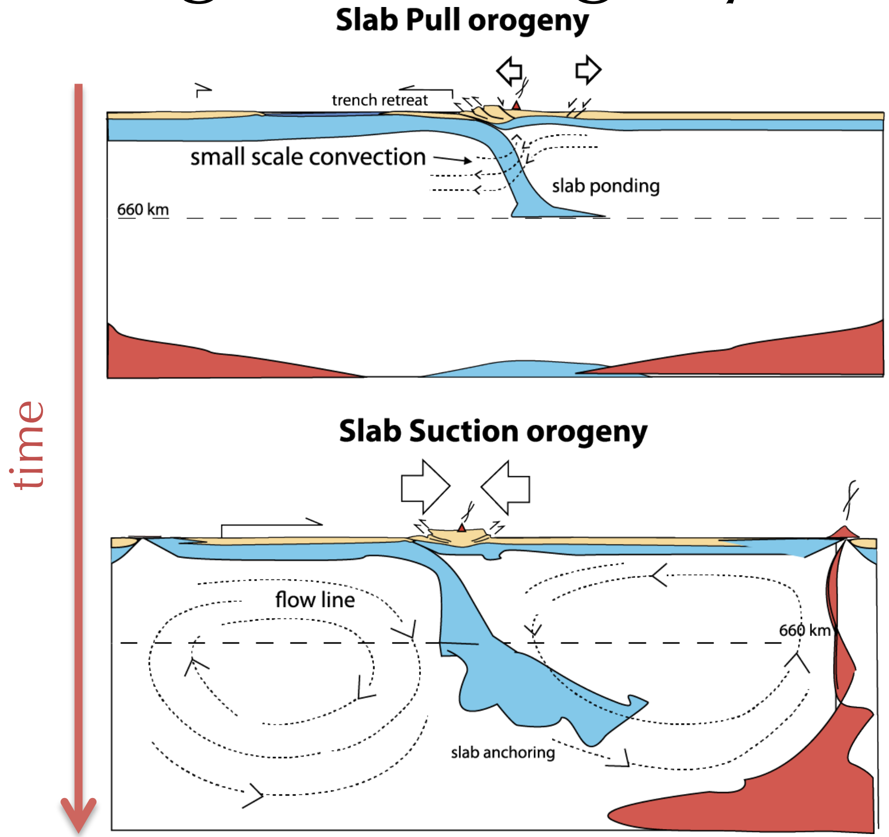


Jagoutz et al. (2015); Holt et al. (2017)

India’s motion in the past:
Double slab dynamics?

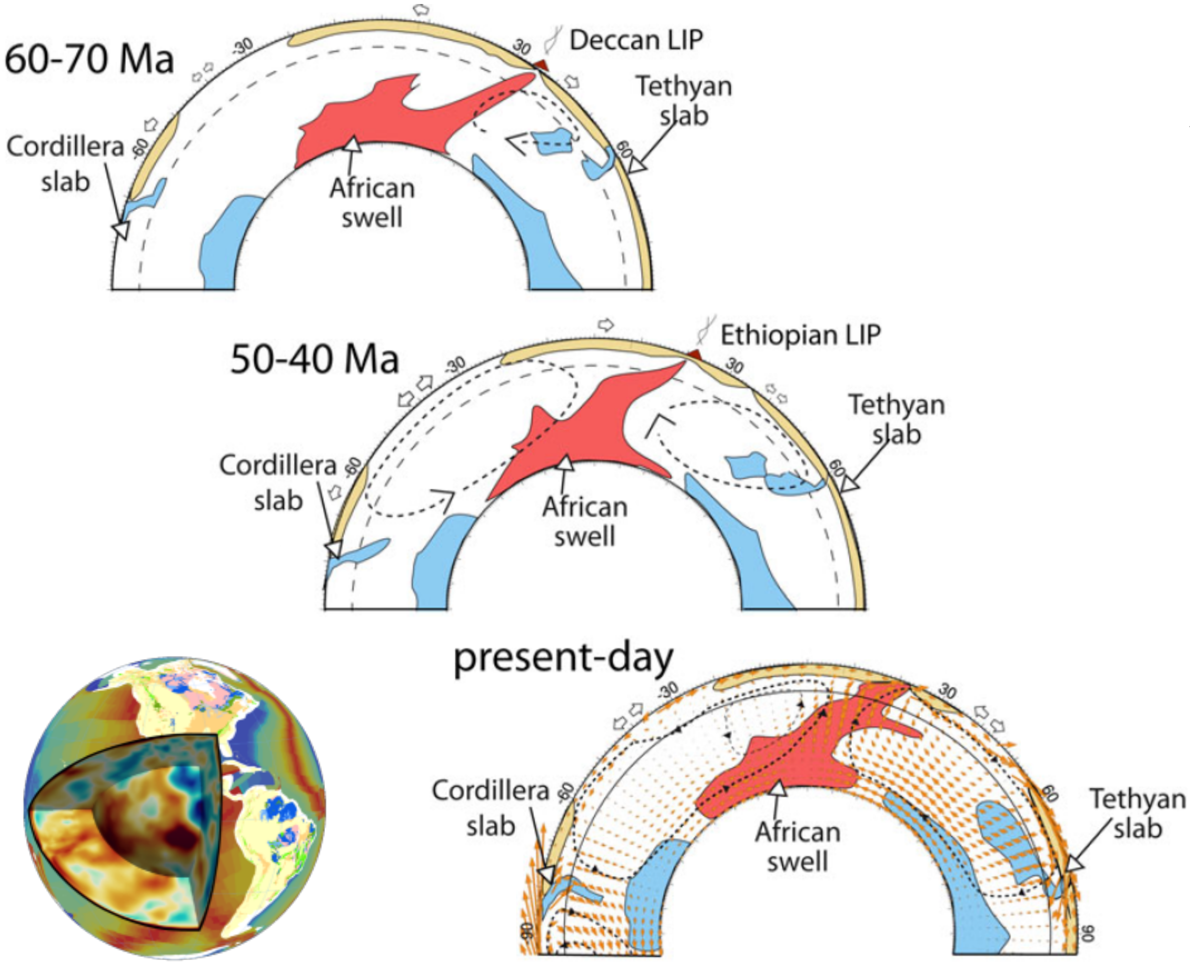
Link between mantle forcing and orogeny

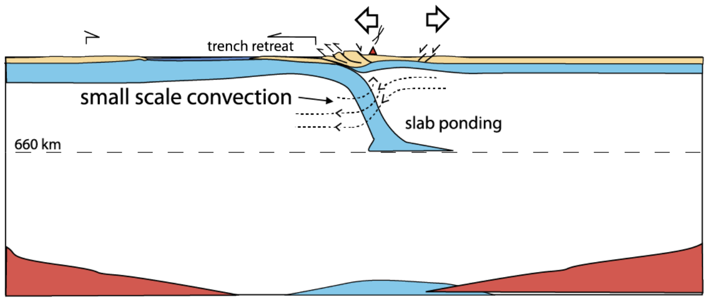


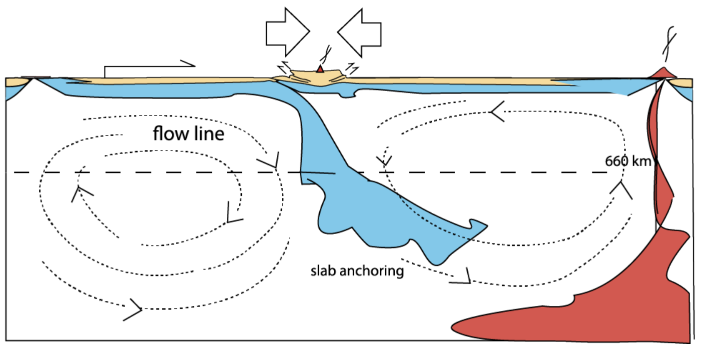


Faccenna et al. (2013); Yamato et al. (2013)

Tibetan orogeny linked to establishment of whole mantle convection cell

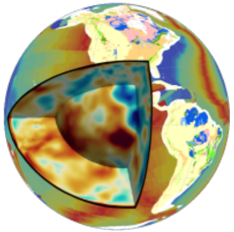




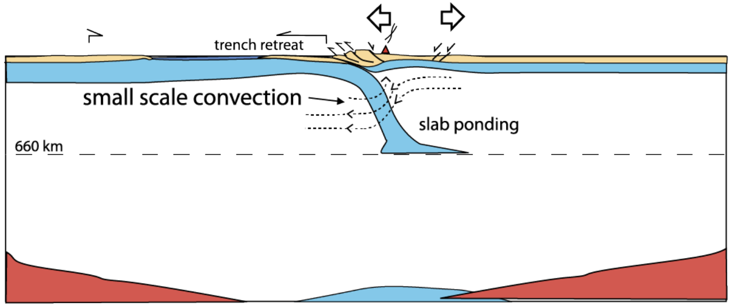


Faccenna et al. (2013)

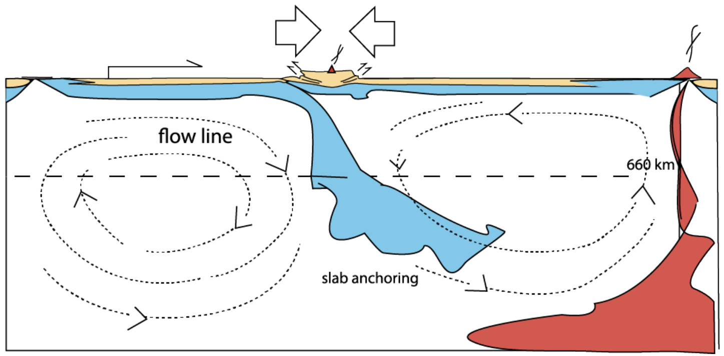
Subduction and orogeny: links between convection and continental geology (Andes)



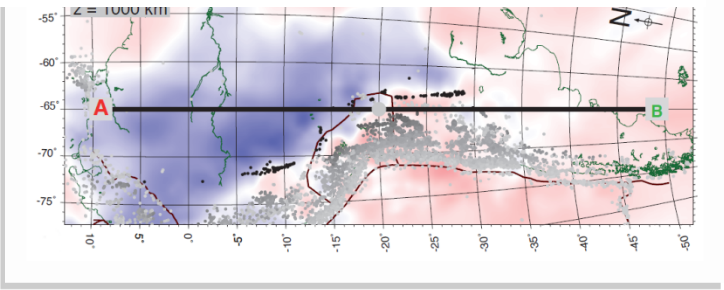
Slab Pull orogeny

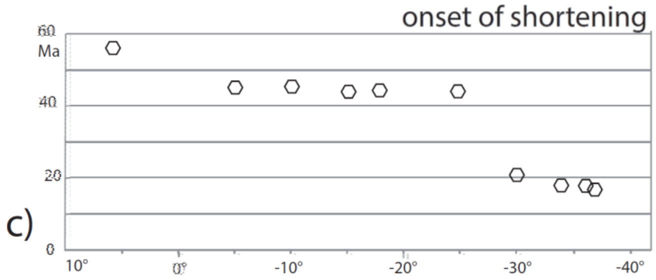


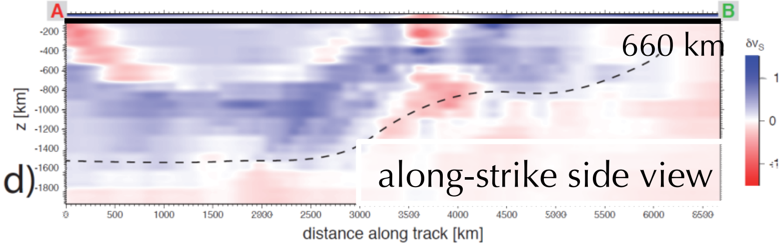
Slab Suction orogeny



map view of seismic tomography under Andes







Faccenna et al. (2017)

Mantle convection

- energy equation governs planetary heat loss
- introduces time-dependence and non-linearity (coupling between velocity and temperature)
- can time reverse advection, but not diffusion

conservation of momentum

$$\frac{\partial \sigma_{ij}}{\partial x_j} = -Ra\tilde{T}\delta_{ir} - Ra_C\tilde{C}\delta_{ir}$$

constitutive law

$$\sigma_{ij} = -p\delta_{ij} + 2\eta(\sigma, T, d, H_2O, \varepsilon)\dot{\varepsilon}_{ij}$$

conservation of mass

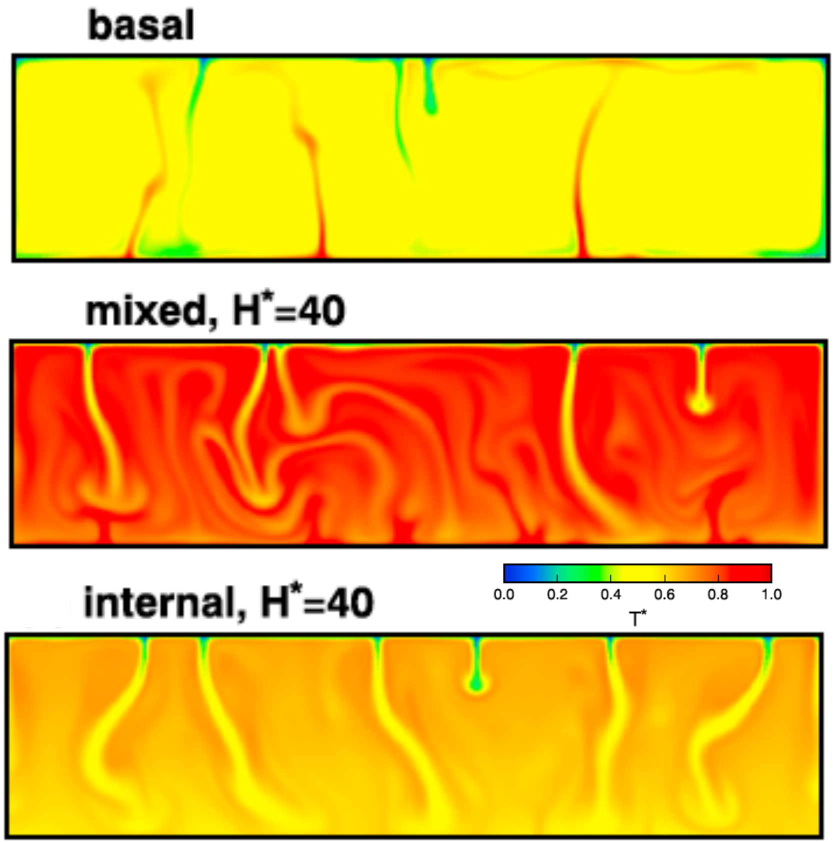
$$\frac{\partial v_i}{\partial x_i} = 0$$

conservation of energy

$$\frac{\partial T}{\partial t} = -v_i\frac{\partial T}{\partial x_i} + \kappa\frac{\partial^2 T}{\partial x_j \partial x_j} + H$$

advection — diffusion — heat generation

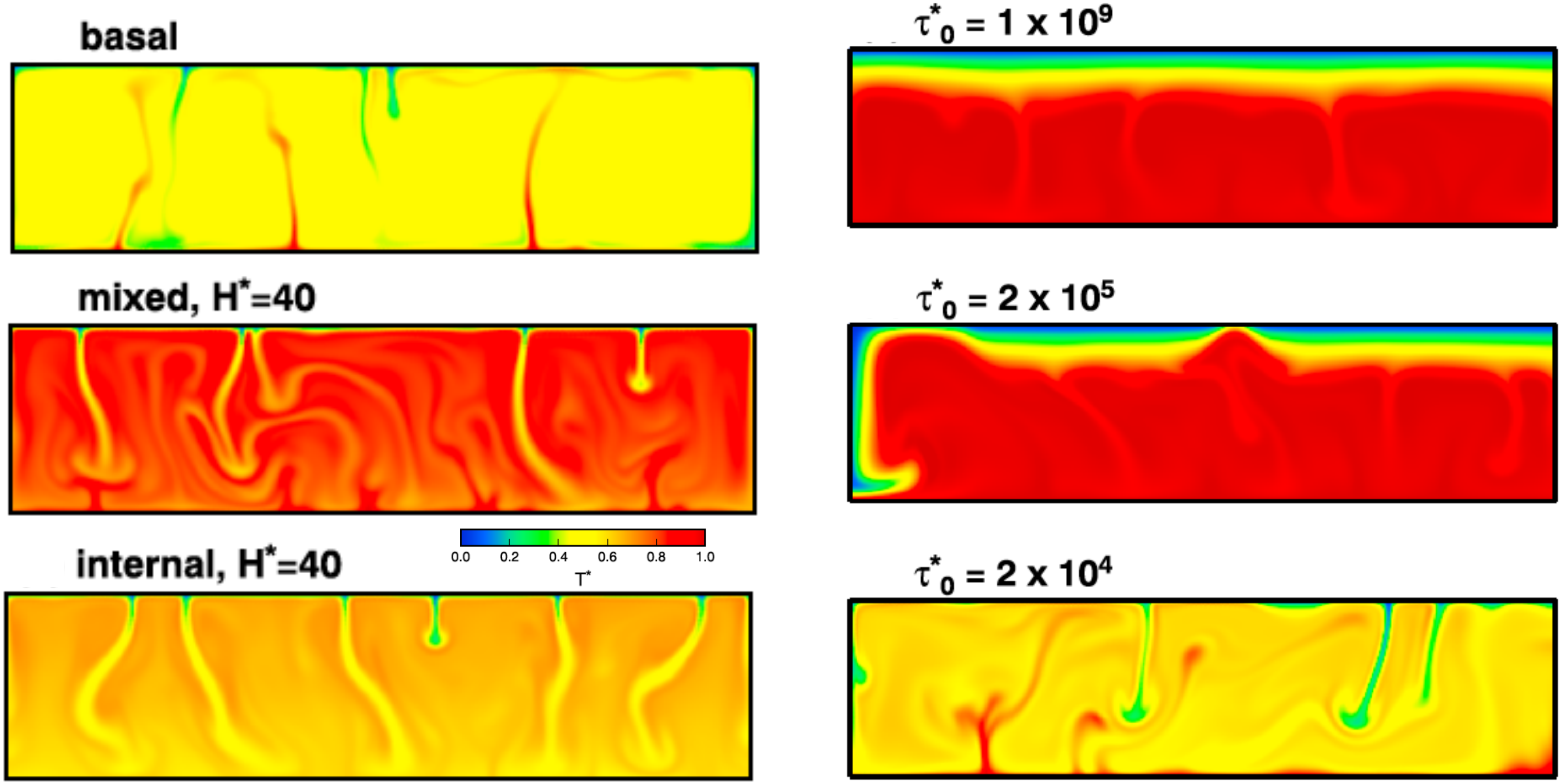
Slabs are part of heat transport – effect of heating mode isoviscous fluid



Korenaga (2017)

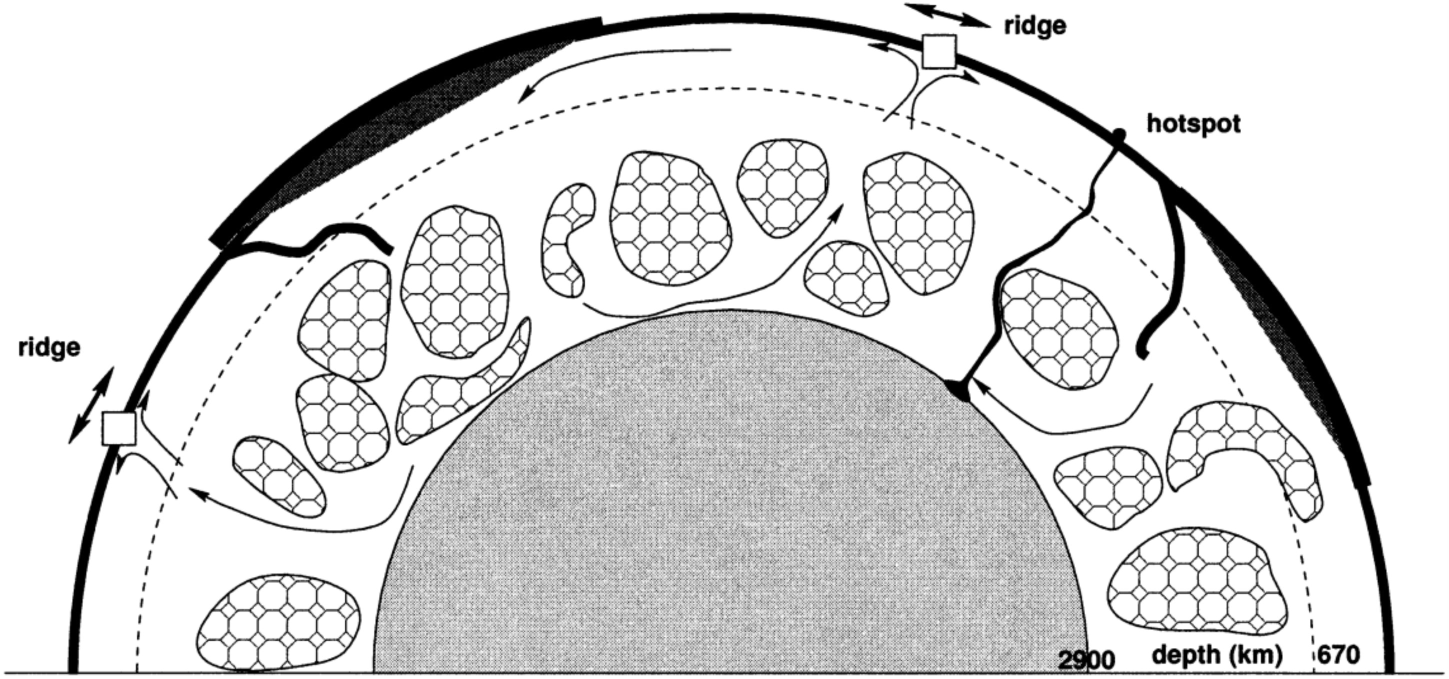
Slabs are part of heat transport – effect of heating and plate mode

isoviscous $\eta(T)$ + yielding (mixed heating)



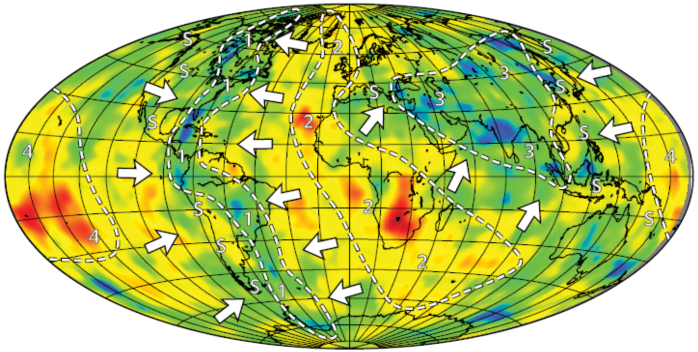
Korenaga (2017), cf. Foley and Becker (2009)

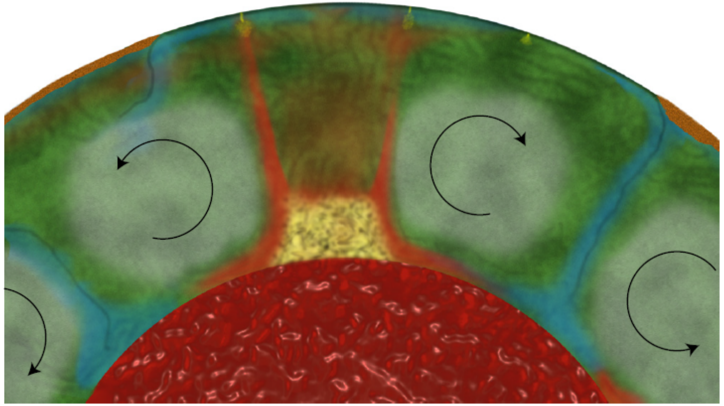
The role of viscous blobs and other (e.g. LPO induced) mechanical anisotropy for convective stability

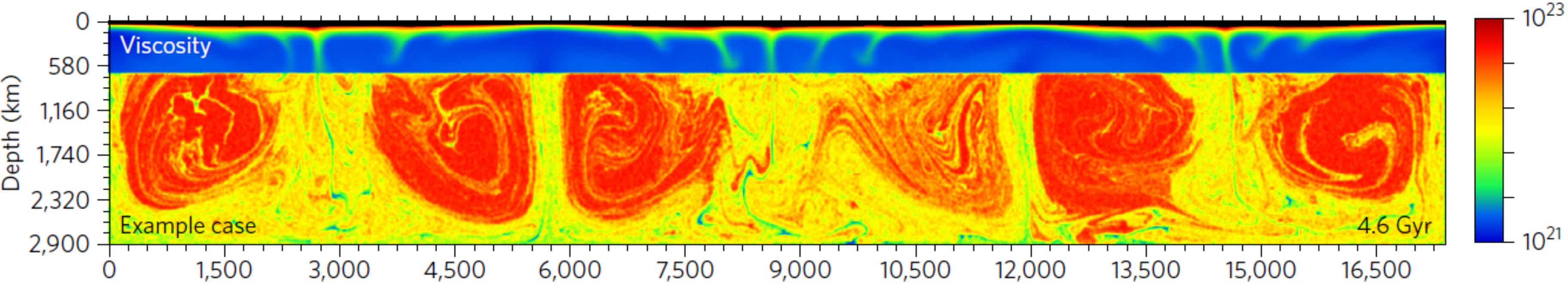


Becker et al. (1999), cf. Manga (1996)

BEAMs stabilizing conveyor belts?

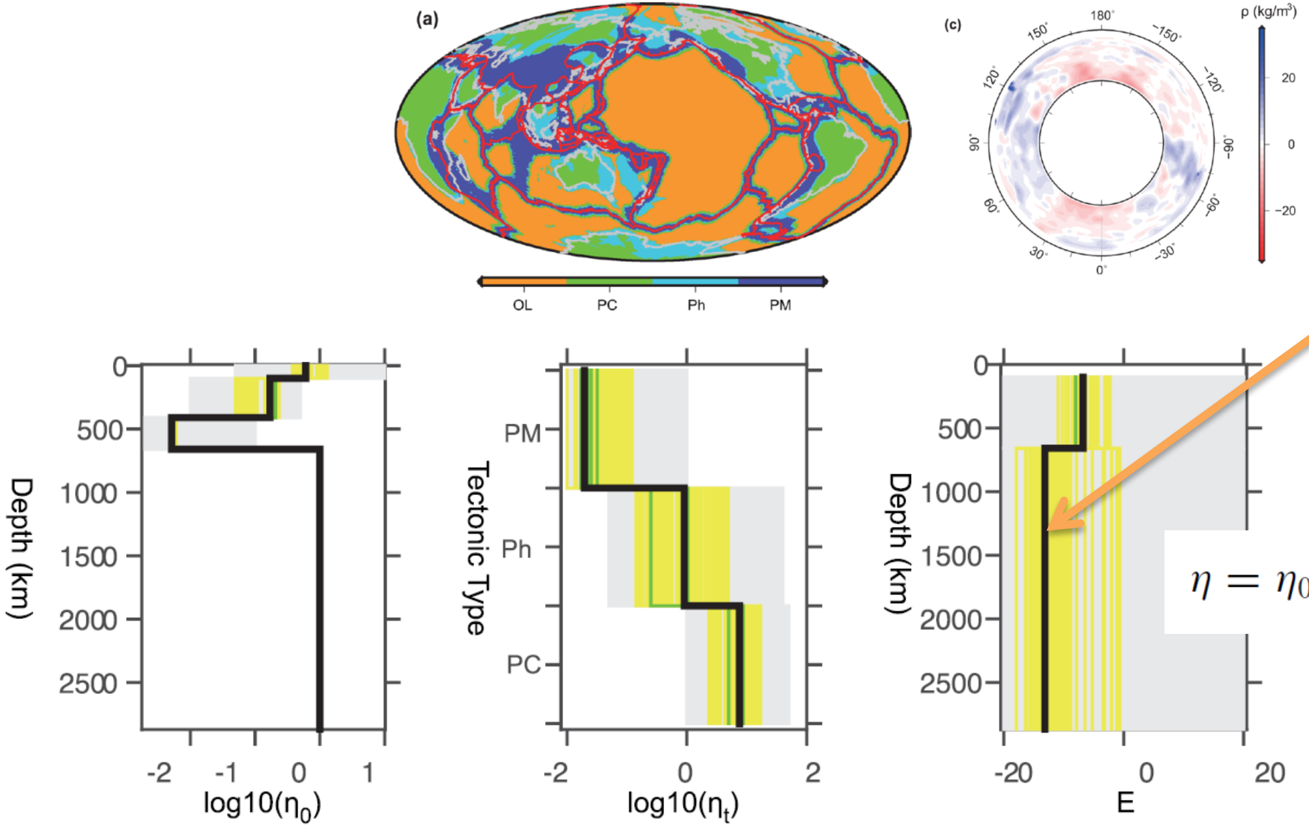






Ballmer et al. (2017)

Inversions for lateral viscosity variations



inverse temperature dependence of viscosity

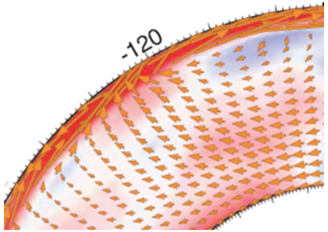
$$\eta = \eta_0 \eta_t f\left(\varepsilon_{\amalg}\right) \exp\left[-E\left(T - T_0\right)\right]$$

Yang and Gurnis (2016)

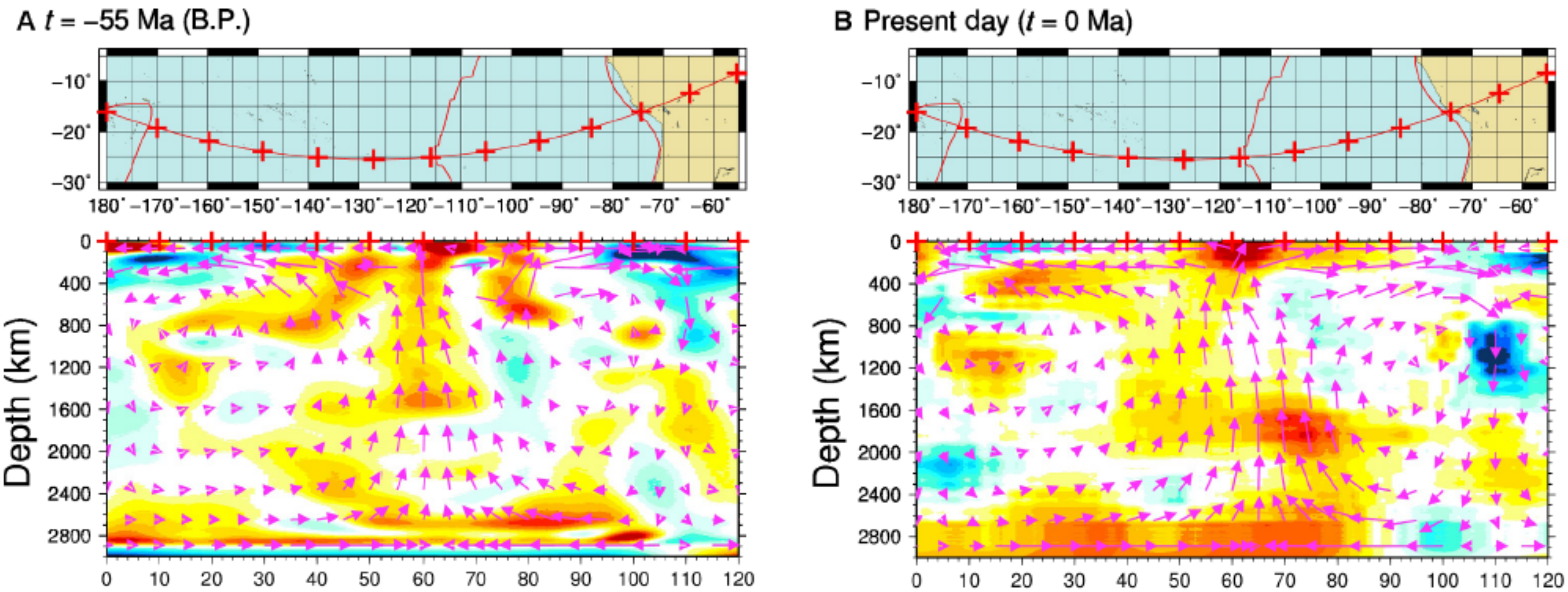
Conclusions

- subduction controls tectonics (including orogeny) and heat loss (by setting mantle convection's spatio-temporal scales)
  - subduction interface may affect plate velocities in a weak slab world
- potential links between continental dynamics and deep mantle may help decipher planetary evolution
- make progress by integrating diverse datasets in inverse models, e.g. to better constrain mantle and slab rheology
- use tools that capture global, multi-scale interactions of mantle flow for regionally realistic subduction models

Additional slides



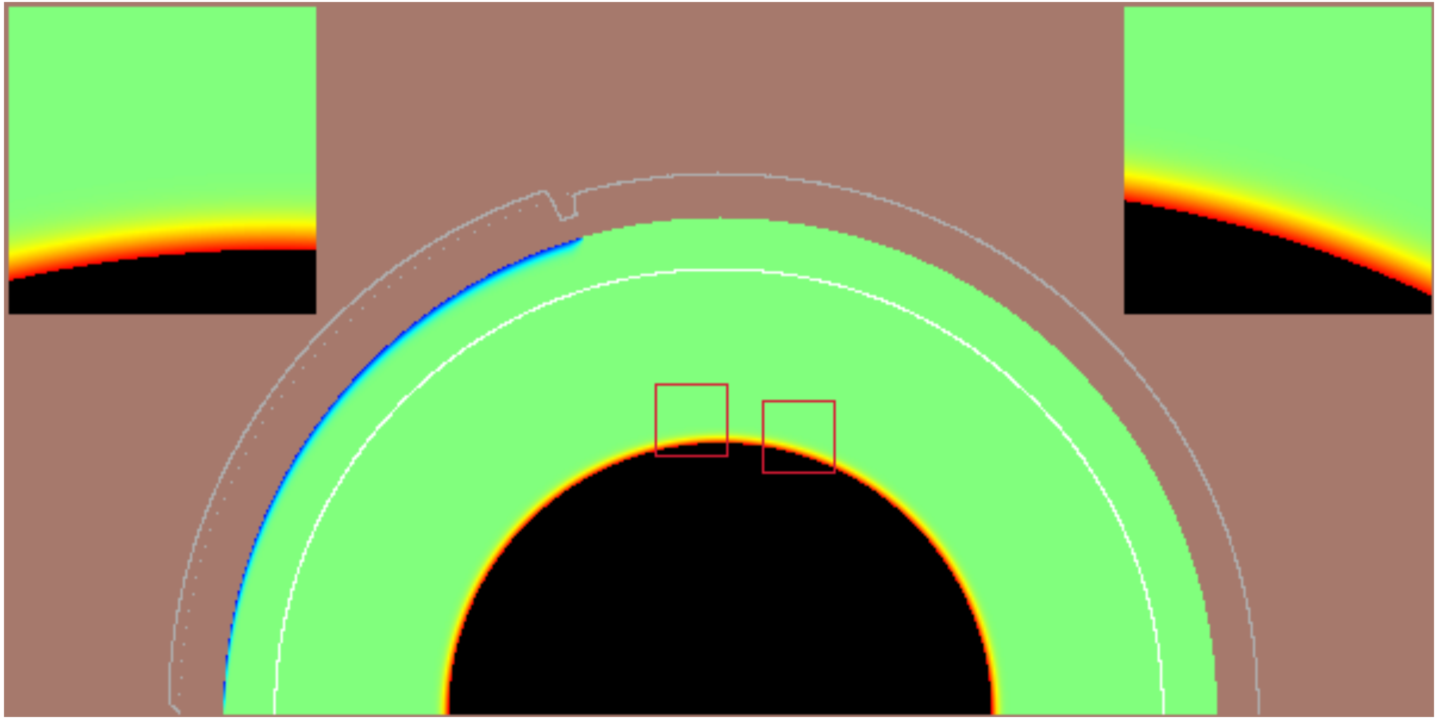
Persistence of upwellings?



- active upwelling underneath East Pacific Rise since 50 Ma?

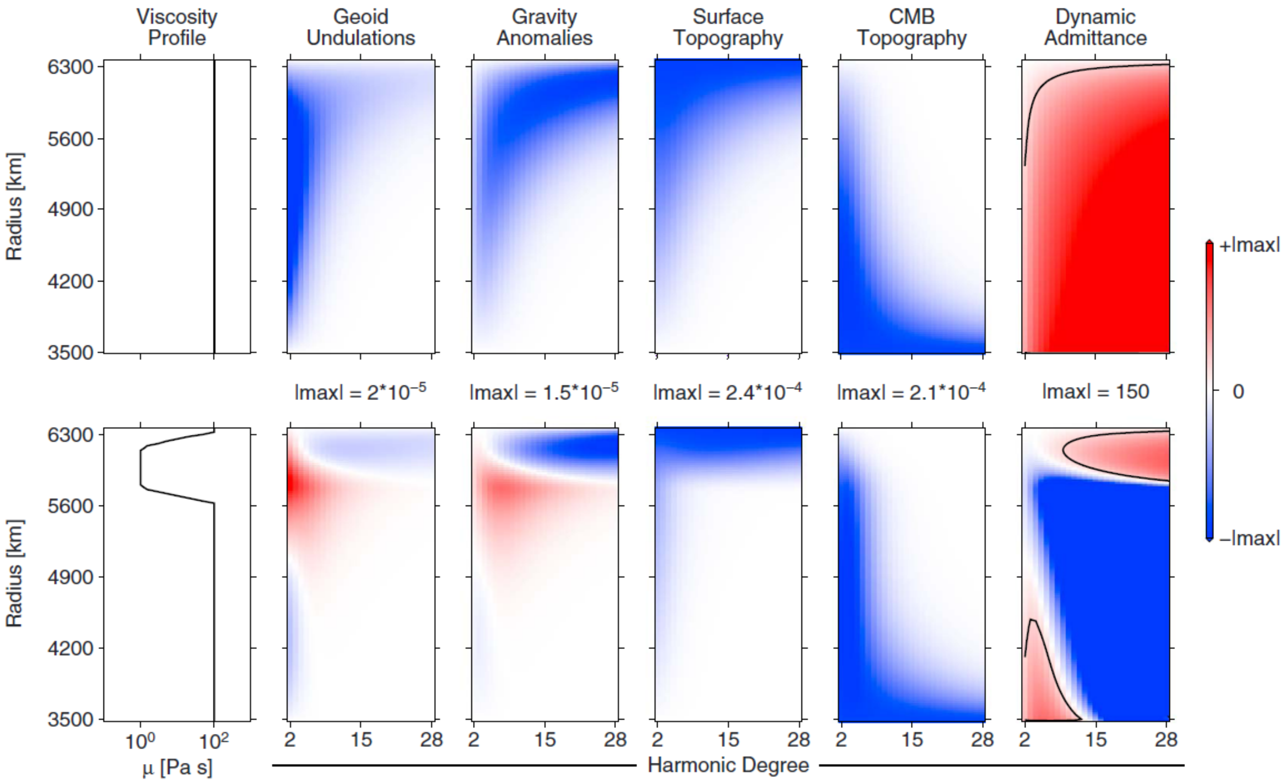
Rowley et al. (2016)

Ying and yang of up and downwellings



Tan et al. (2001)

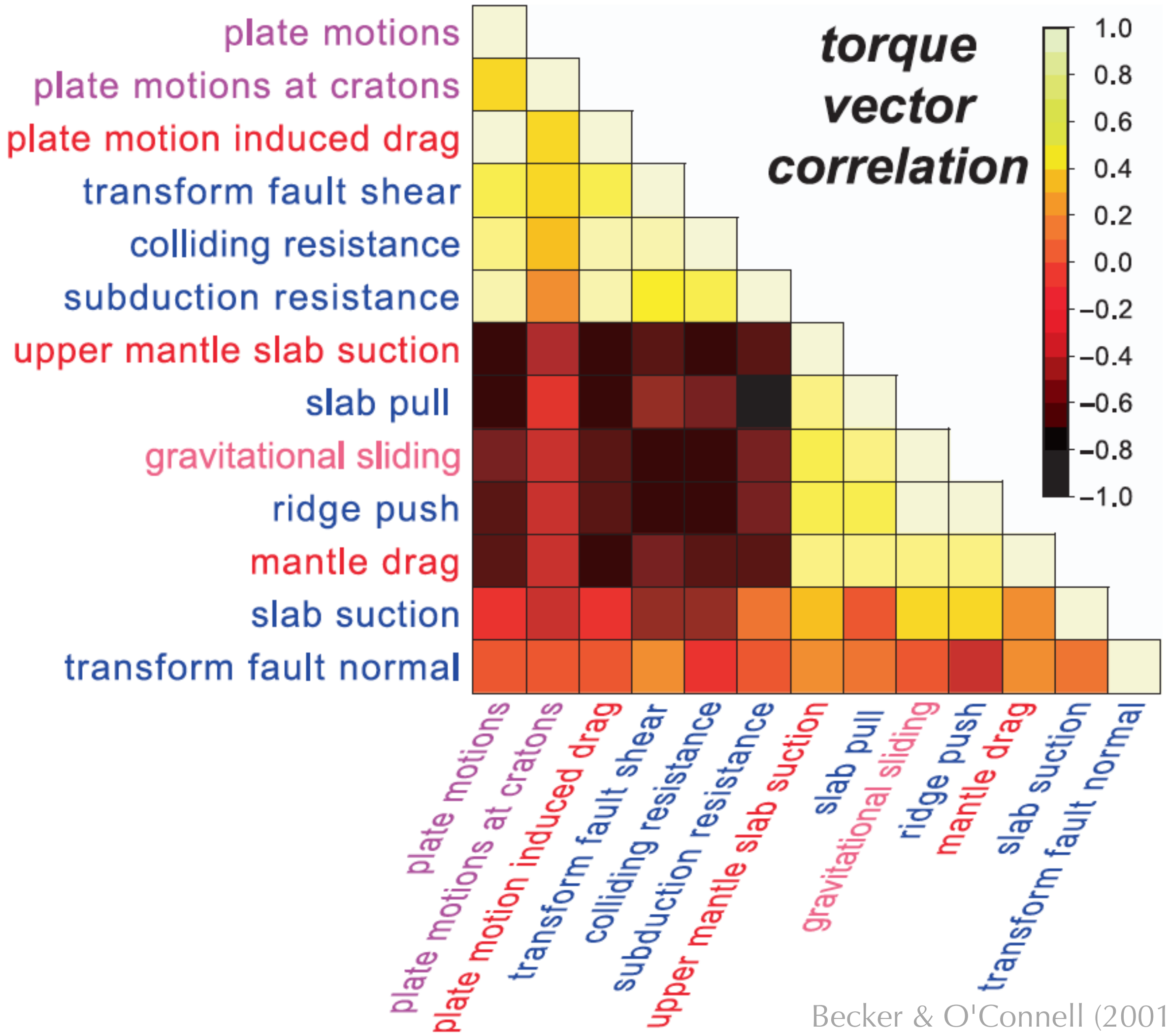
Kernels for layered viscosity mantle



Colli et al (2016)
cf. Hager & Richards (1984); Ricard (1984)

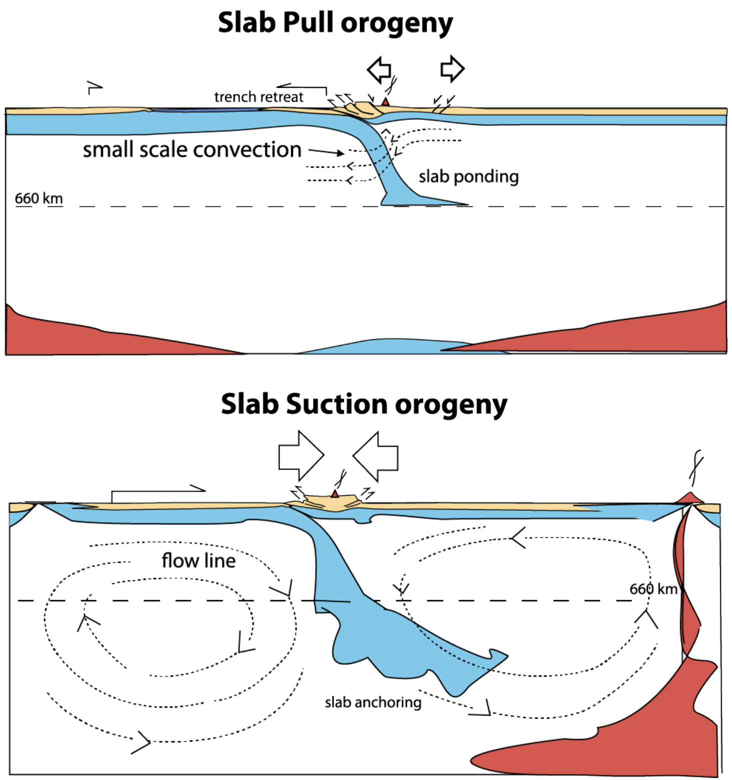
edge forces

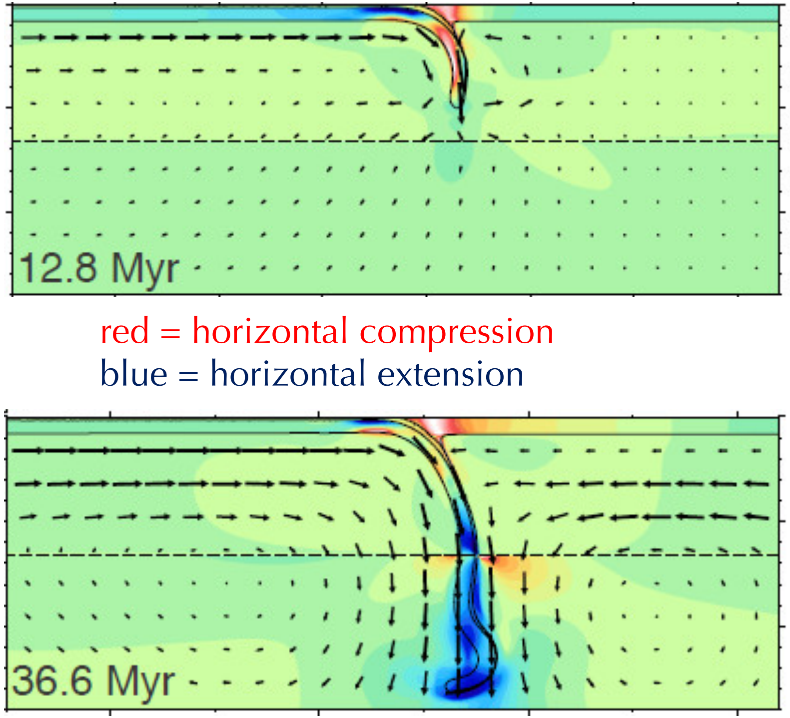
mantle tractions



Becker & O'Connell (2001)

Time-dependent compressional stresses during subduction penetration related to onset of crustal shortening?





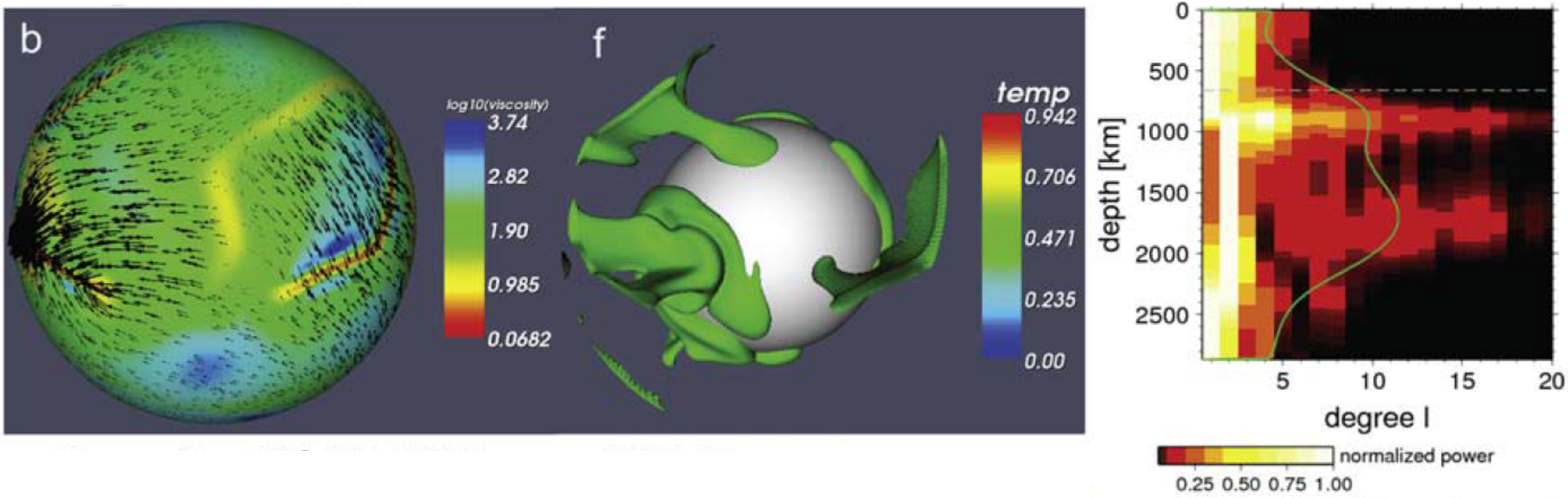
red = horizontal compression
blue = horizontal extension

cf. Machetel and Weber (1991); Tackley et al. (1993); Pysklywec and Mitrovica (1997)

Faccenna et al. (2017)

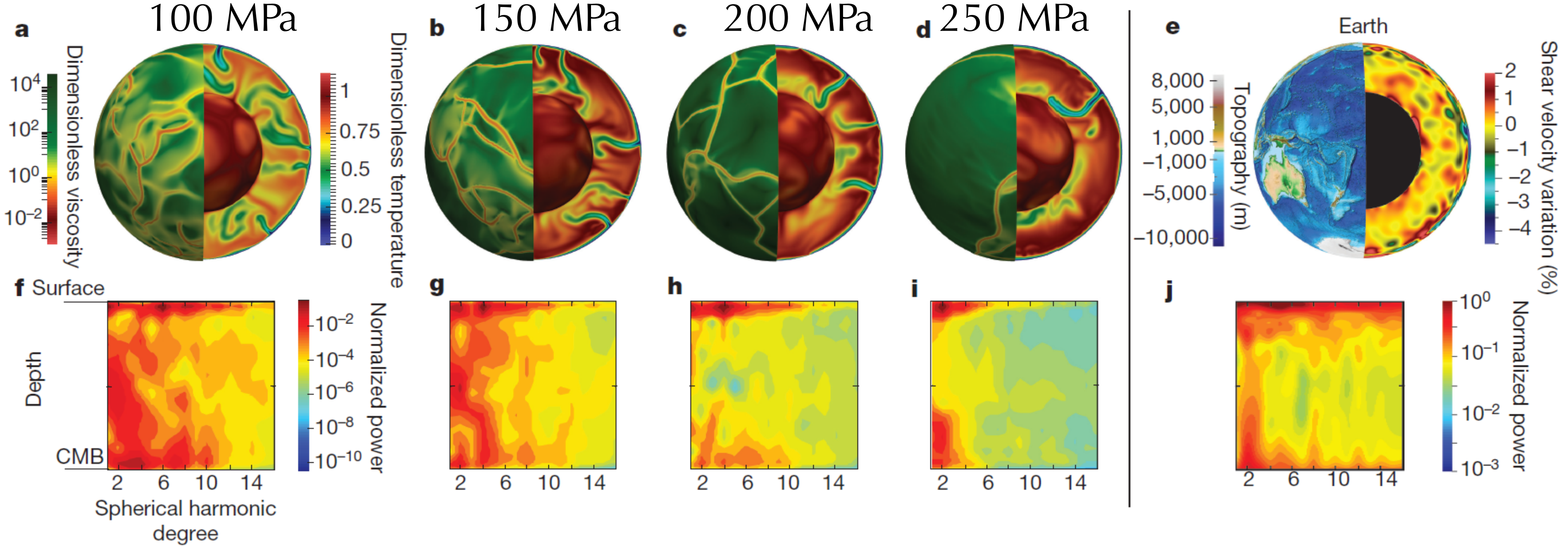
How are the plates made?

$\eta(T)$ & τ_{yield}, $\eta(z)/f_{melt}$, $\Delta\rho_c$, $\eta(\phi)$



Foley and Becker (2009)

Slabs control convection: Effect of yield stress on plateness

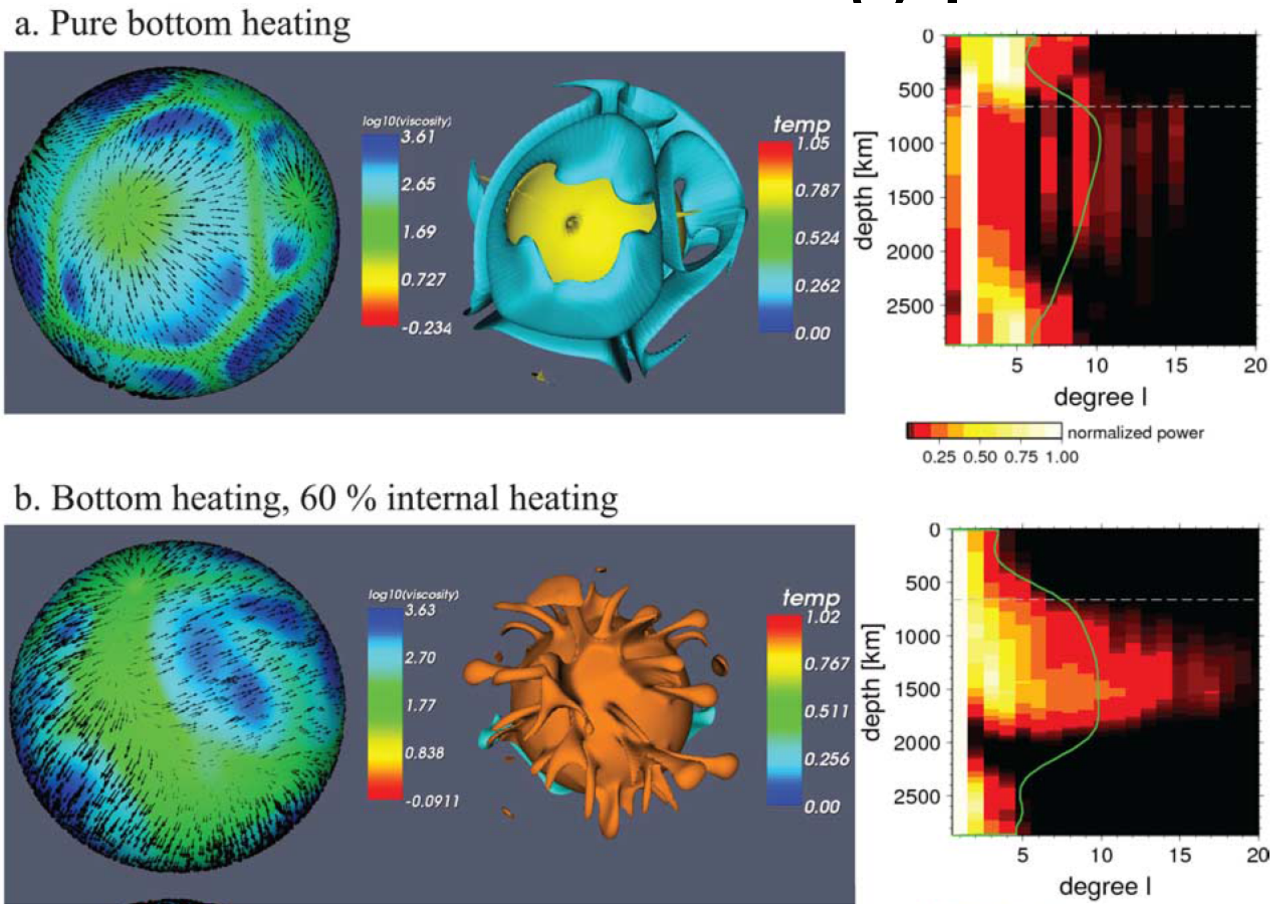


Mallard et al. (2016)

cf. Tackley (2000a,b), Richards et al. (2001), van Heck and Tackley (2008), Foley and Becker (2009)

But: effect of asthenosphere, internal vs. bottom heating, Ra #, continents, and damage/memory

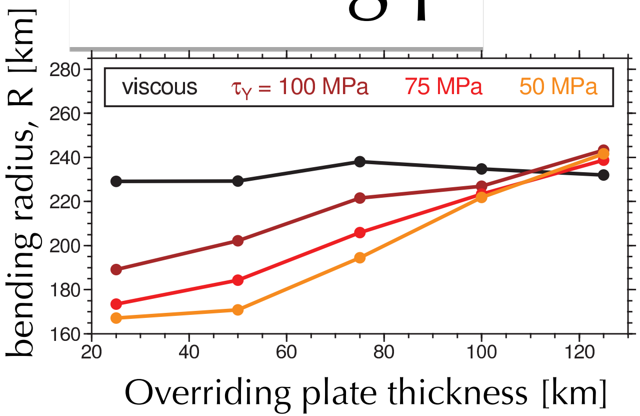
Plumes breaking plates

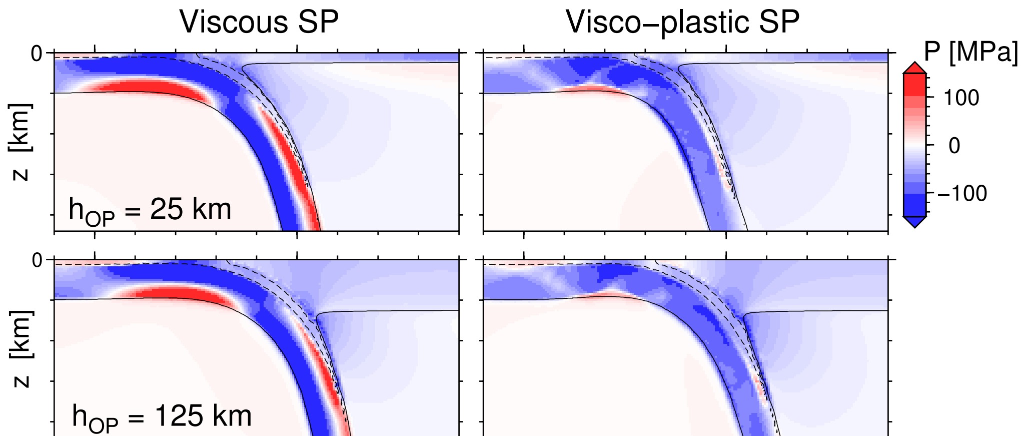


Foley and Becker (2009)

Effectively plastic slab: Bending radius affected by overriding plate thickness

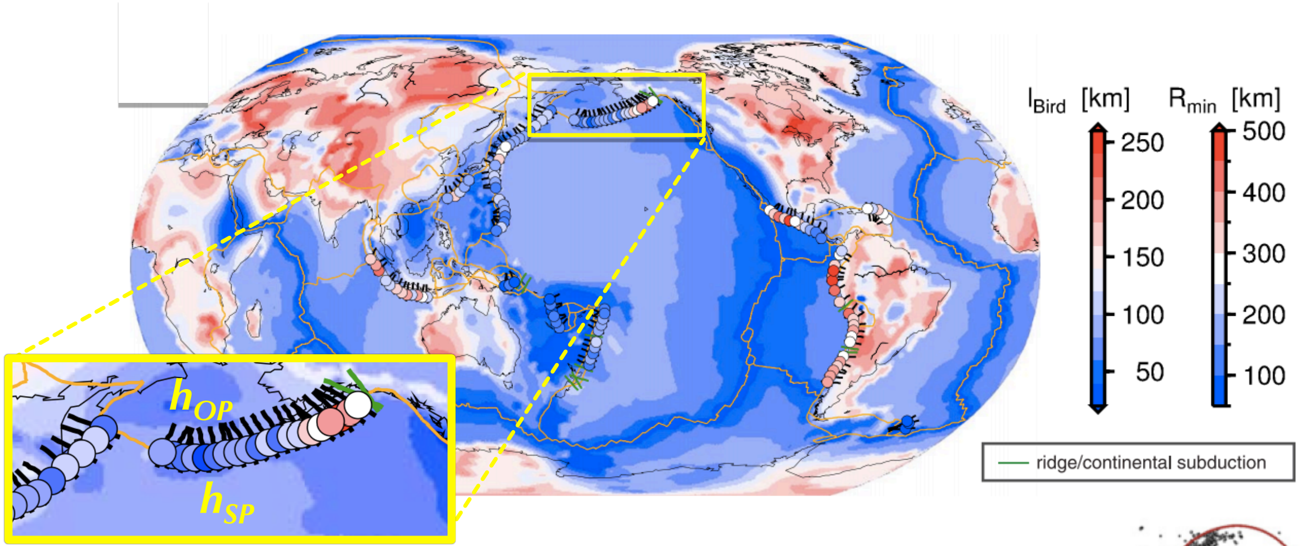
Plastic slab more strongly affected by lifting force ($F_{\Delta P}$) associated with overriding plate, weak bending stresses



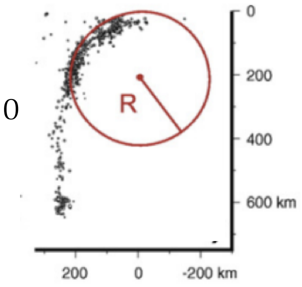


Holt et al. (2015)

Bending radius and plate thickness in nature



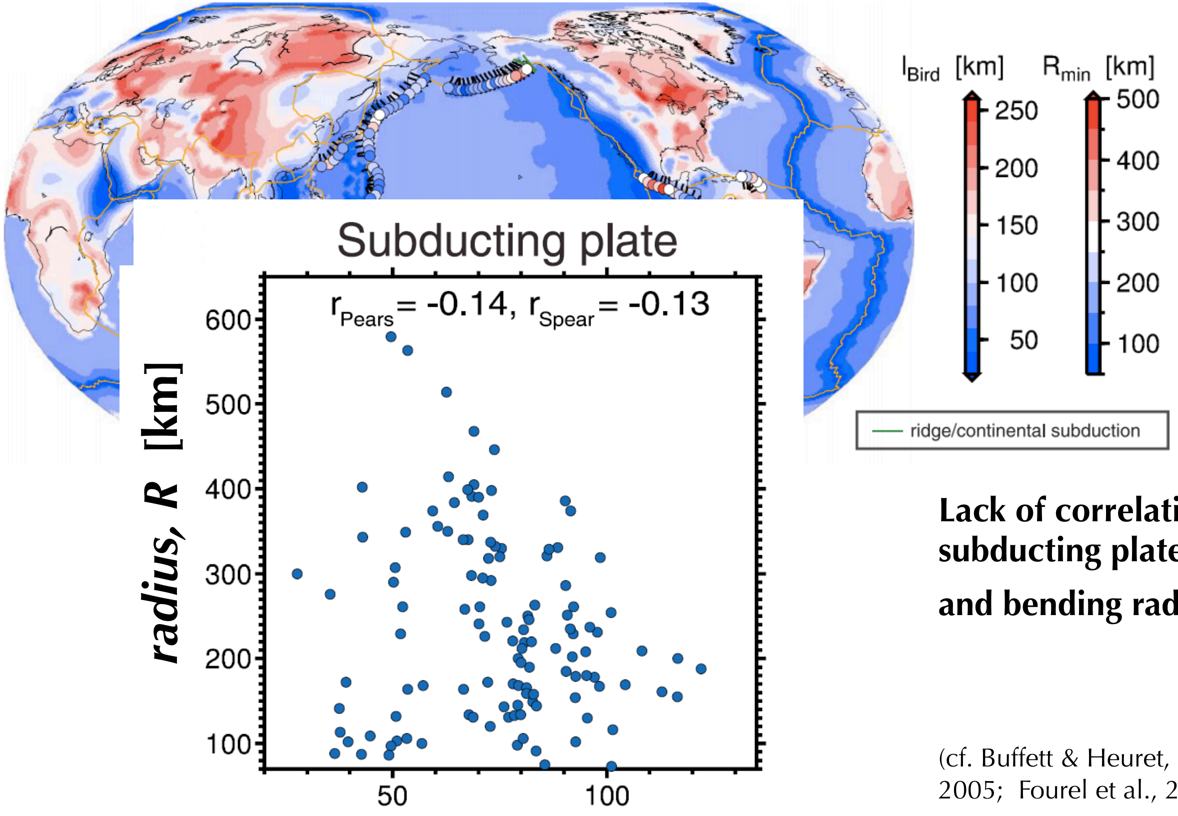
Aleutian Trench



- Radii of curvature from Benioff zone spline fits (Buffett & Heuret, 20
- Lithospheric thickness estimated from seismic tomography and seafloor age (Bird et al., 2008)

Holt et al. (2015)

No subducting plate control on slab curvature



radius, R [km]

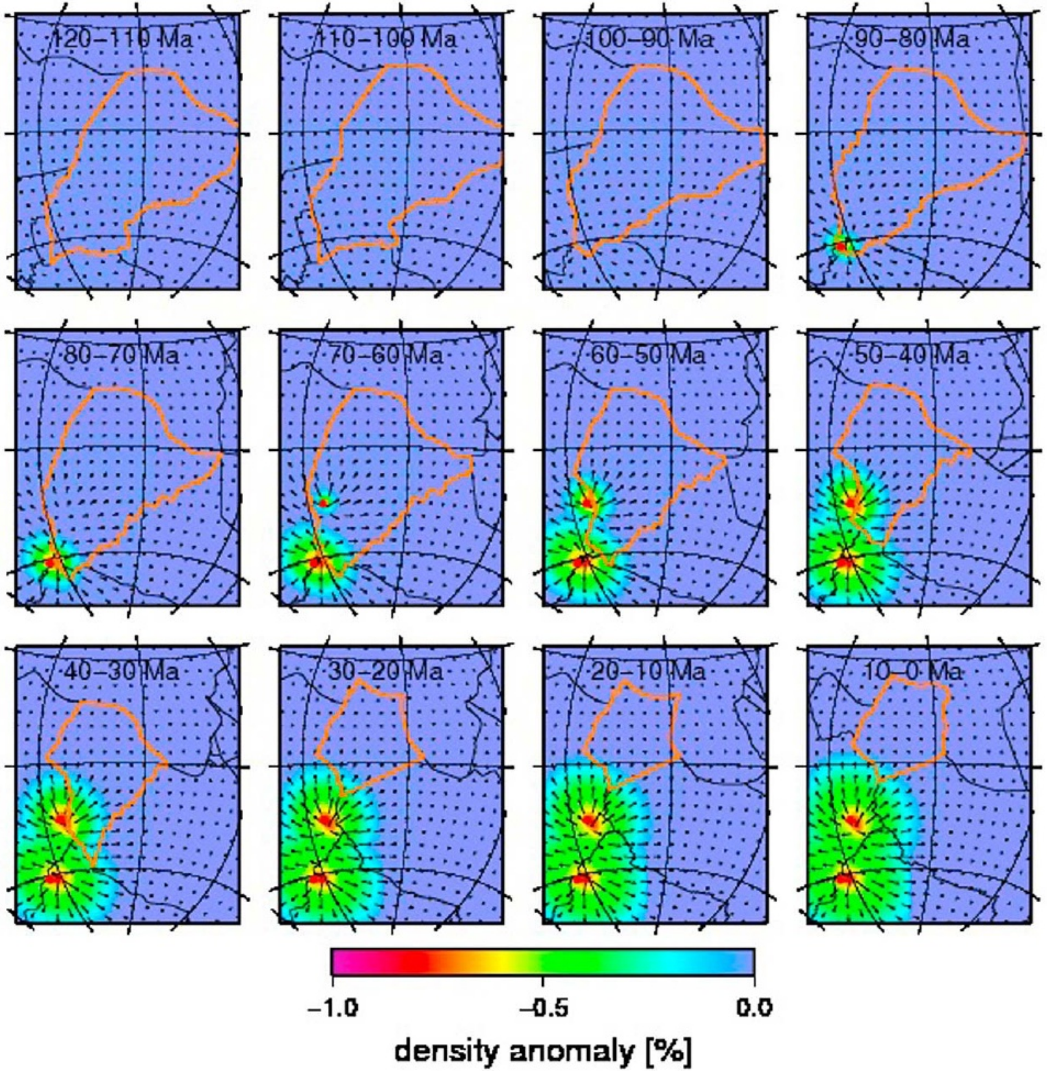
subducting plate thickness, h_{SP} [km]

Lack of correlation between subducting plate thickness, h_{SP} and bending radius, R

(cf. Buffett & Heuret, 2011; Cruciani et al., 2005; Fourel et al., 2014).

Holt et al. (2015)

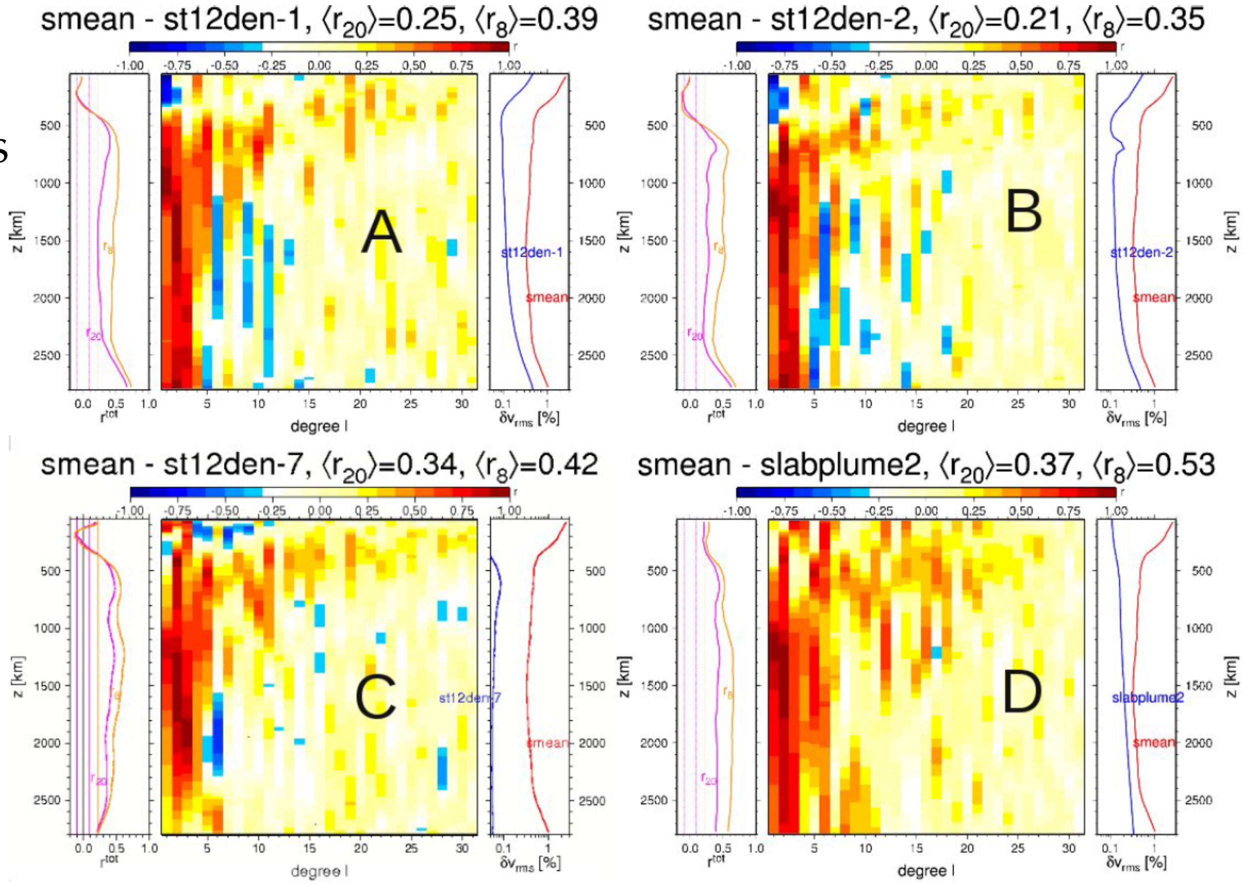
Plate driving forces: plumes



van Hinsbergen et al. (2011)

Slab plus piles I

Slab plus piles II



Slabs only

Slabs and plumes

Steinberger et al. (2012)