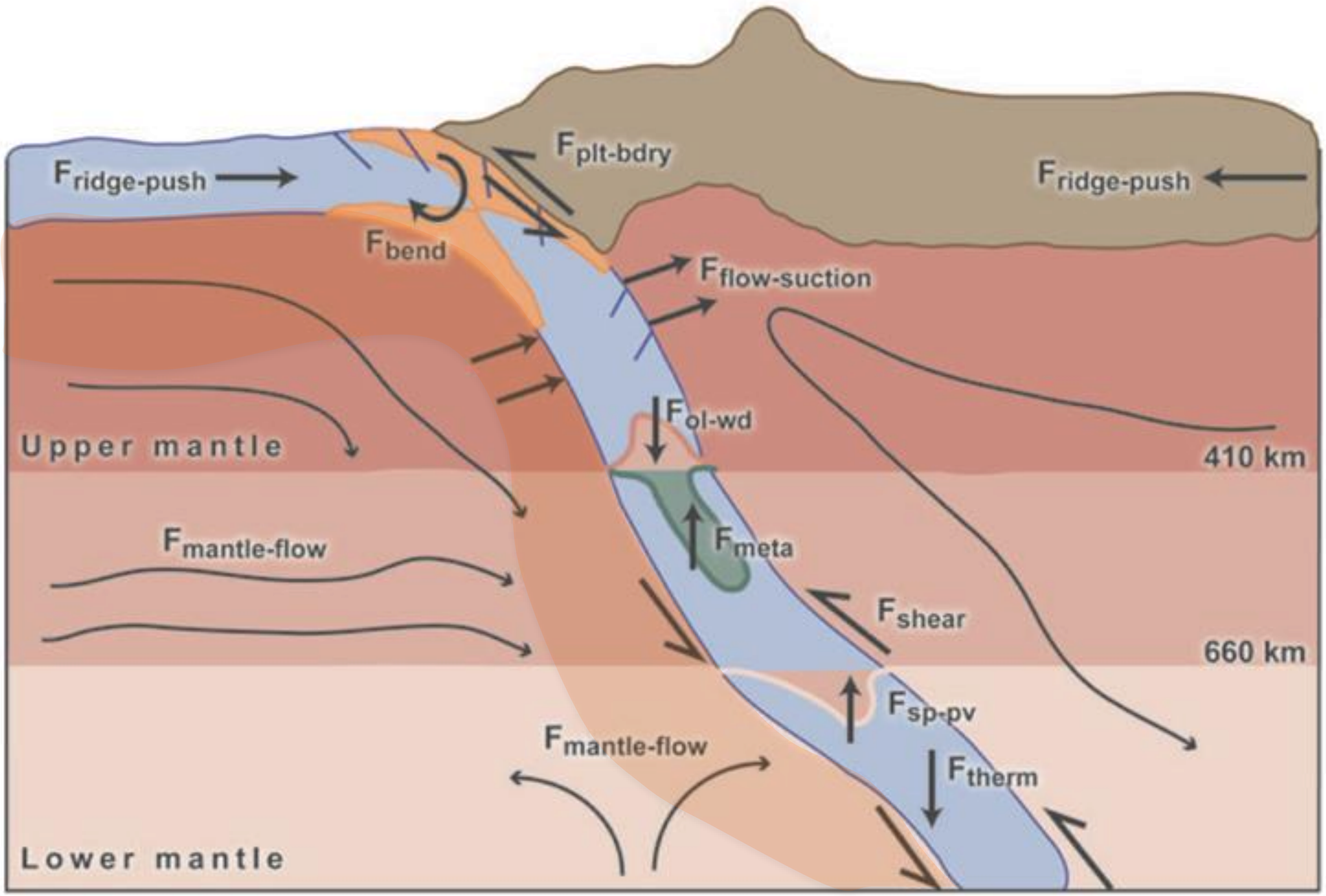
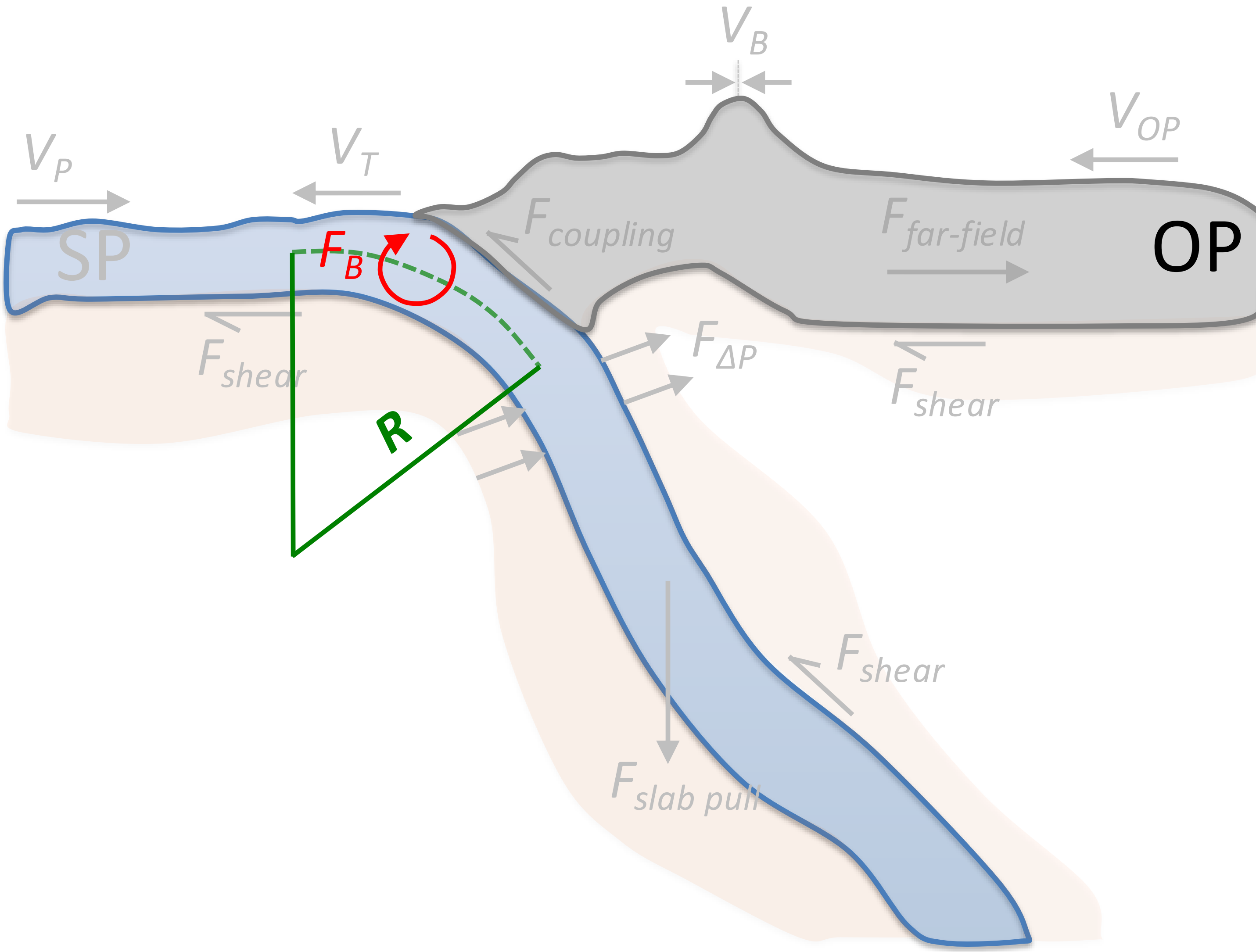
Slab bending



F ridge-push
F plt-bdry
F ridge-push
F bend
F flow-suction
F ol-wd
Upper mantle
410 km
F meta
F mantle-flow
F shear
660 km
F sp-pv
F mantle-flow
F therm
Lower mantle

Billen, 2008



V_B
V_P
V_T
V_{OP}
SP
OP
F_B
$F_{coupling}$
$F_{far\text{-}field}$
F_{shear}
$F_{\Delta P}$
F_{shear}
R
F_{shear}
$F_{slab\ pull}$

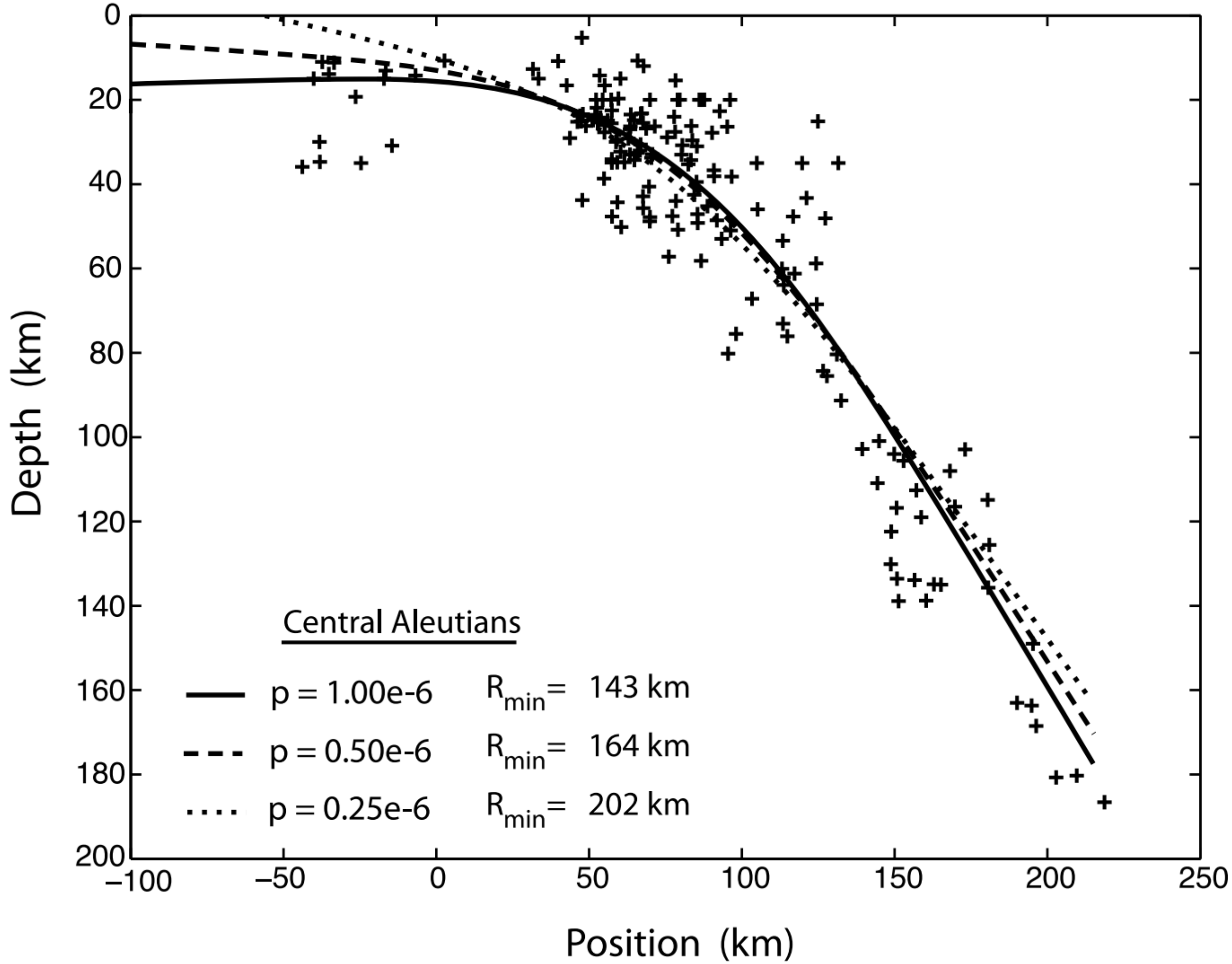
- **Radius of curvature**
- **Viscous bending**

  Dissipation, force, plate motions, time-dependence.
- **More complex viscous rheologies**

  Visco-plasticity; Elasticity
- **Visco-elasto-plastic and comparing with seismicity.**

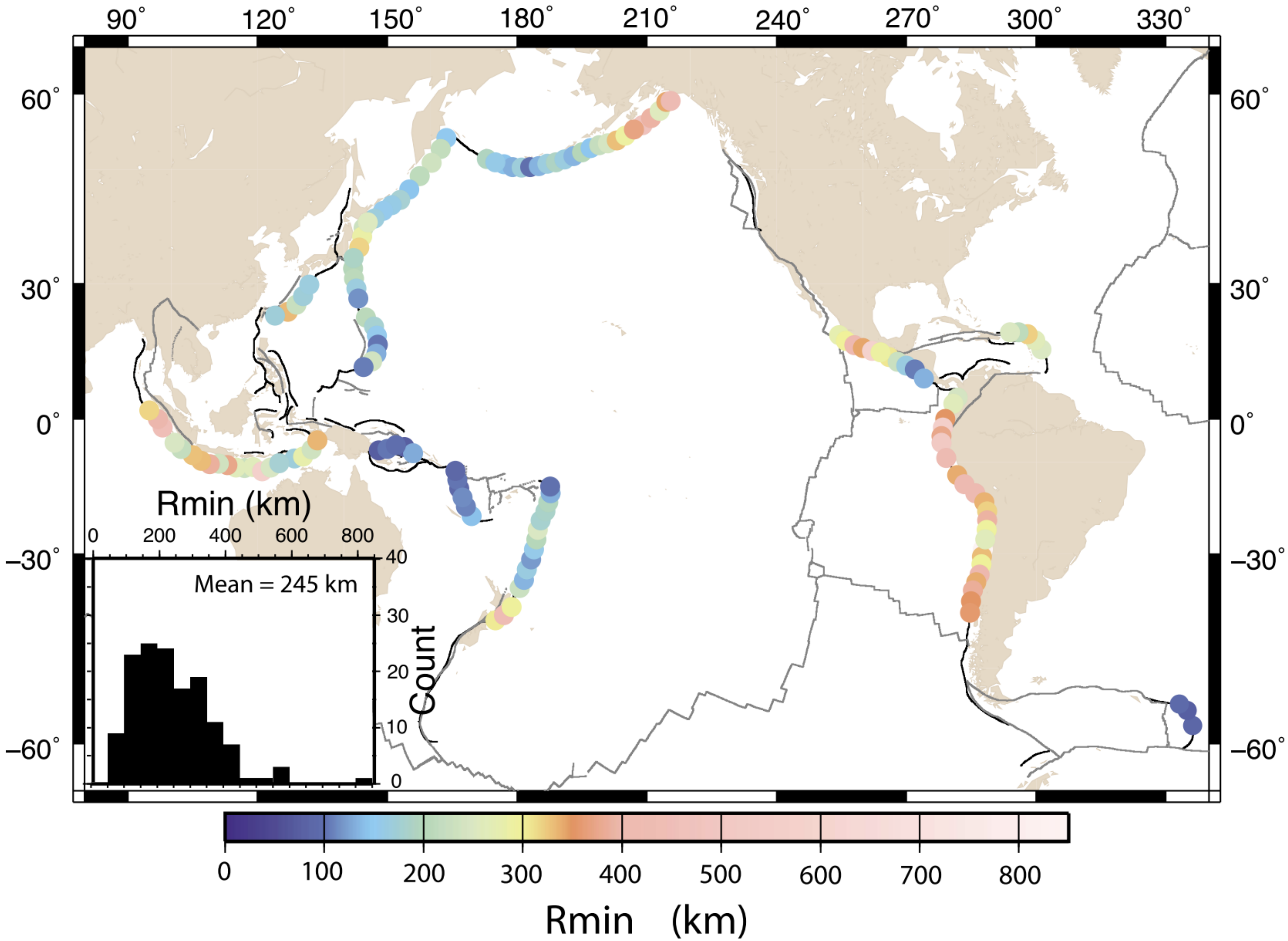
Radius of curvature

Fitting splines (piecewise polynomials) through earthquake locations



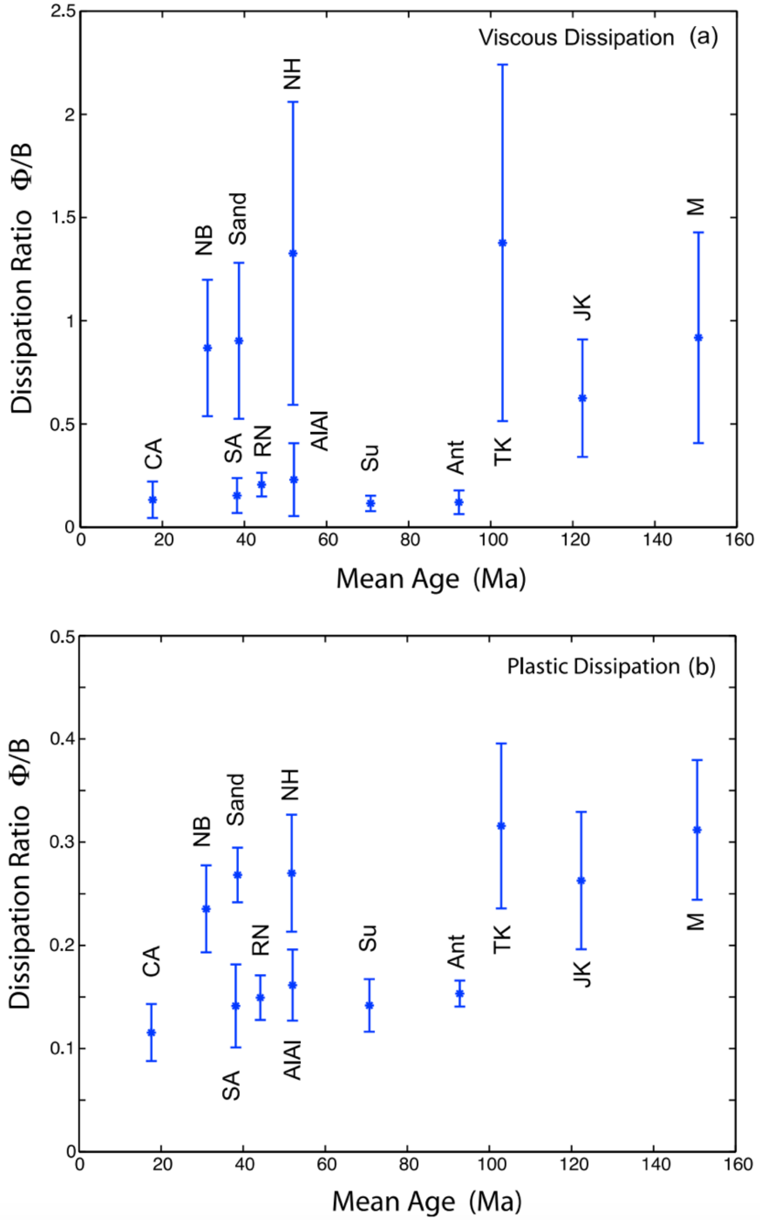
Buffett & Heuret, 2011

Radius of curvature



Buffett & Heuret, 2011

Radius of curvature

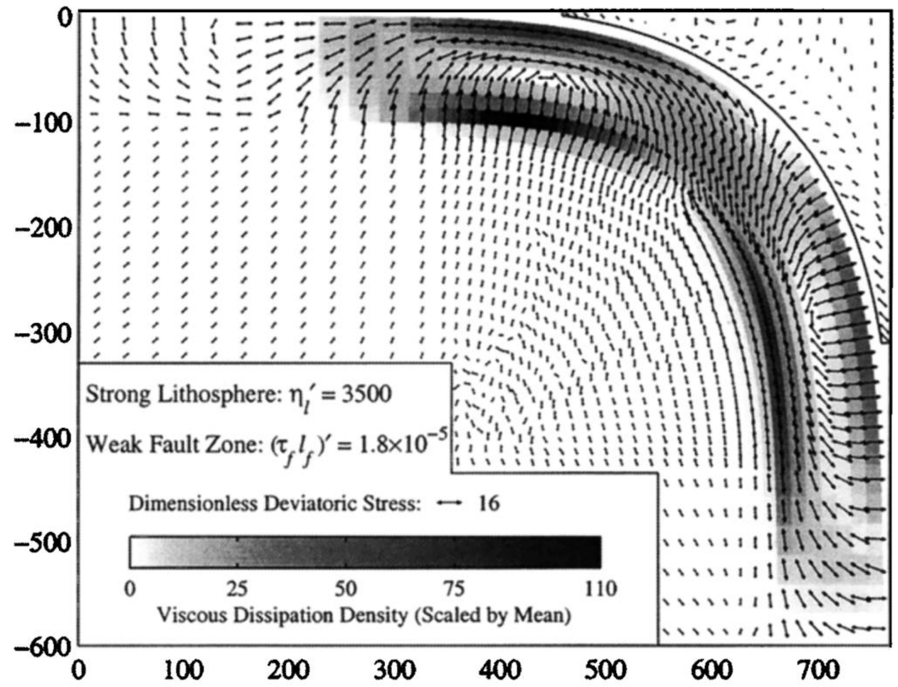


Radius of curvature – R – a key control on bending dissipation or forces, irrespective of assumed rheology (more to come…).

Buffett & Heuret, 2011

The baseline: Viscous bending

- Finite element models to probe the dependence of viscous dissipation (in the bending lithosphere) on subduction zone properties.



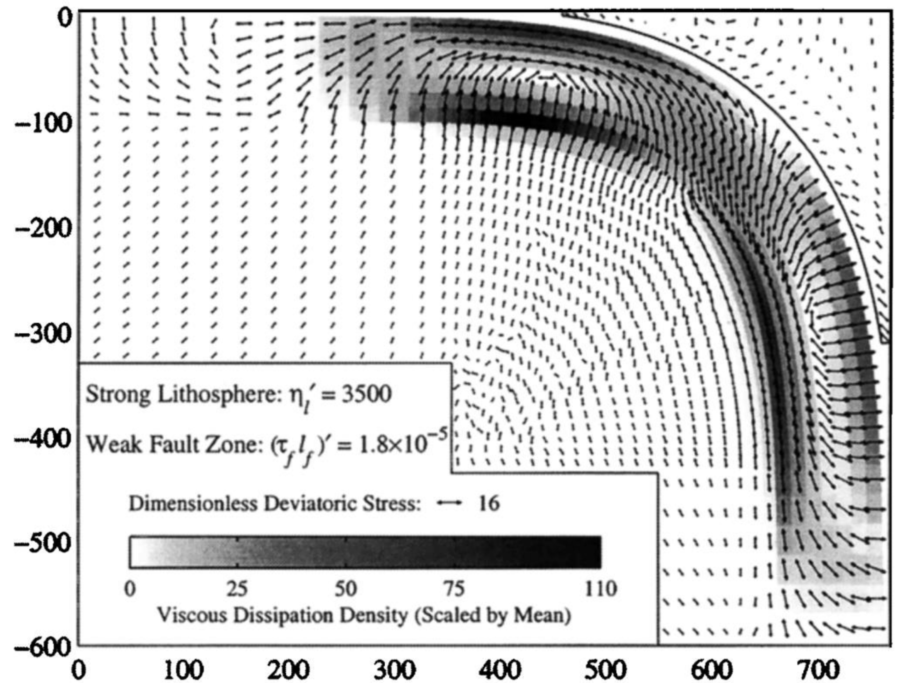
Conrad & Hager, 1999

The baseline: Viscous bending

- Finite element models to probe the dependence of viscous dissipation (in the bending lithosphere) on subduction zone properties.

- Dissipation balance assuming a totally viscous system:

$$\Phi^{pe} = \Phi_m^{vd} + \Phi_f^{vd} + \Phi_l^{vd}$$



(The rate of energy supplied by mass anomalies moving through the gravity field is to equal the work done by stresses in deforming the material.)

Conrad & Hager, 1999

The baseline: Viscous bending

- Finite element models to probe the dependence of viscous dissipation (in the bending lithosphere) on subduction zone properties.

- Dissipation balance assuming a totally viscous system:

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- Dissipation balance assuming a totally viscous system:
- Where the ϕ_f^{vd} given by:

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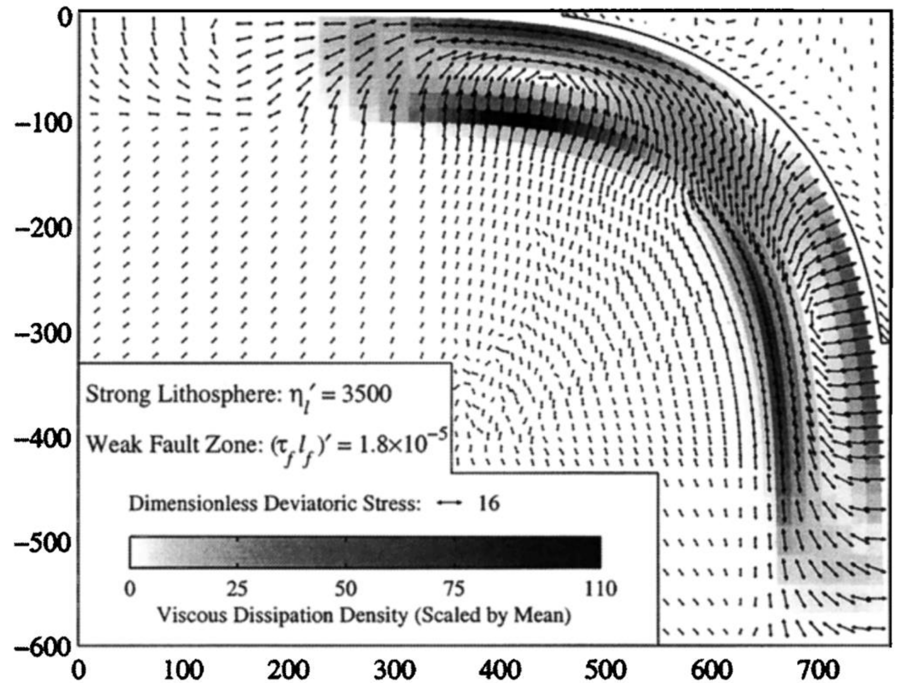
$$\Phi_l^{\mathbf{vd}} = C_l v_p^2 \eta_l \left(\frac{h_s}{R}\right)^3$$



Conrad & Hager, 1999

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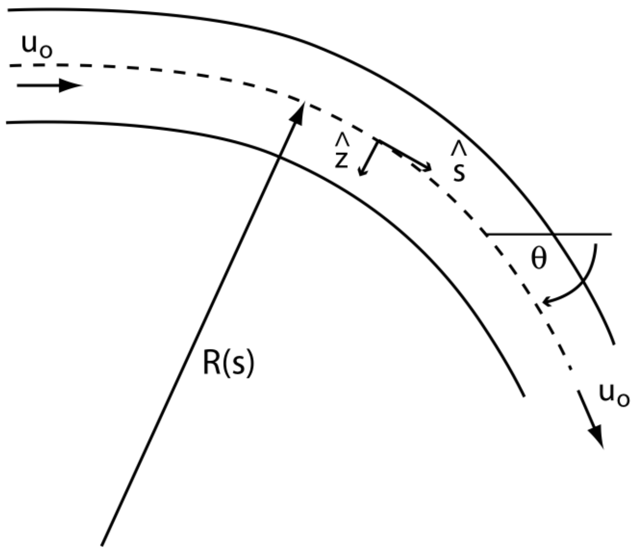


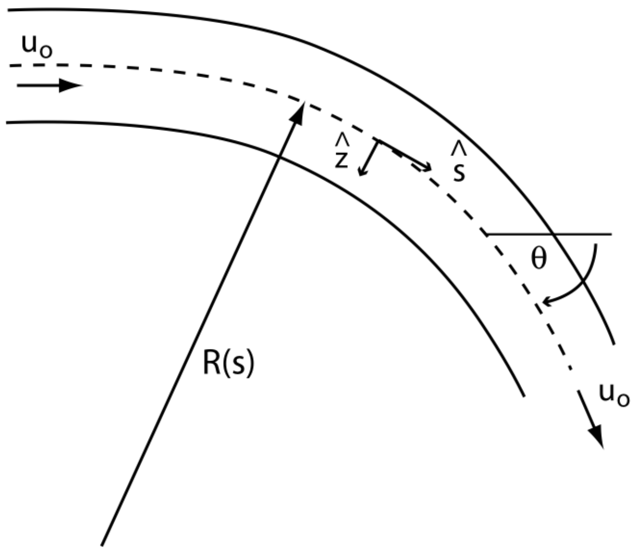
$$N = \int_{-H/2}^{H/2} \tau_{ss}\, dz \qquad M = \int_{-H/2}^{H/2} \tau_{ss} z\, dz$$

$$M(s) = -\frac{1}{3}\eta u_0 H^3 \left(\frac{dK}{ds}\right) \qquad \frac{dK}{ds} \approx \frac{1}{R_{\min}^2}$$

$$\Delta N(0) = -\frac{2}{3}\left(\frac{H}{R_{\min}}\right)^3 \eta u_0$$

Buffet, 2006; Buffet & Rowley, 2006

The baseline: Viscous bending



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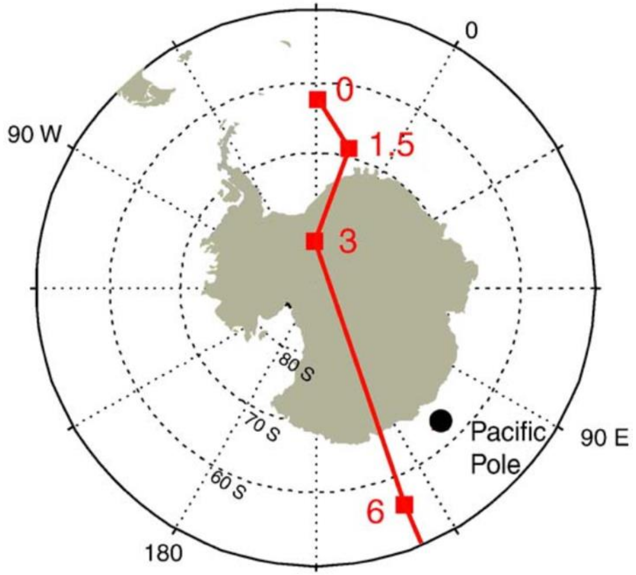
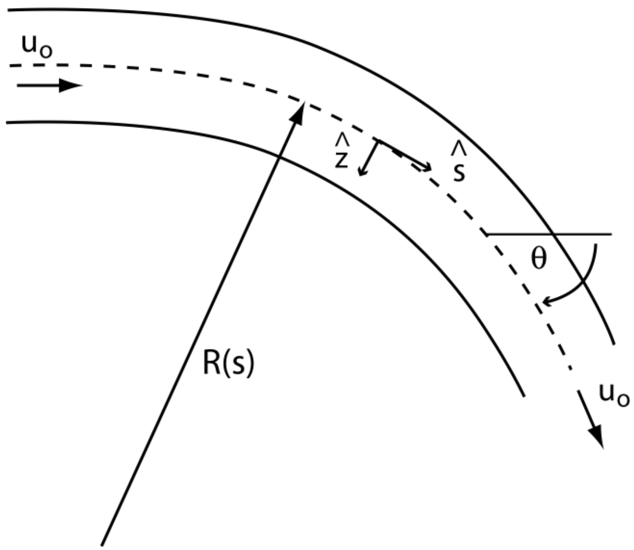


Proposed to affect plate velocities. Plot shows predicted (red) and observed (black) Euler poles for different slab viscosities (units of 10^{22} Pas).

Buffet, 2006; Buffet & Rowley, 2006

The baseline: Viscous bending



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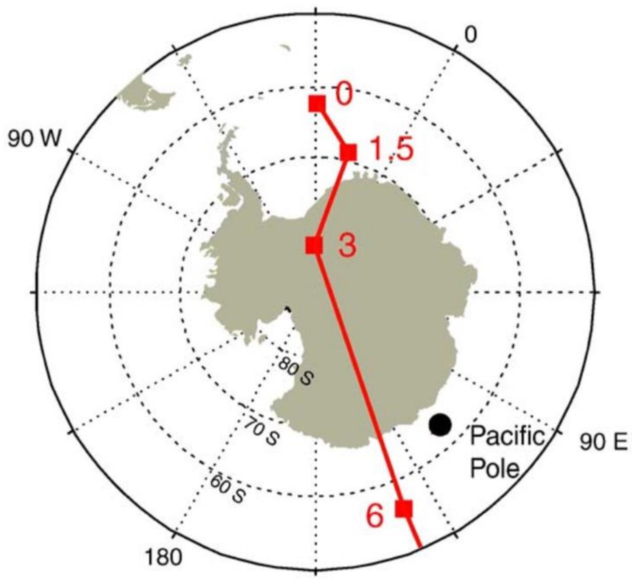

Proposed to affect plate velocities. Plot shows predicted (red) and observed (black) Euler poles for different slab viscosities (units of 10^{22} Pas). Assumes *R* = 200 km and proposes that bending dissipates ~40 % of slab's potential energy.

Buffet, 2006; Buffet & Rowley, 2006

The baseline: Viscous bending

But not so quick, e.g.:

Geochemistry Geophysics Geosystems
AN ELECTRONIC JOURNAL OF THE EARTH SCIENCES
Published by AGU and the Geochemical Society

Article
Volume 10, Number 4
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Q04002, doi:10.1029/2008GC002348
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Dynamics of plate bending at the trench and slab-plate coupling

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Evolution of the slab bending radius and the bending dissipation in three-dimensional subduction models with a variable slab to upper mantle viscosity ratio

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(Friday's discussion!)

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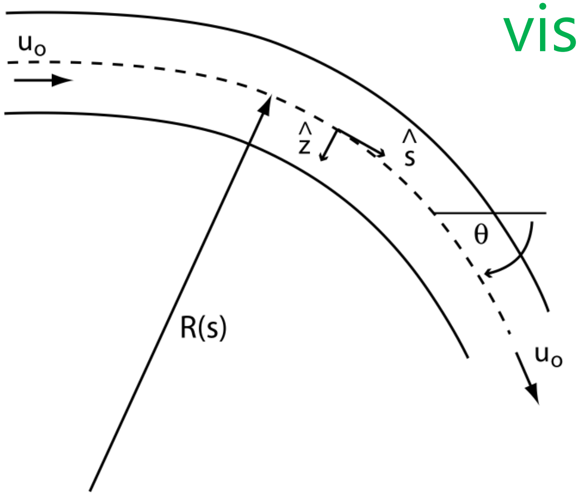
Adding complexity: Plastic bending



viscous:

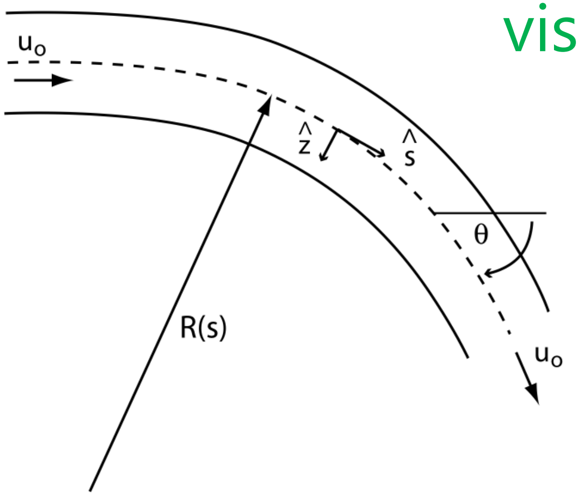
$$N = \int_{-H/2}^{H/2} \tau_{ss}\, dz \qquad M = \int_{-H/2}^{H/2} \tau_{ss} z\, dz$$

$$\Delta N(0) = -\frac{2}{3}\left(\frac{H}{R_{\min}}\right)^3 \eta u_0$$

$$\Phi = \frac{2}{3}\left(\frac{H^3}{R_{\min}^3}\right)\eta u_0^2$$

Buffet, 2006; Buffet & Rowley, 2006

Adding complexity: Plastic bending



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plastic:

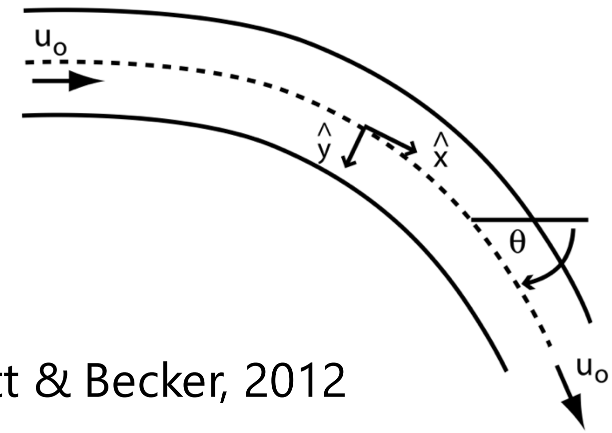
z < 0: $\tau_y(z) = \tau_y(0)(1 + 2z/H)$

z > 0: $\tau_y(z) = \tau_y(0)(1 - 2z/H)$

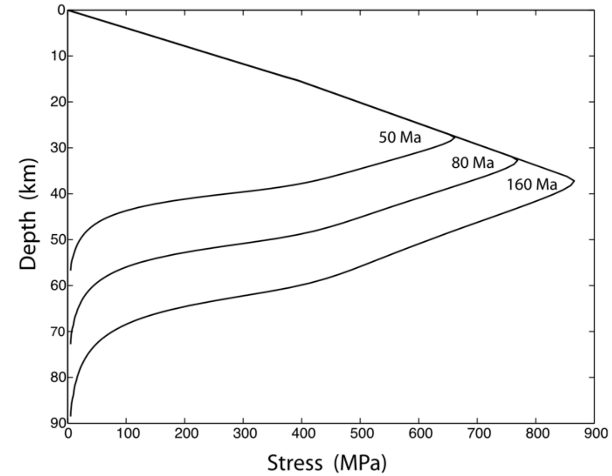
$$\Phi = \frac{1}{6}\left(\frac{H^2}{R_{\min}}\right)\tau_y(0) u_0 \qquad \Delta N(0) = -\frac{1}{6}\left(\frac{H^2}{R_{\min}}\right)\tau_y(0)$$

Buffet, 2006; Buffet & Rowley, 2006

More sophisticated visco-plastic rheologies



Buffett & Becker, 2012



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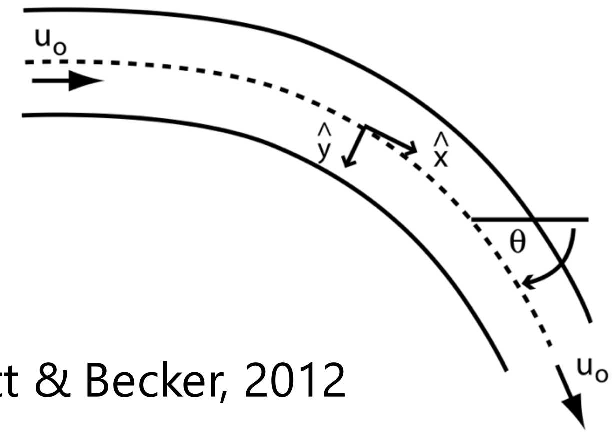

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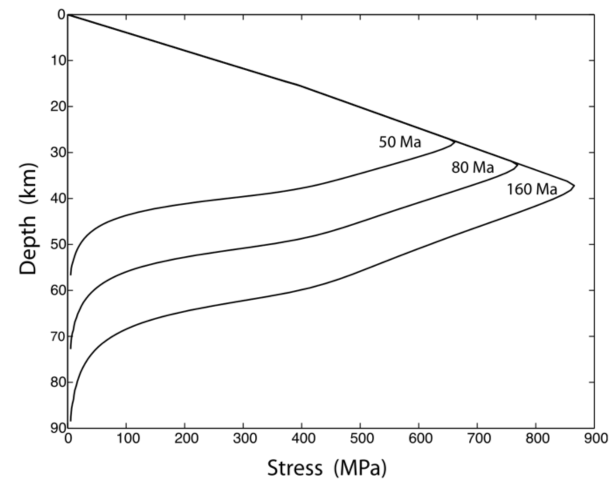
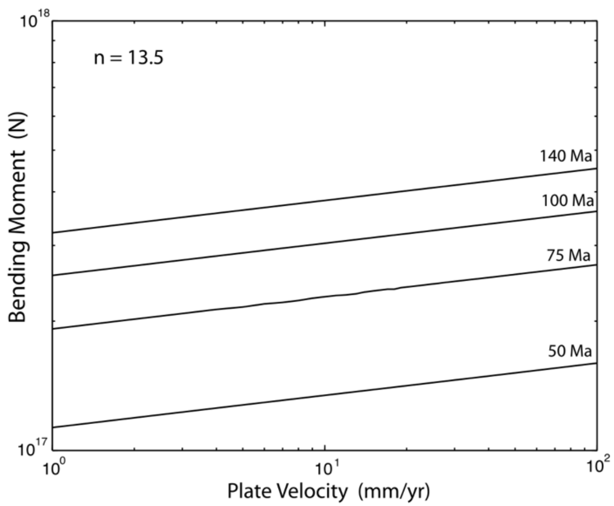


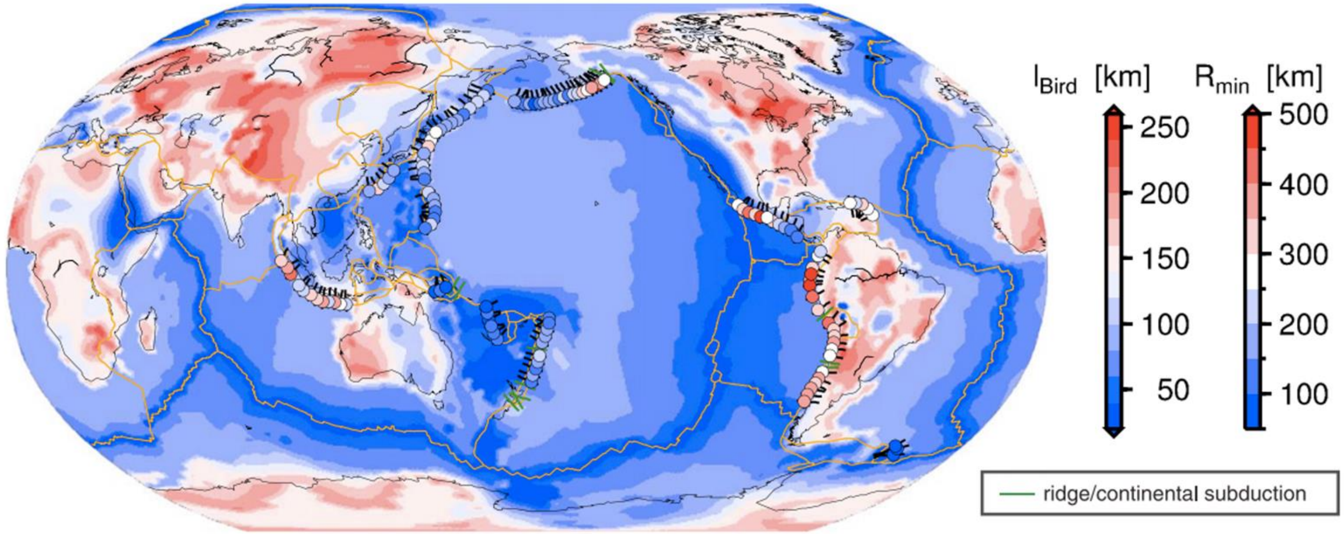


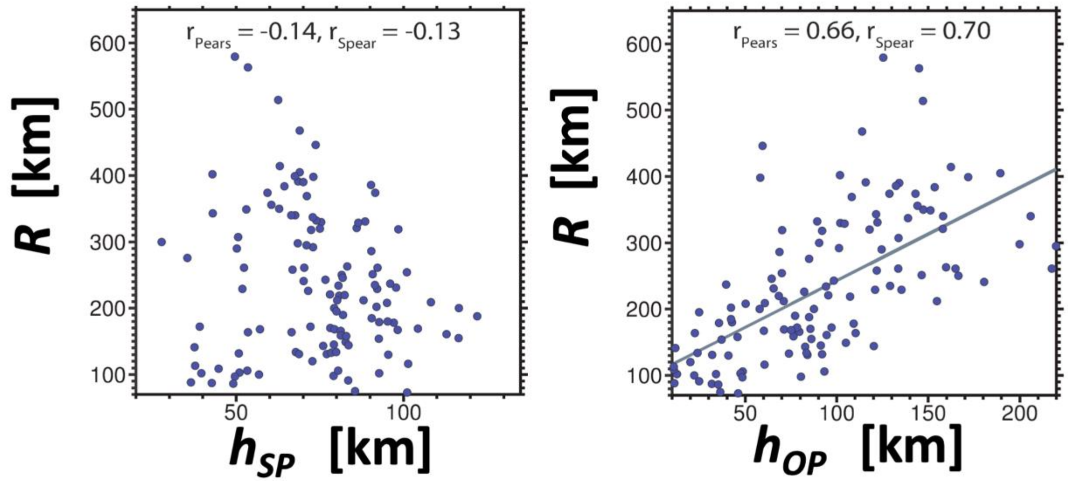
- Both bending moment (M) and bending force (N) relatively insensitive to subduction velocity.
- Moment and force can be approximated by a power-law fluid with n = 13.5 (i.e., almost perfectly plastic).

"Stresses associated with bending in a plastic plate cannot balance the torque associated with buoyancy forces. Instead, surface forces on the plate must play an important role: the conditions in the OP should contribute, and possibly control, to the evolution of curvature."

More sophisticated visco-plastic rheologies

R from Benioff zone spline fits (Buffett & Heuret, 2011)
Lithospheric thickness estimated from seismic tomography (Bird et al., 2008)



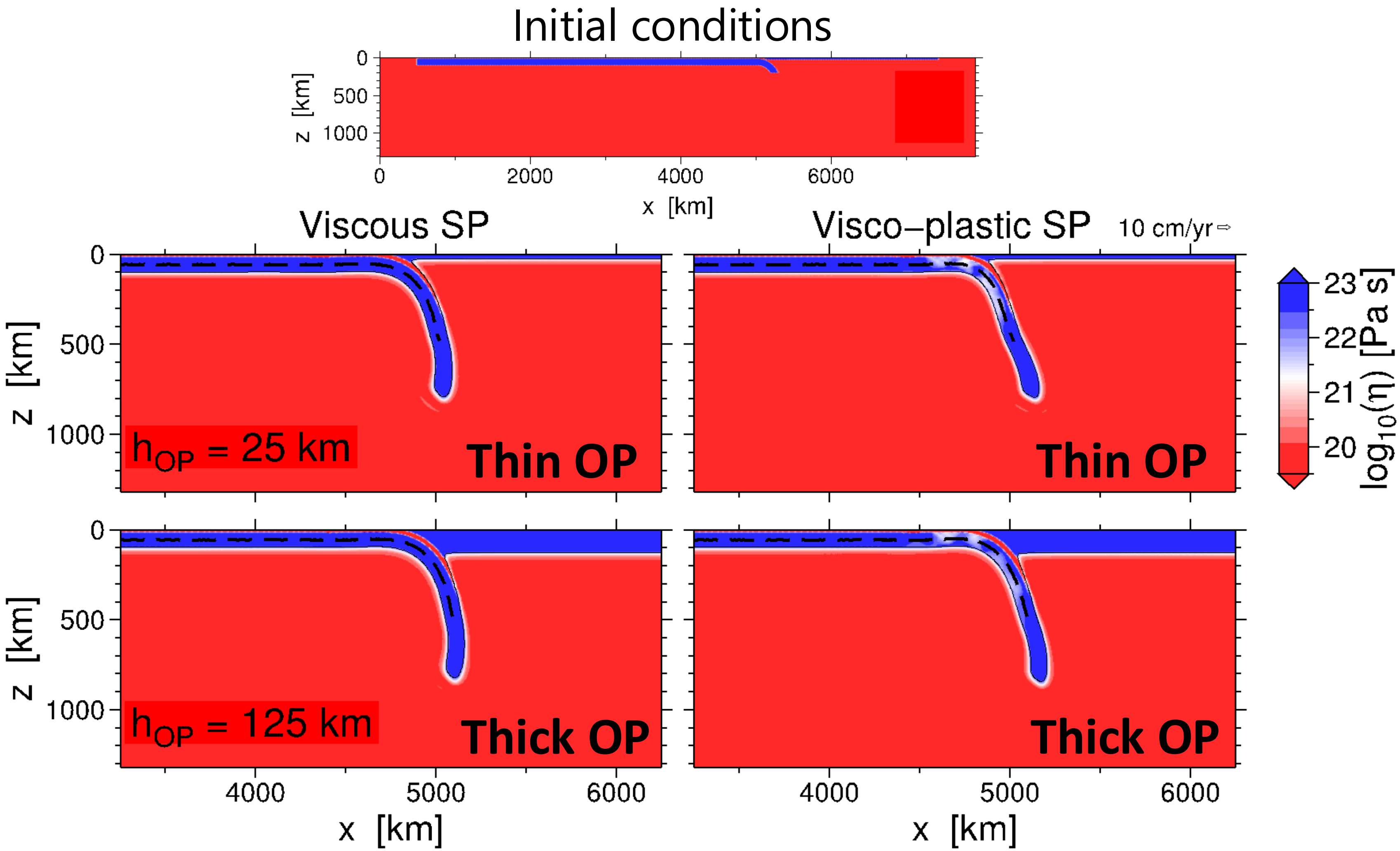


Lack of significant correlation between h_{SP} and R_{min}

Strong positive correlation between h_{OP} and R_{min}

Holt et al., 2015

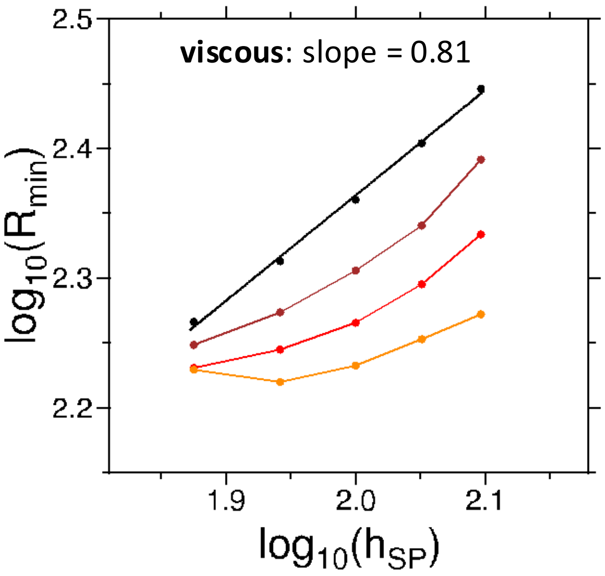
More sophisticated visco-plastic rheologies

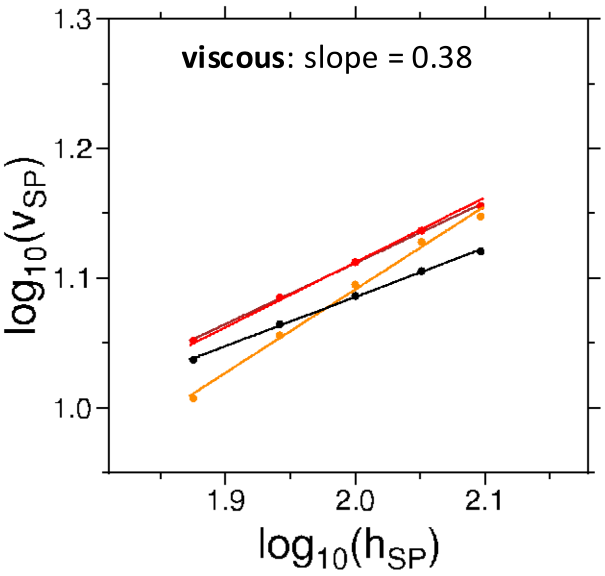


Holt et al., 2015

More sophisticated visco-plastic rheologies

Modeled dependence on **SP thickness:**





More sophisticated visco-plastic rheologies

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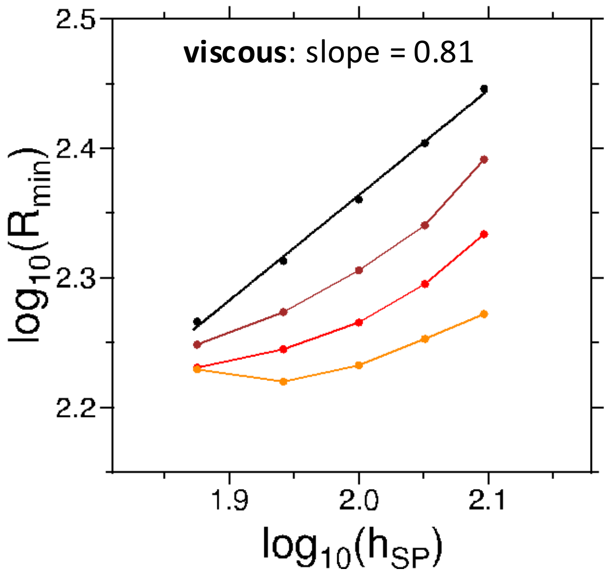
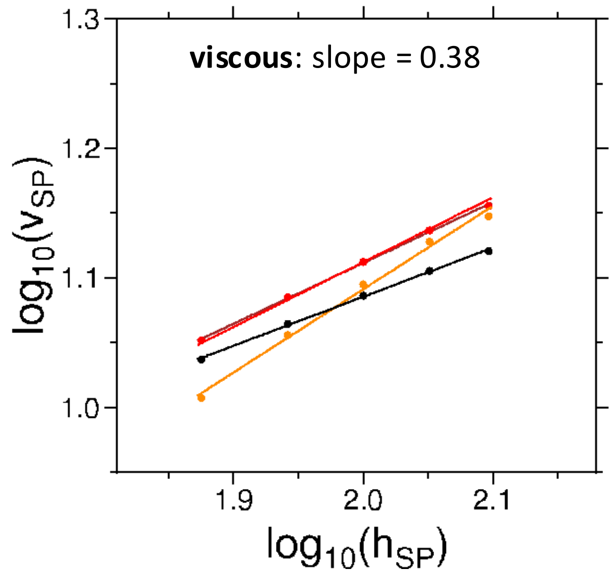




For viscous SP, follows from a simple scaling:

buoyancy flux $\propto$ bending dissipation

$$\Delta\rho g h_{SP} D v_{SP} \propto \left(\frac{h_{SP}}{R_{min}}\right)^3 \eta' v_{SP}^2,$$

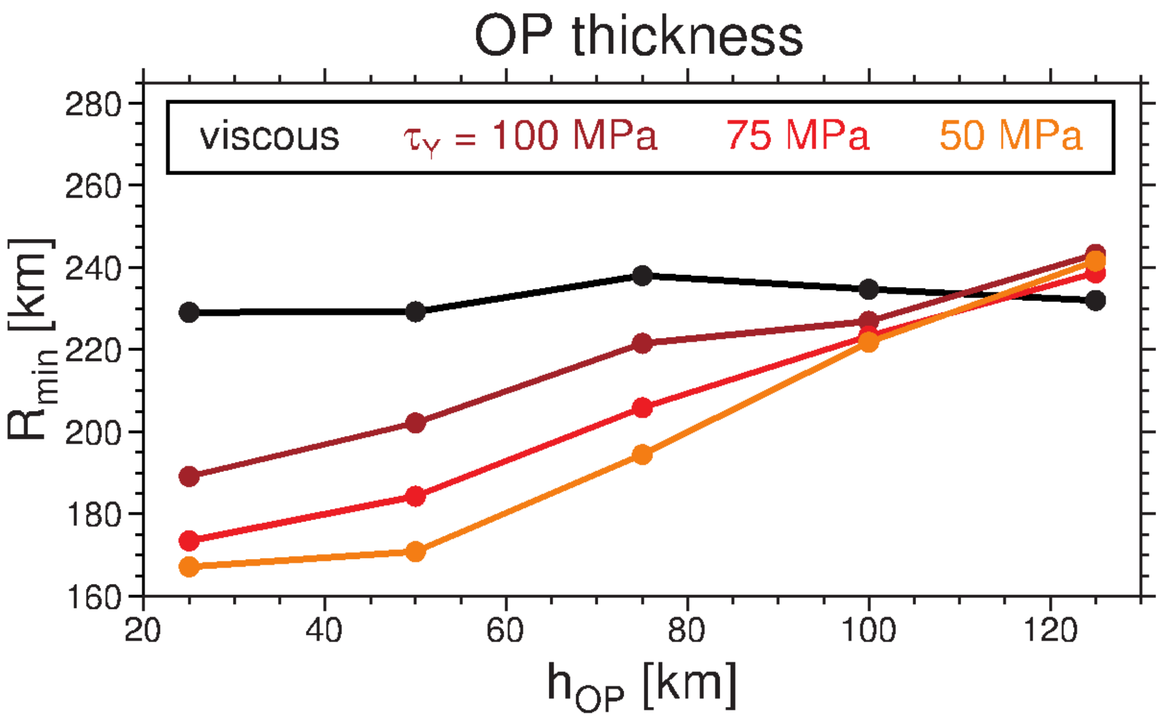
$$R_{min} \propto h_{SP}^{2/3} v_{SP}^{1/3}$$

$$R_{min} \propto h_{SP}^{0.79}$$

But no positive correlation on Earth: **Plasticity reduces this!**

More sophisticated visco-plastic rheologies

Now, **OP thickness**, h_{OP}:

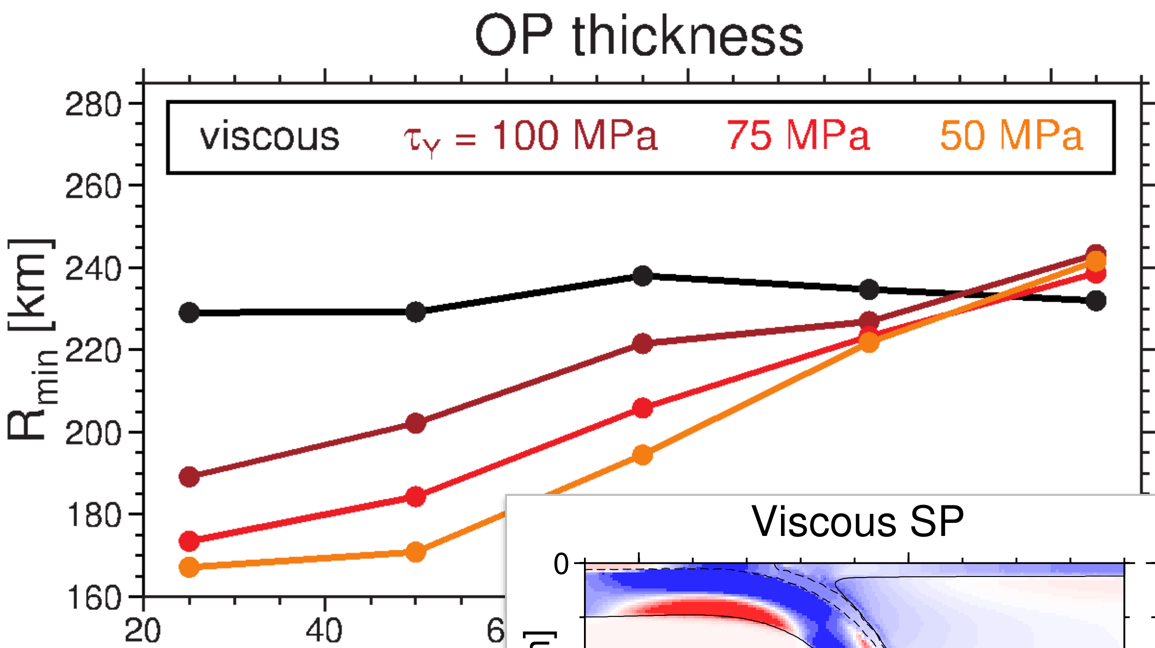


Increasing the degree of SP plasticity, i.e. reducing yield stress:

- Reduces the strength of R dependence on h_{SP}.
- Introduces dependence of R on h_{OP}.

More sophisticated visco-plastic rheologies

Now, **OP thickness**, h_{OP}:



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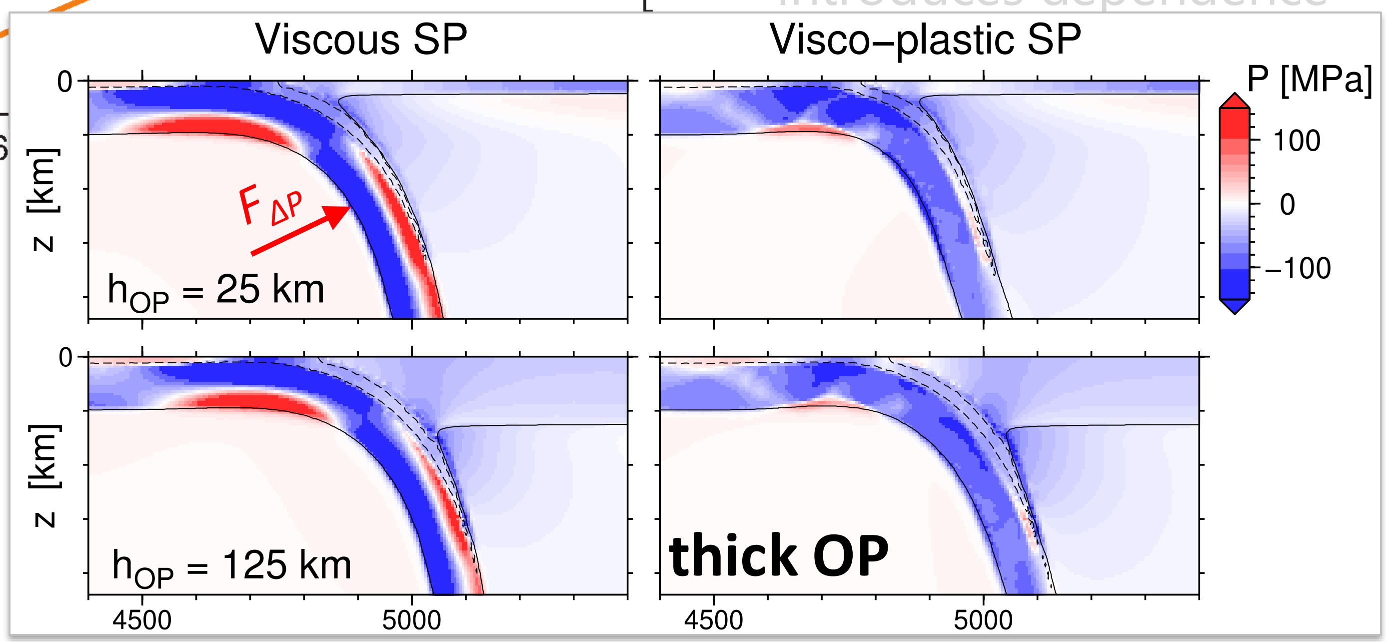
- Introduces dependence



Weaker plastic slab more strongly affected by lifting force associated with OP?

Testing variable <u>viscous</u> and <u>visco-plastic</u> rheologies

Like Conrad & Hager 1999 but with more sophisticated rheologies (including lab-derived olivine flow laws)

Rose & Korenaga, 2011

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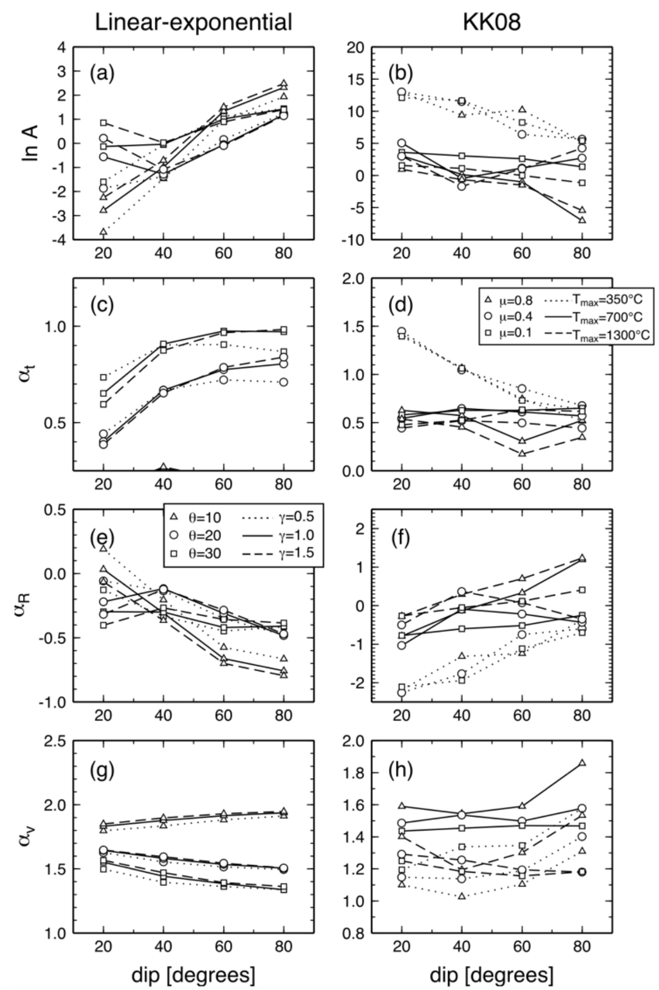


Linear regression for dissipation scaling factors points to values that are highly variable relative to is viscous case.

$$\Phi_{\mathrm{BD}}(t, R, v, \phi) = A(\phi) t^{\alpha_t(\phi)} R^{\alpha_R(\phi)} v^{\alpha_v(\phi)},$$

How about elasticity?

$$D_{ij} = D_{ij}^{v} + D_{ij}^{e} = \frac{\tau_{ij}}{2\eta} + \frac{\dot{\tau}_{ij}}{2\mu}$$

$$\dot{\tau}_{ij} = \lim_{\delta t \to 0} \frac{\tau(t, x(t)) - \tau(t - \delta t, x(t - \delta t))}{\delta t}$$

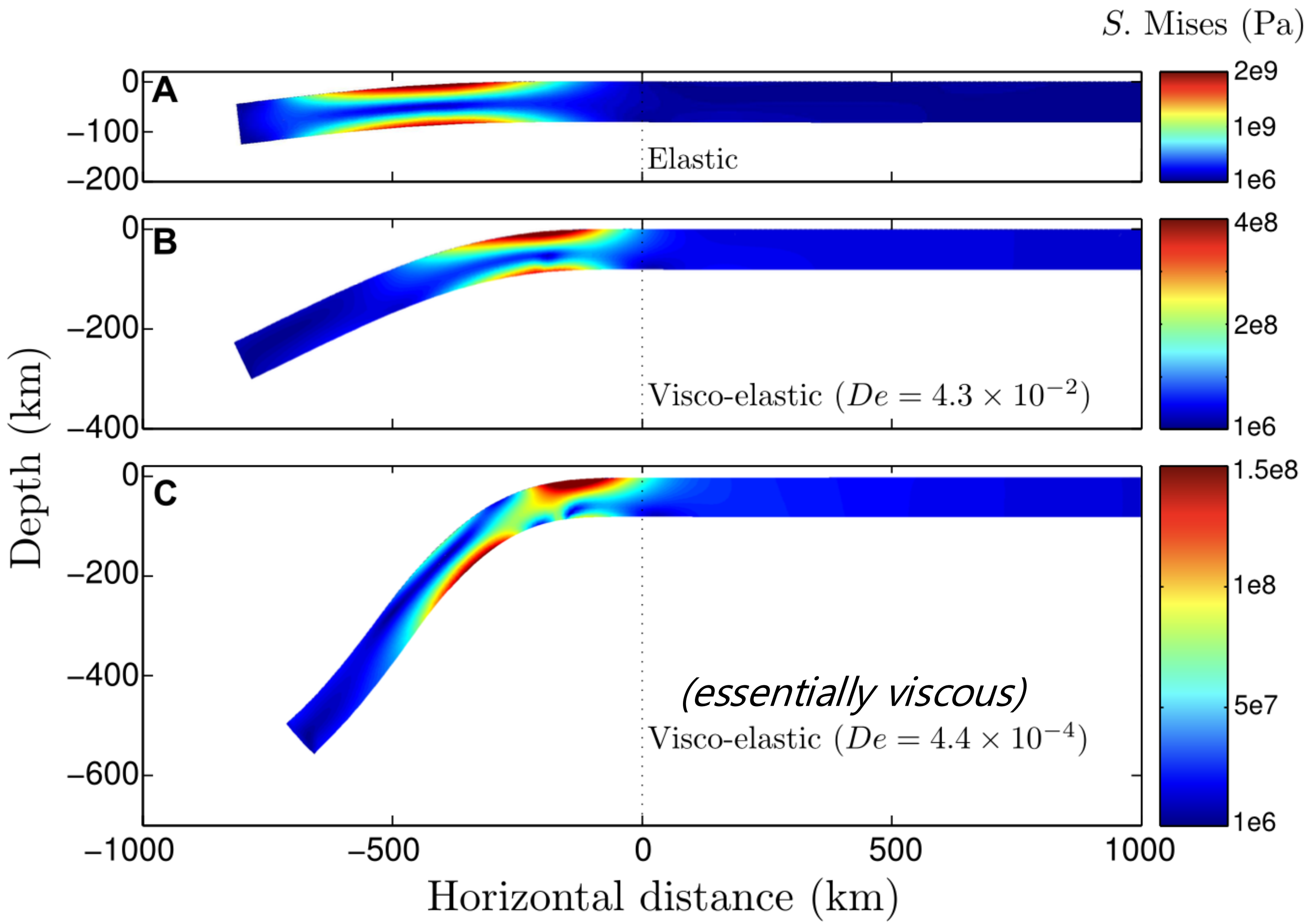
$$\tau_{ij}(t, x(t)) = 2\eta_{\text{eff}} D_{ij}(t, x(t)) + \frac{\eta_{\text{eff}}}{\mu \Delta t} \overset{\vee}{\tau}(t - \Delta t, x(t))$$

$$\sigma_{ij,j} = \tau_{ij,j} - p_i = f_i$$

$$(2\eta_{\text{eff}} D_{ij})_{,j} - p_{,i} = f_i - \frac{\eta_{\text{eff}}}{\mu \Delta t} \tau_{ij,j}^{\vee}$$

Example implementation from Moresi et al., 2003 (and Farrington et al., 2014)

How about elasticity?

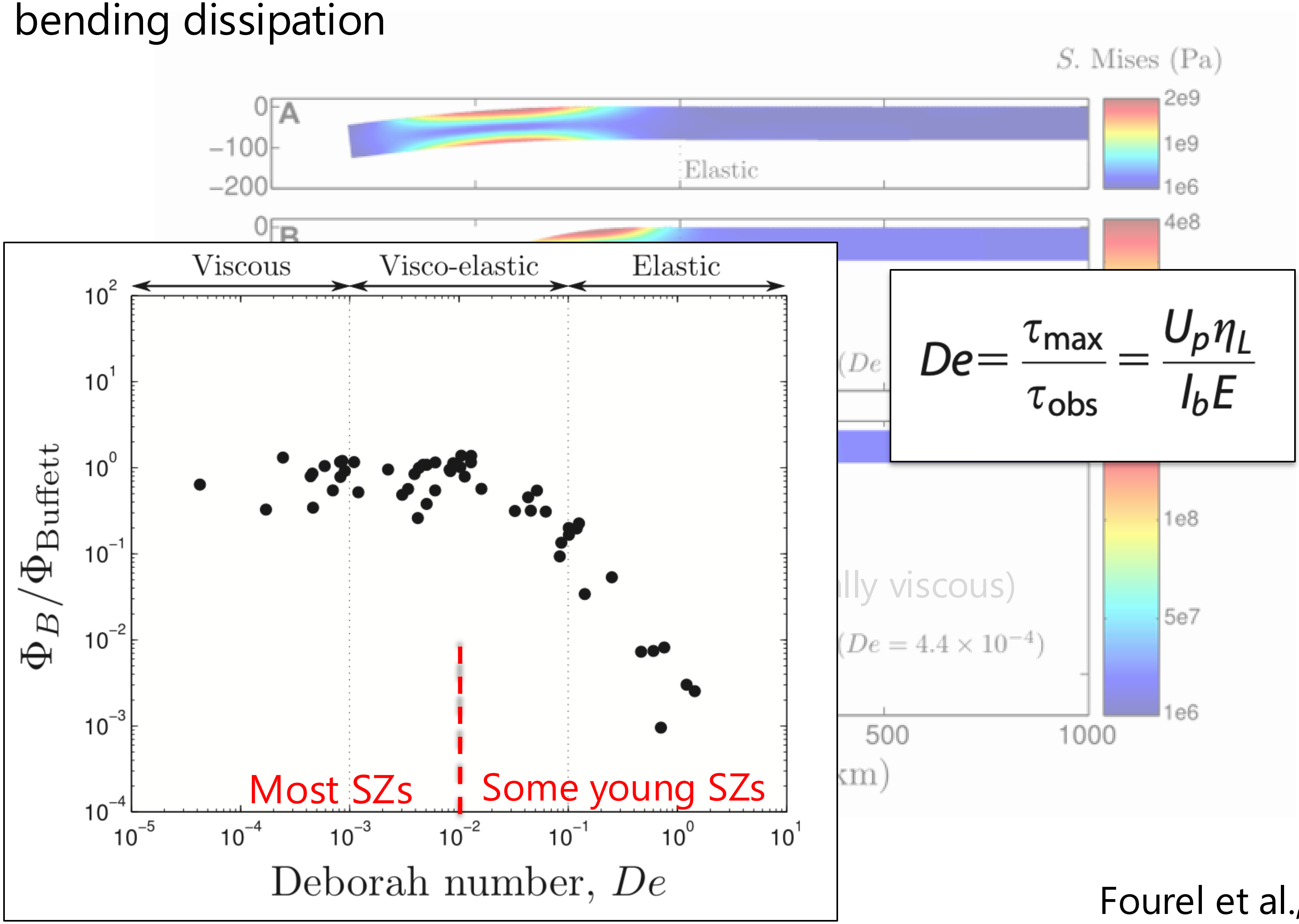


Fourel et al., 2014

cf. Farrington et al., 2014

How about elasticity?

For high Deborah numbers, viscous scaling significantly overestimate bending dissipation



$$De = \frac{\tau_{max}}{\tau_{obs}} = \frac{U_p \eta_L}{l_b E}$$

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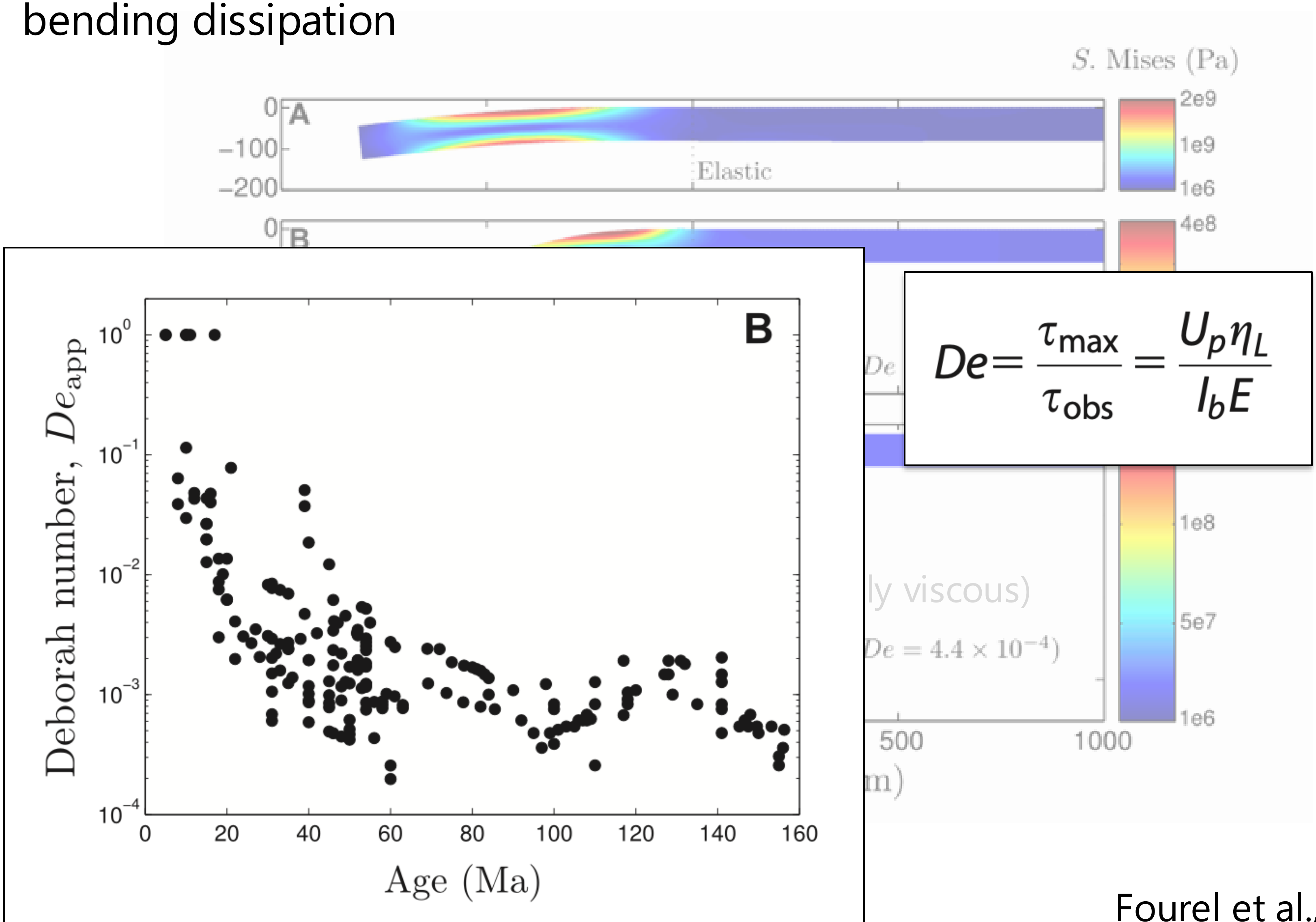

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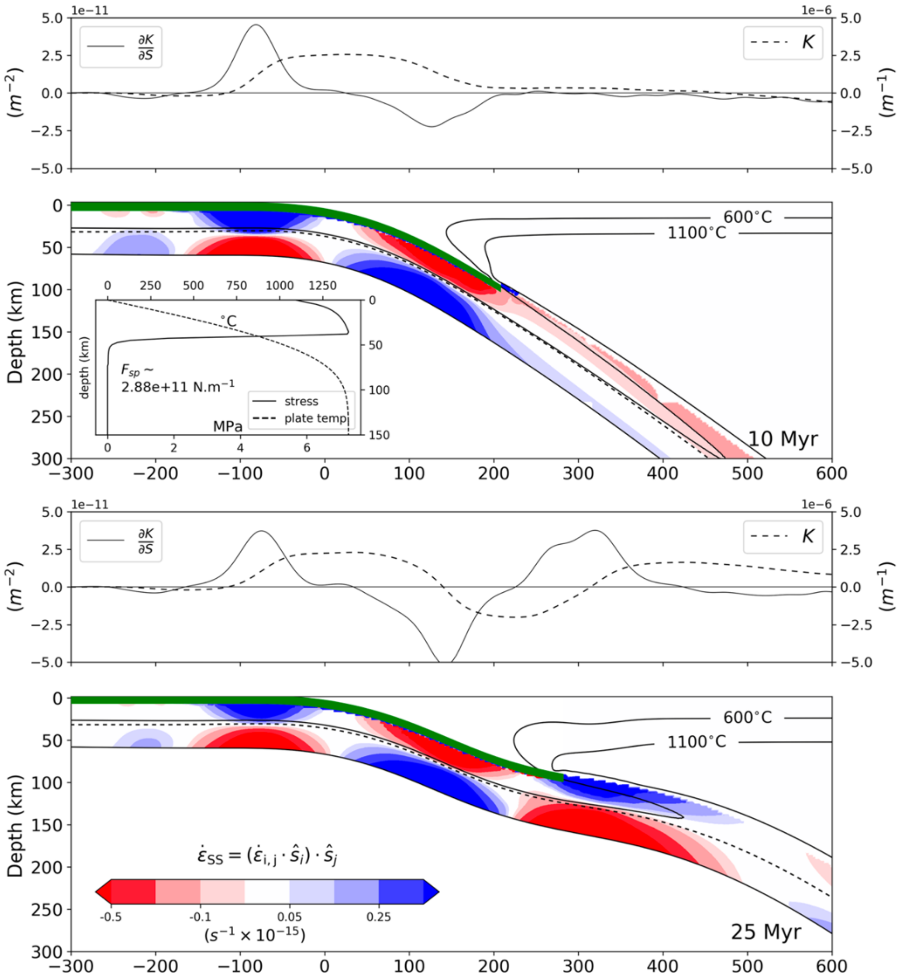
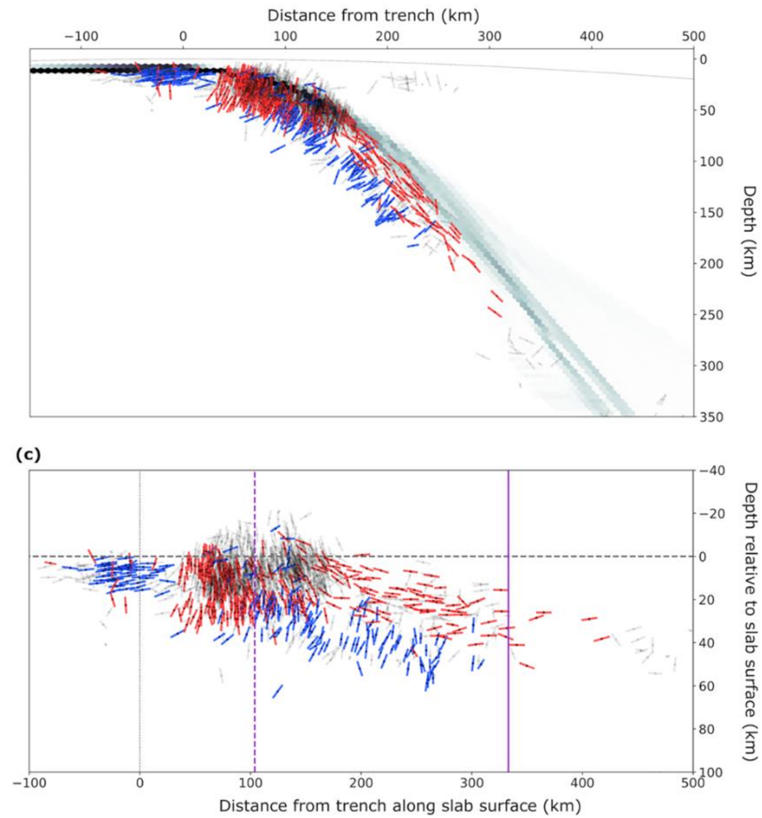
Visco-elasto-plastic





Sandiford et al., 2020

cf. Sandiford & Craig, 2023; Craig et al., 2023