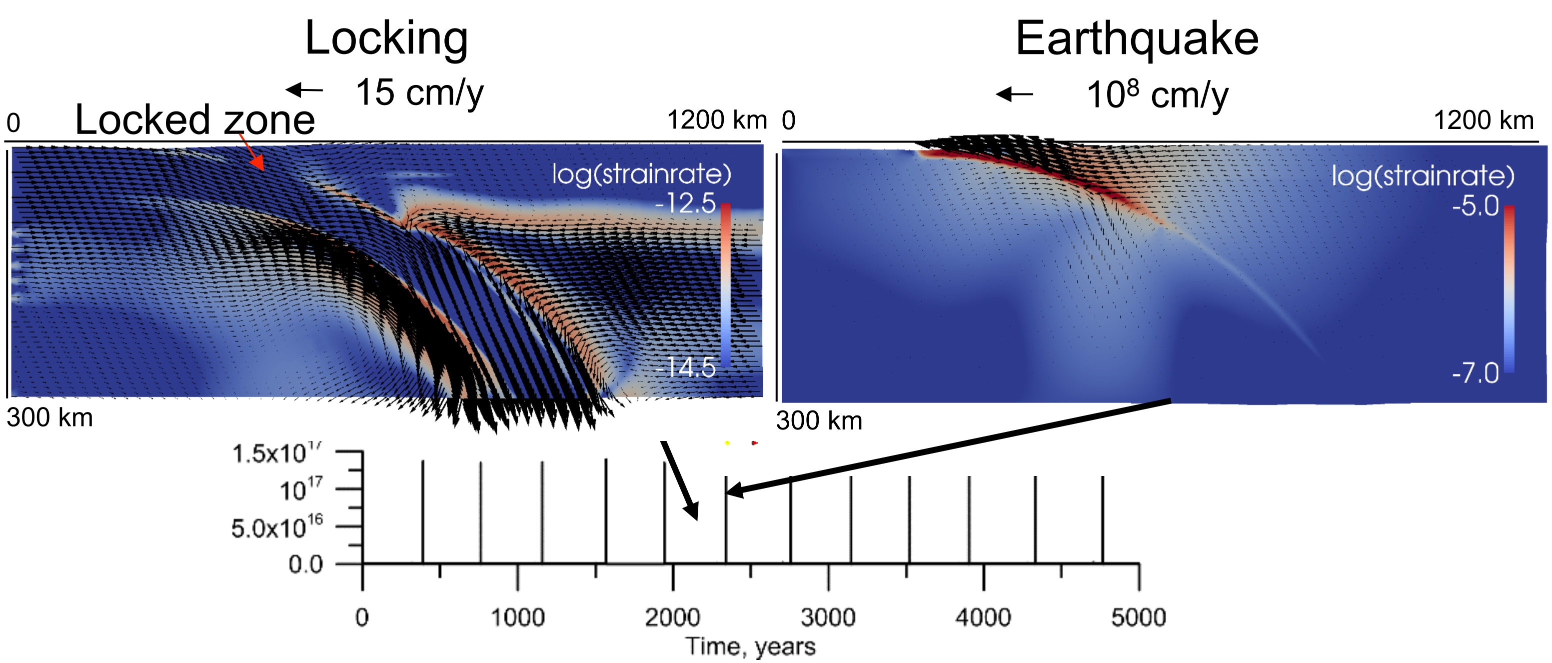
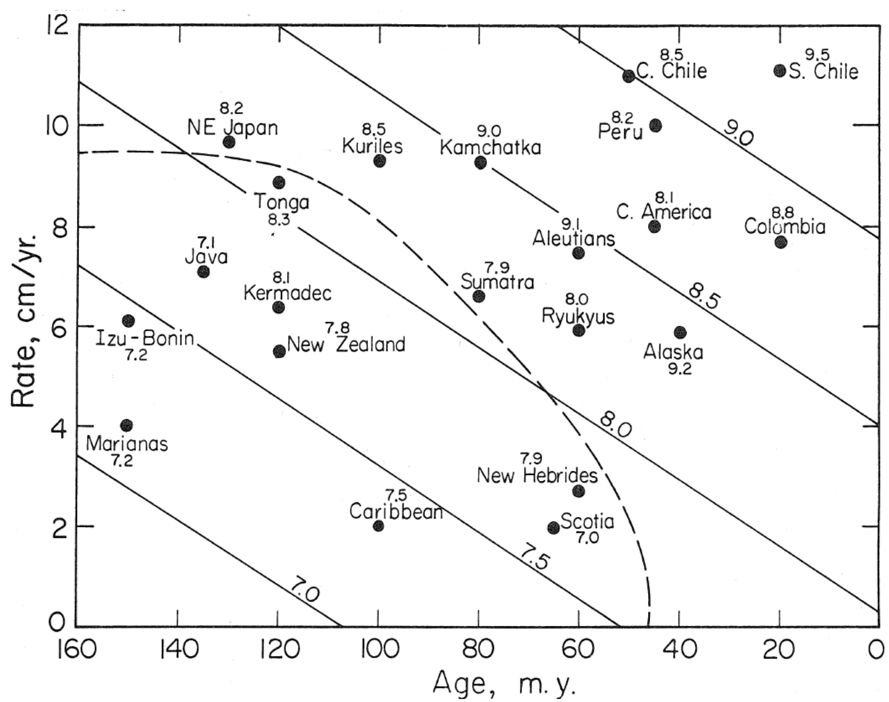
Why Great Earthquakes? A modeling approach

Stephan Sobolev
in cooperation with Iskander Muldashev



Mechanical coupling as a key factor
(Ruff and Kanamori,1980)

The strength of coupling between upper and downgoing plates may be determined as the product of the area of contact and the average stress on the contact zone.



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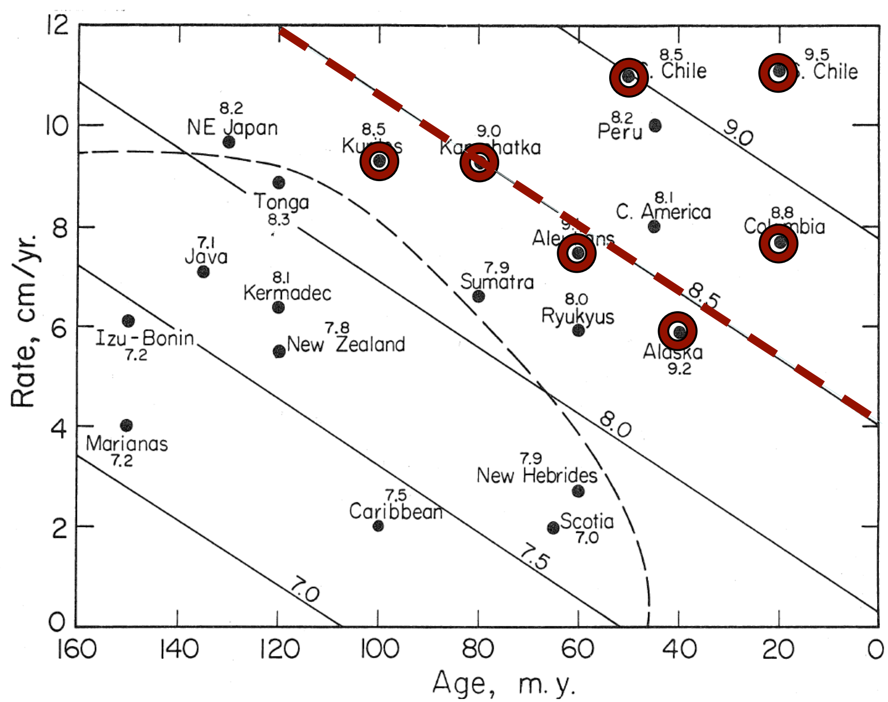

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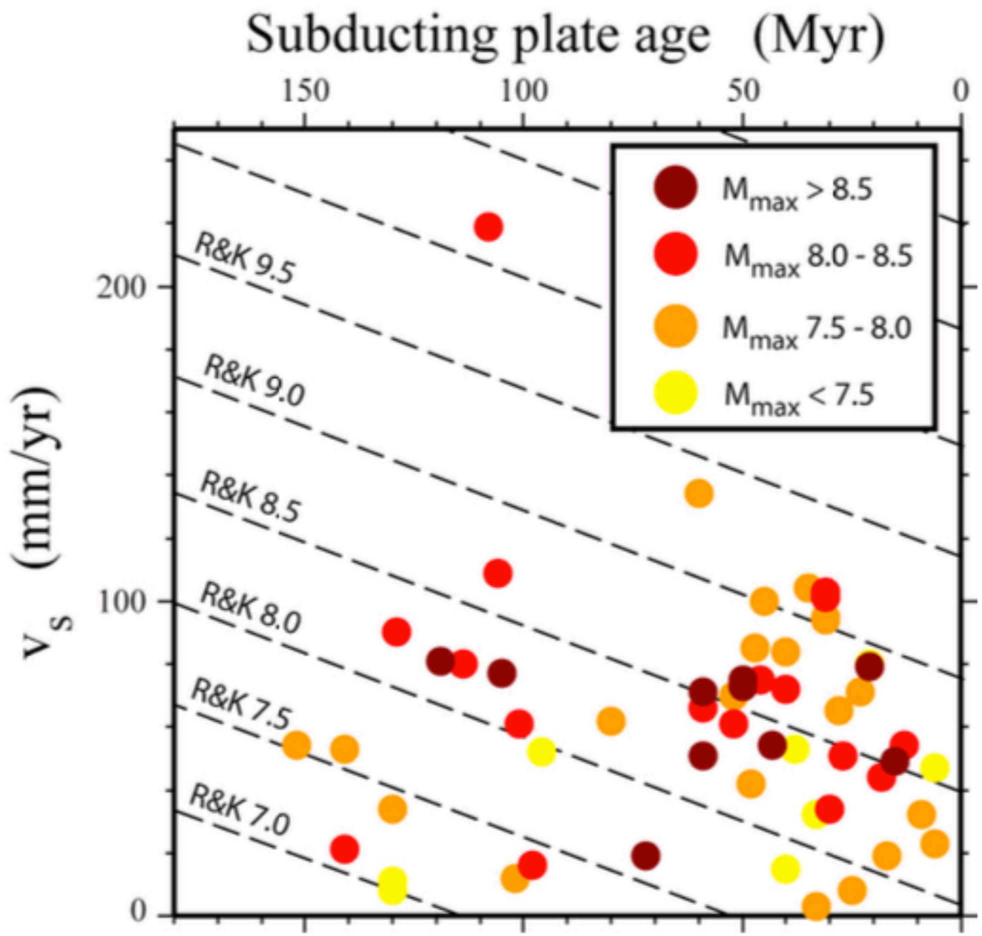

New data on Ruff and Kanamori's diagram according to Heuret et al. (2011)

The strength of coupling between upper and downgoing plates may be determined as the product of the area of contact and the average stress on the contact zone. Since large thrust earthquakes along sub-

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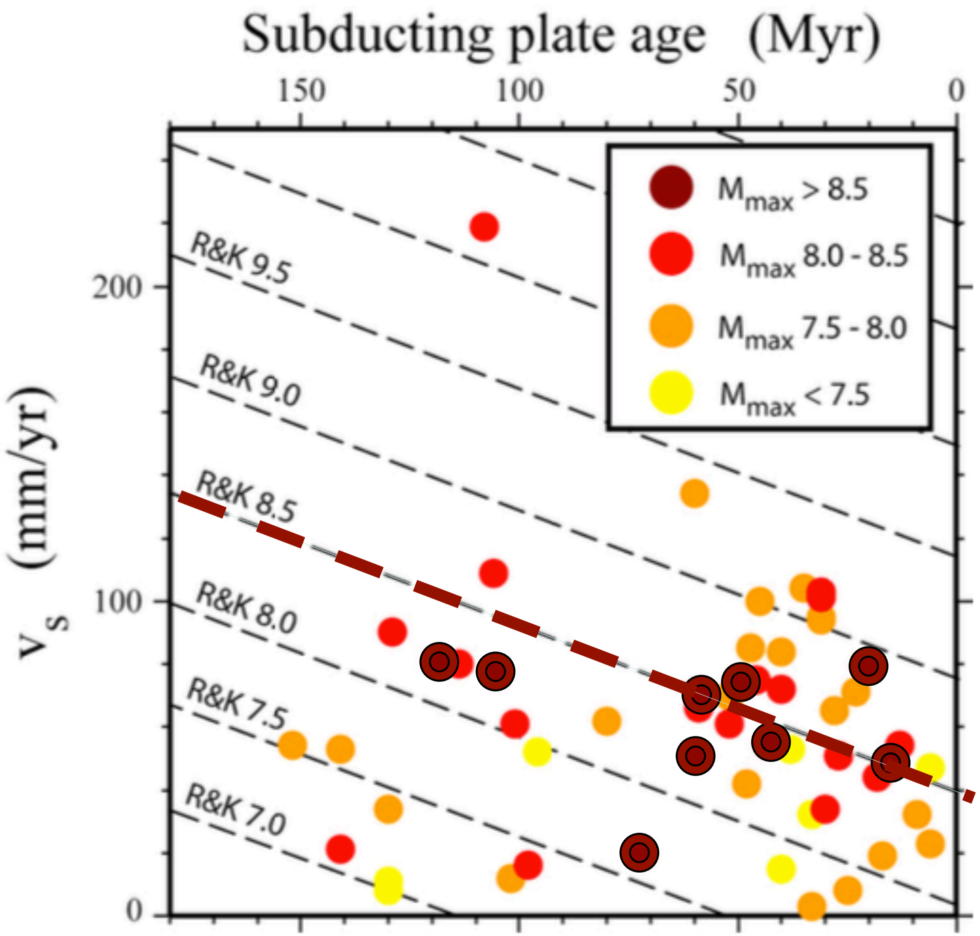

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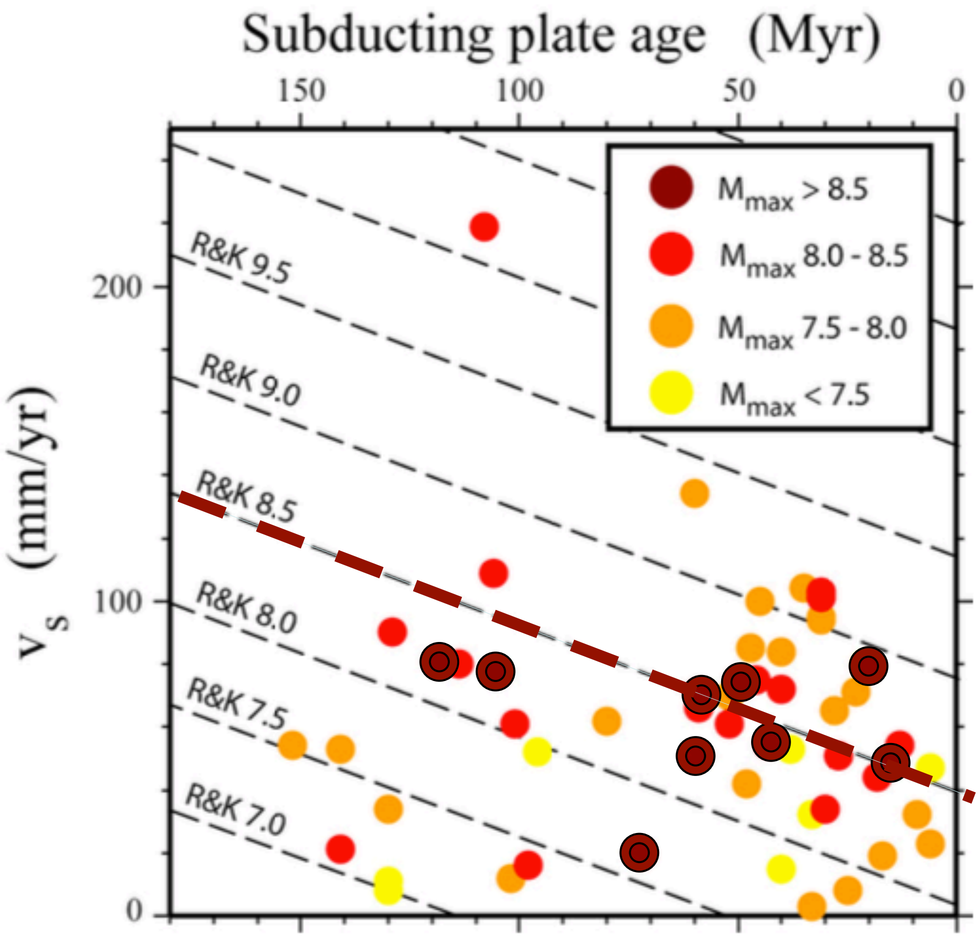

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Does not work!

Also indicated by Stein and Okal (2007) and Gutscher and Westbrook (2009)…

Mechanical coupling as a key factor
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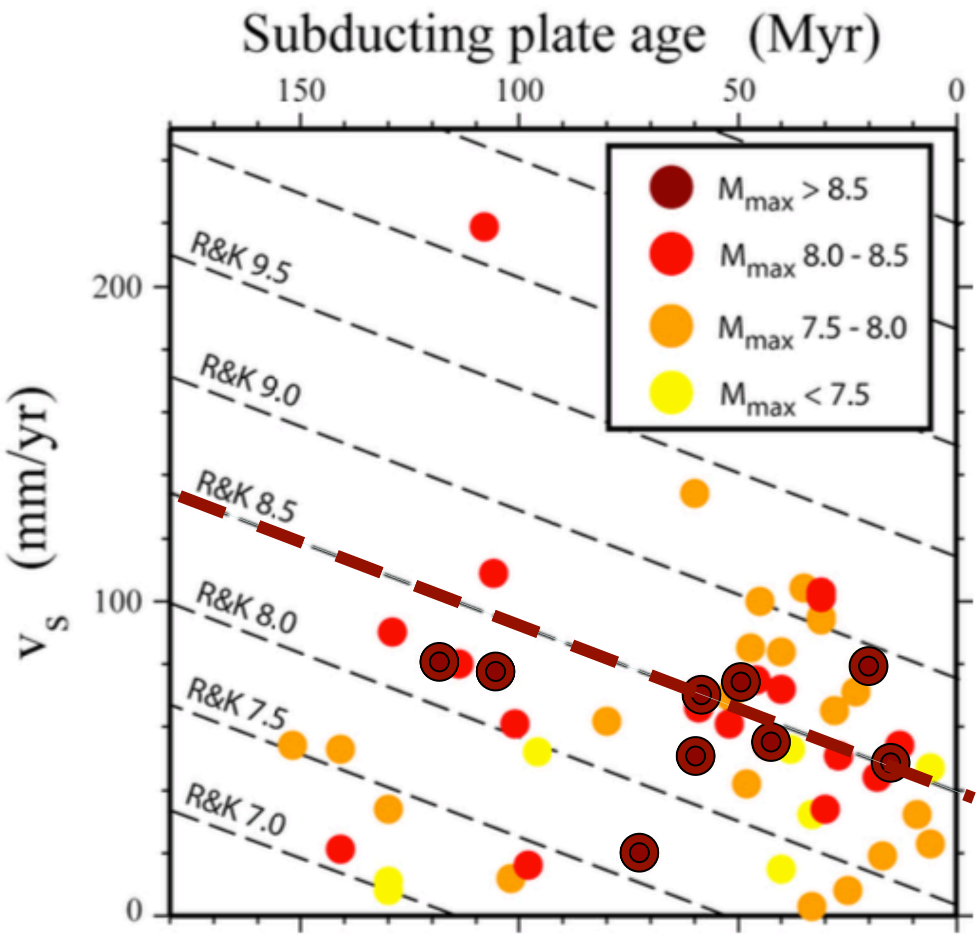

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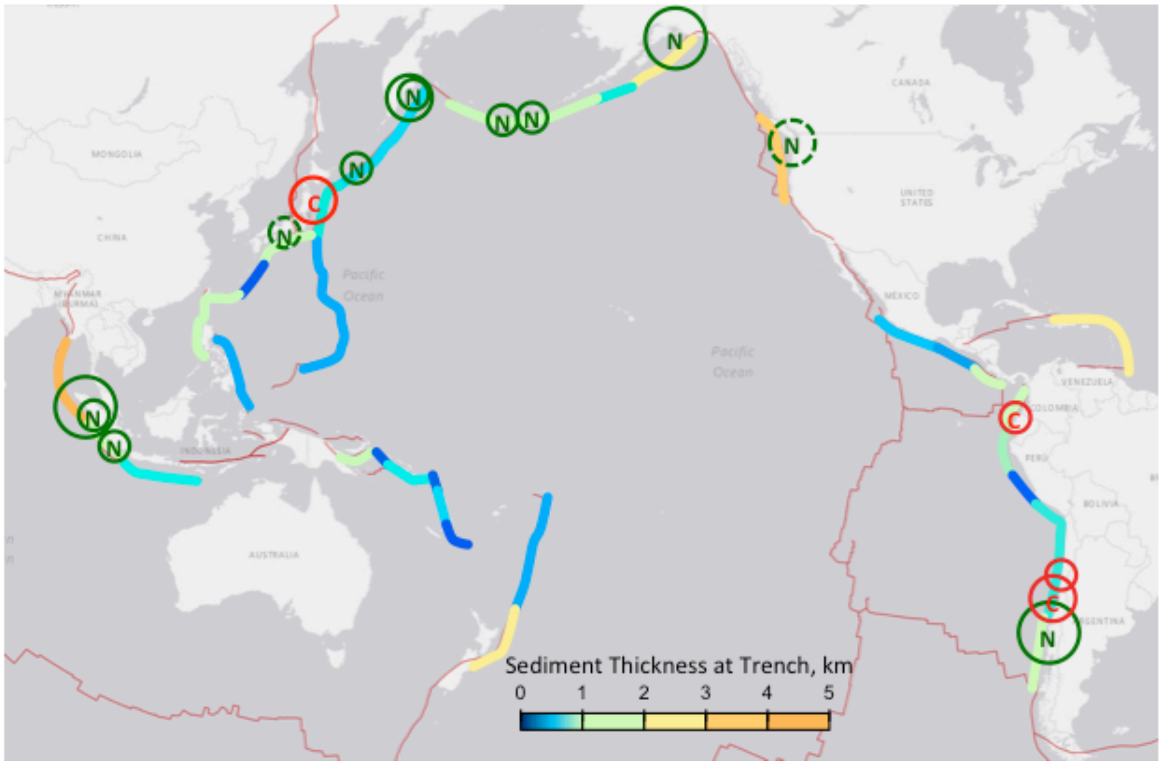
Why does not work?

Sediment Thickness in Trench

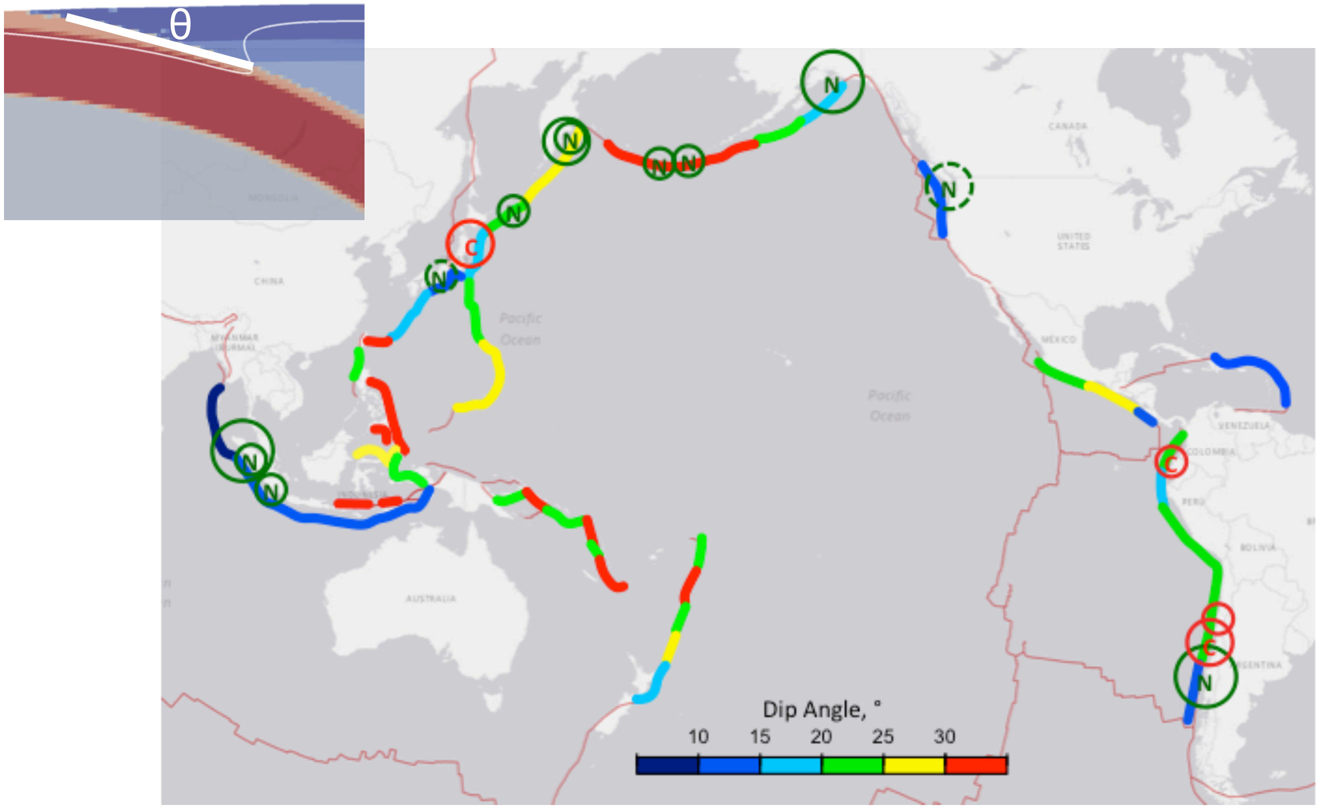


9.2 ≤ Mw   8.8 ≤ Mw < 9.2   8.4 ≤ Mw < 8.8

Compressive UPS   Neutral UPS

(Modified from Heuret et al, 2011)

Dipping Angle



9.2 ≤ Mw   8.8 ≤ Mw < 9.2   8.4 ≤ Mw < 8.8

Compressive UPS   Neutral UPS

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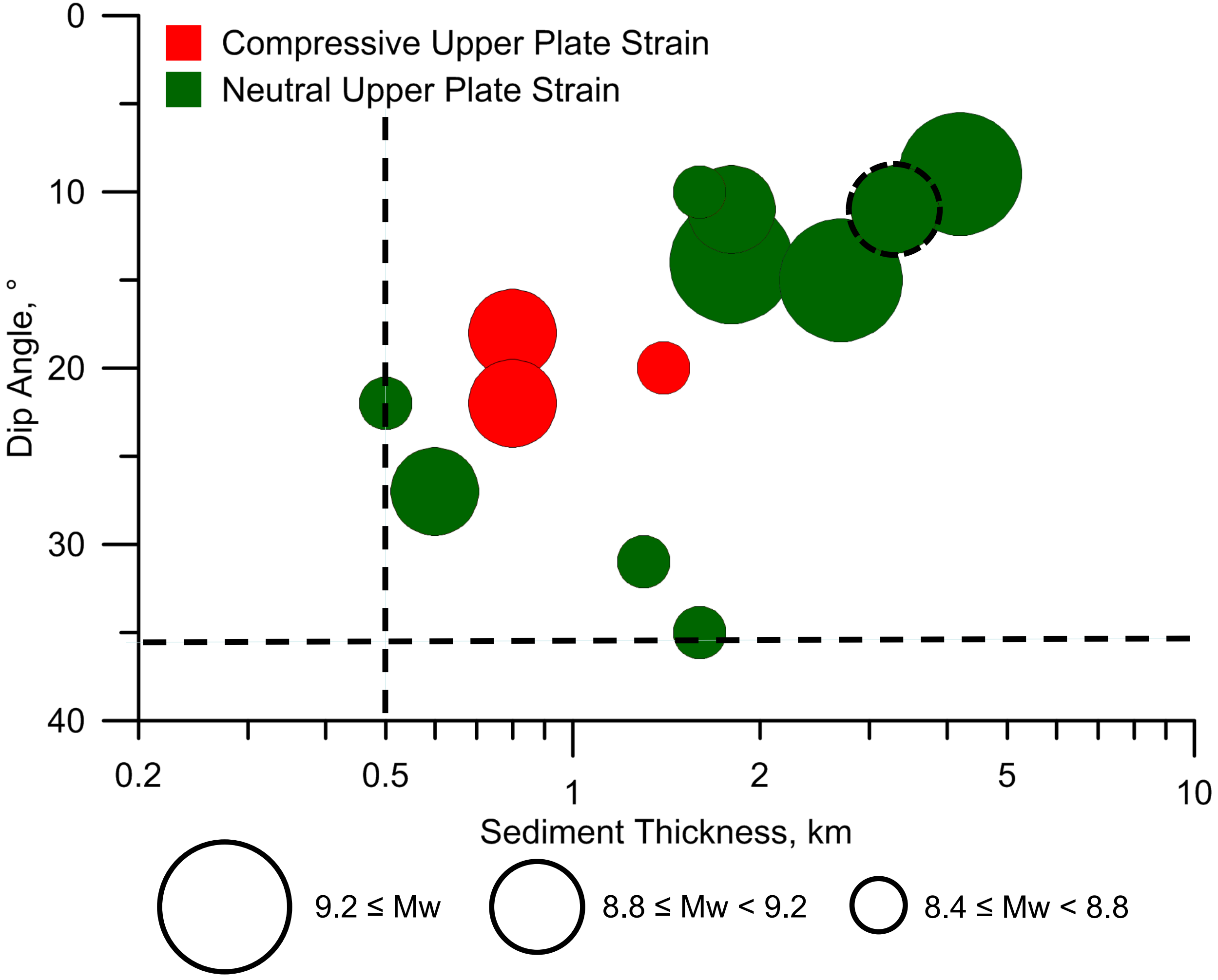
Key parameters



Key questions

What is the long-term strength of subduction interface?

Why the largest earthquakes occur at low-angle subduction interfaces filled with sediments with neutral, or rarely compressional upper plate?

Why the idea of Ruff and Kanamori (1980) does not work?

Technique

FEM codes LAPEX (Babeyko et al., 2002); SLIM3D (Popov and Sobolev PEPI, 2008)

Conservation equations

Mass $$\frac{1}{K}\frac{DP}{Dt} - \alpha \frac{DT}{Dt} + \frac{\partial v_i}{\partial x_i} = 0$$

Momentum $$-\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i = \rho \frac{Dv_i}{Dt}$$

Energy $$\rho C_p \frac{DT}{Dt} = \frac{\partial}{\partial x_i}\left(\lambda \frac{\partial T}{\partial x_i}\right) + \frac{1}{\eta_{eff}} \tau_{ij}\tau_{ij} + \rho A$$

Deformation mechanisms

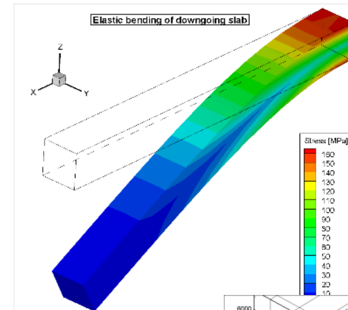
$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}_{ij}^{el} + \dot{\varepsilon}_{ij}^{vs} + \dot{\varepsilon}_{ij}^{pl}$$

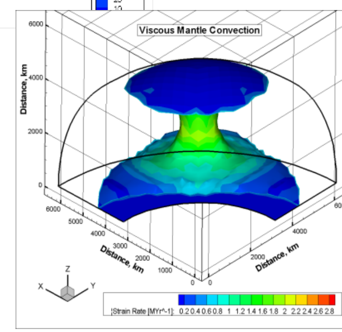
Elastic strain: $$\dot{\varepsilon}_{ij}^{el} = \frac{1}{2G}\hat{\tau}_{ij}$$

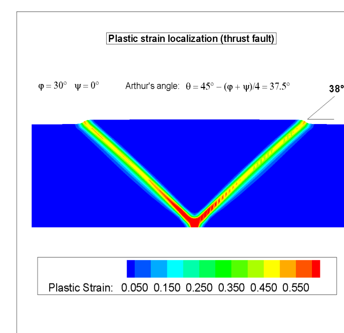
Viscous strain: $$\dot{\varepsilon}_{ij}^{vs} = \frac{1}{2\eta_{eff}}\tau_{ij}$$

Mohr-Coulomb

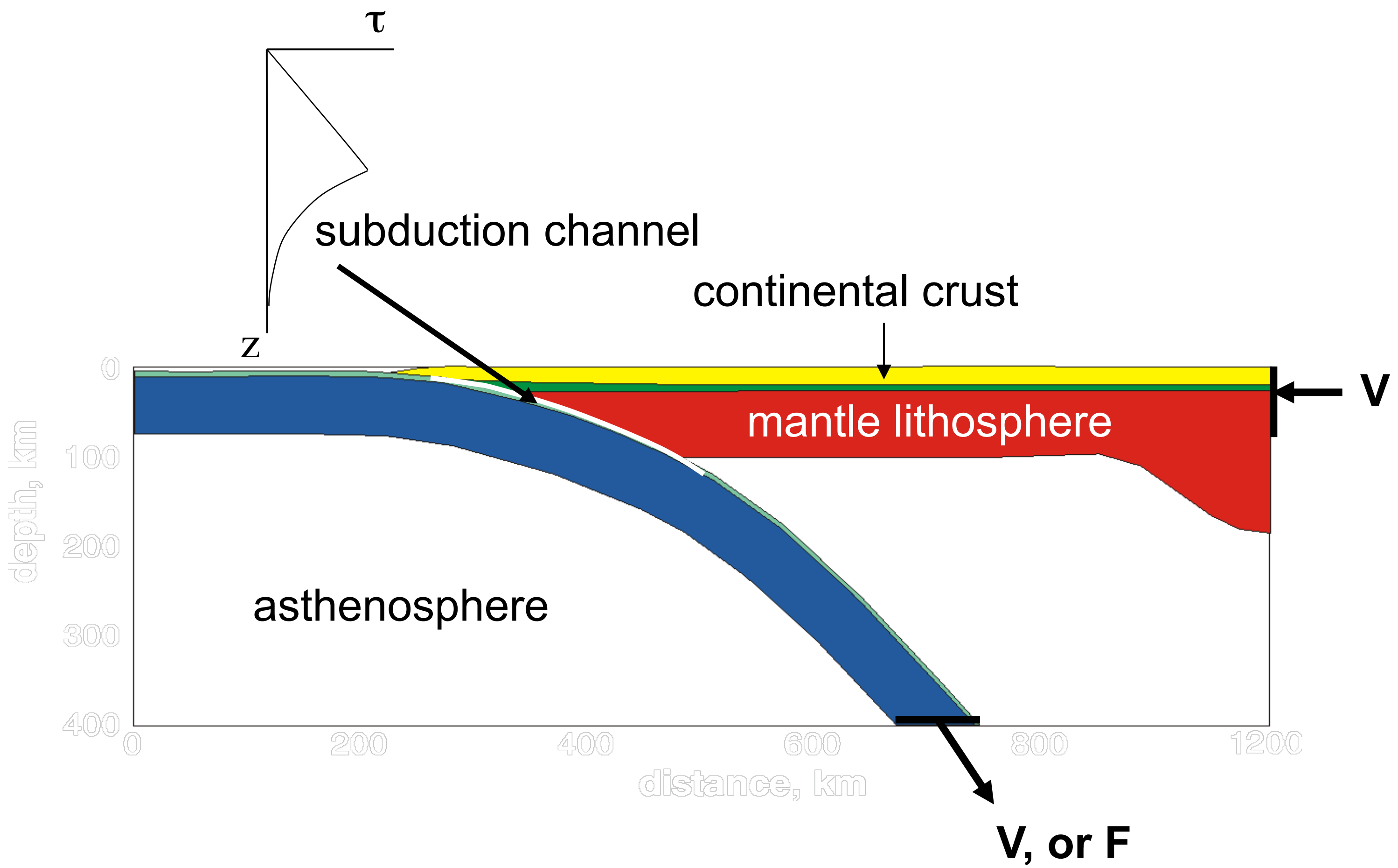
Plastic strain: $$\dot{\varepsilon}_{ij}^{pl} = \dot{\gamma}\frac{\partial Q}{\partial \tau_{ij}}$$





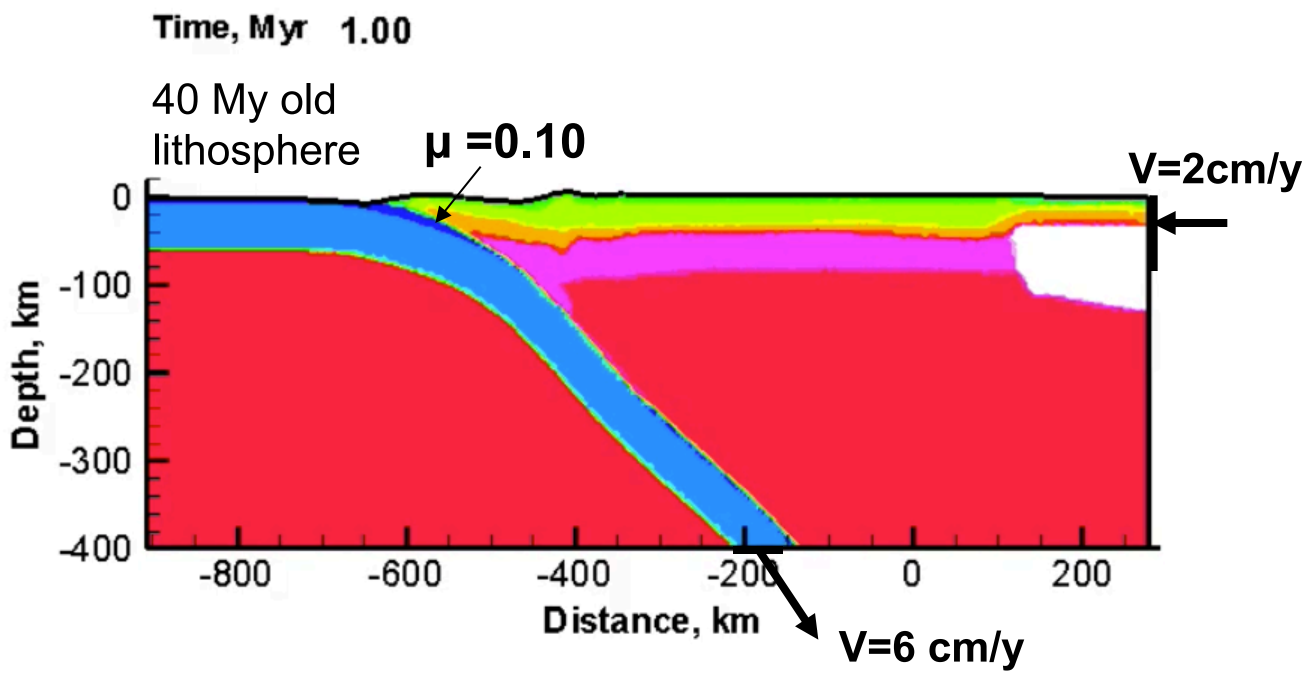


Long-term subduction



Sobolev and Babeyko, 2005, Sobolev et al., 2006

Long-term subduction



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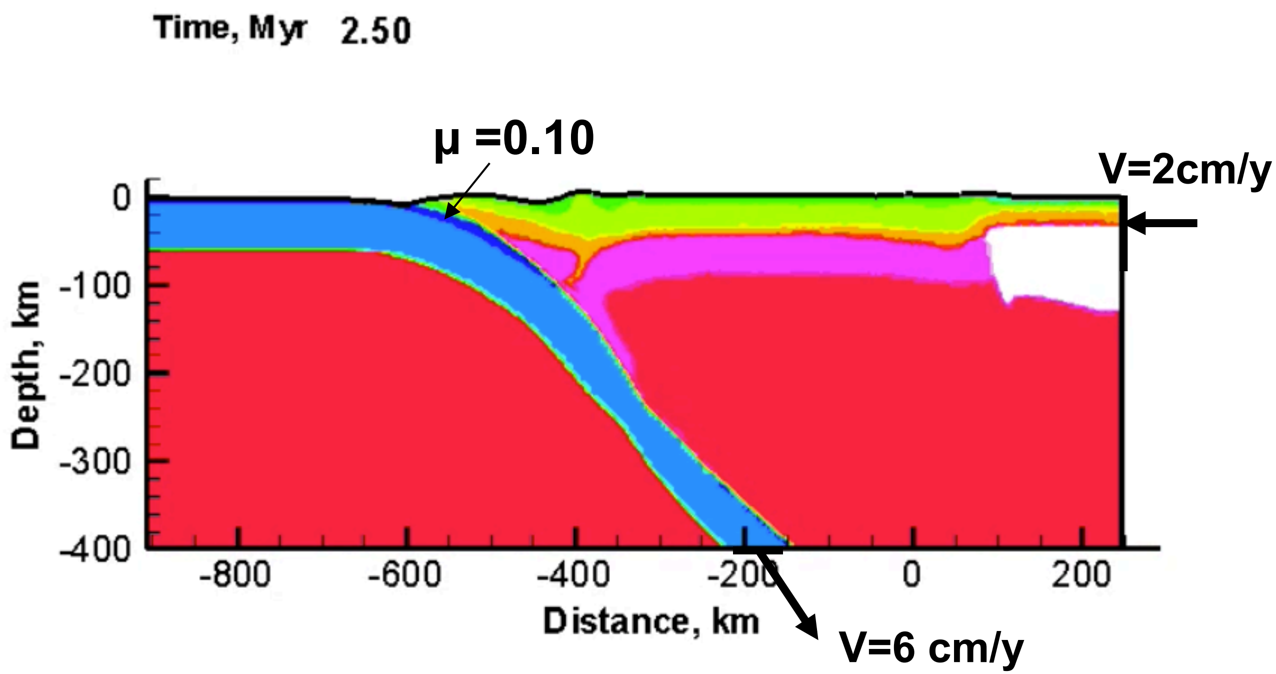

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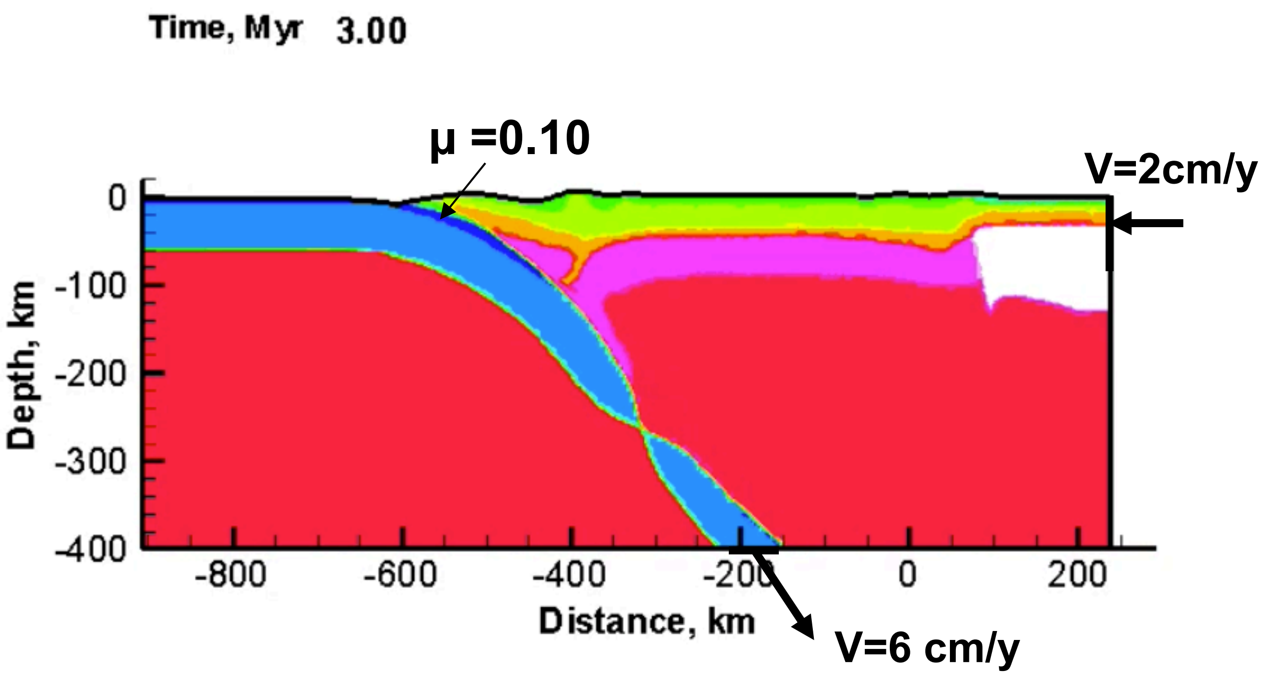
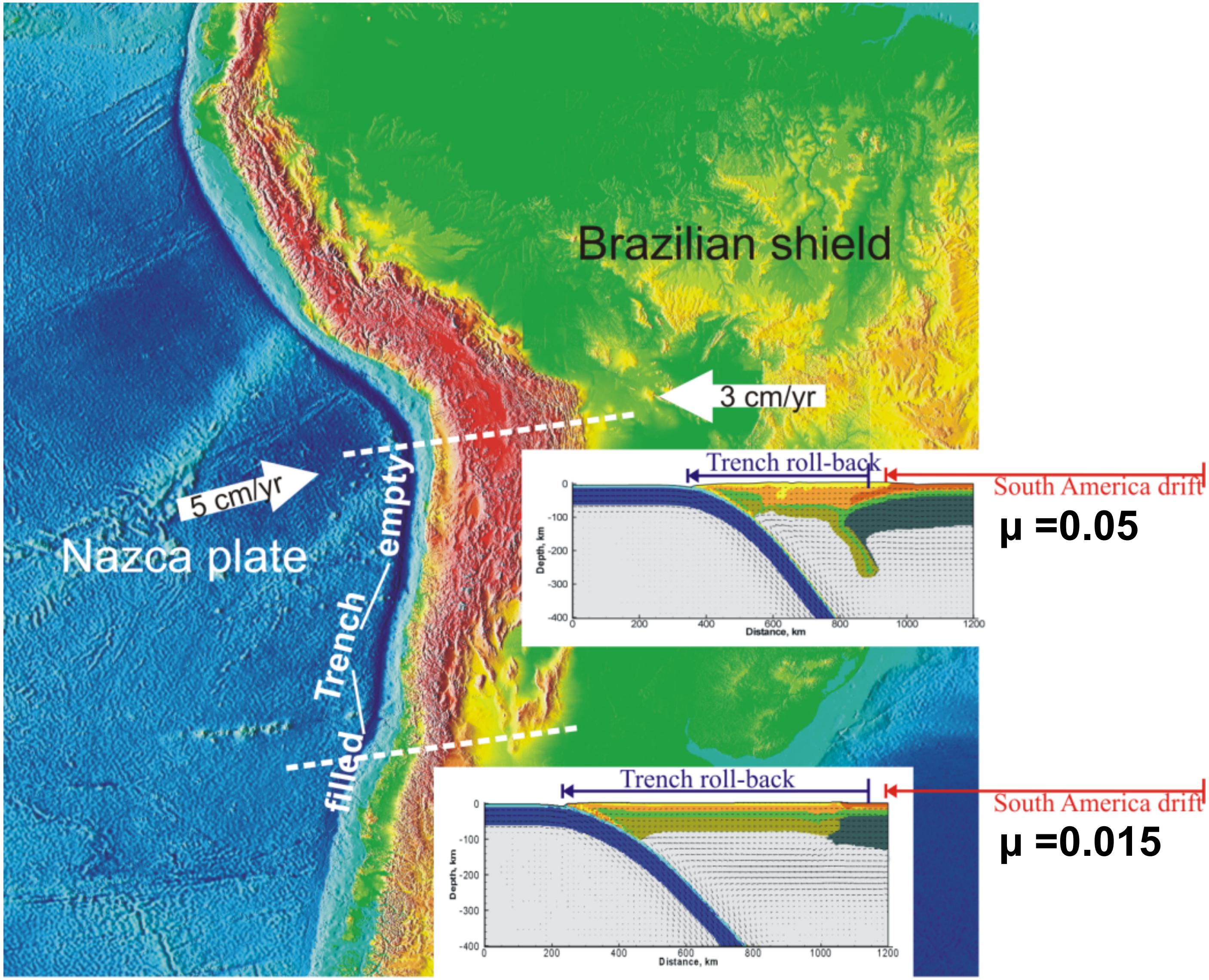


Subduction zone survives only at friction in the channel below 0.1-0.15

Long-term subduction



Sobolev and Babeyko, 2005, Sobolev et al., 2006

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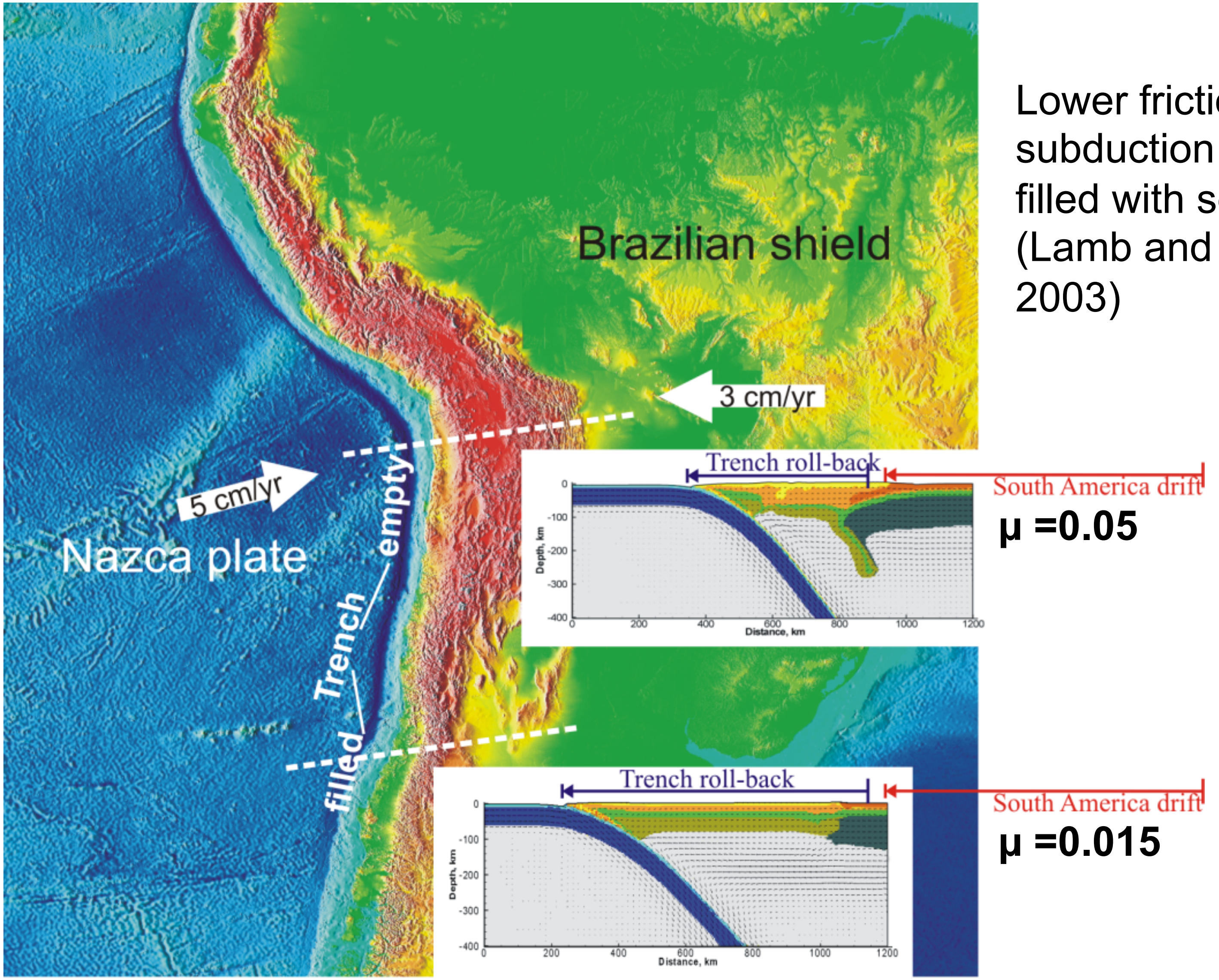
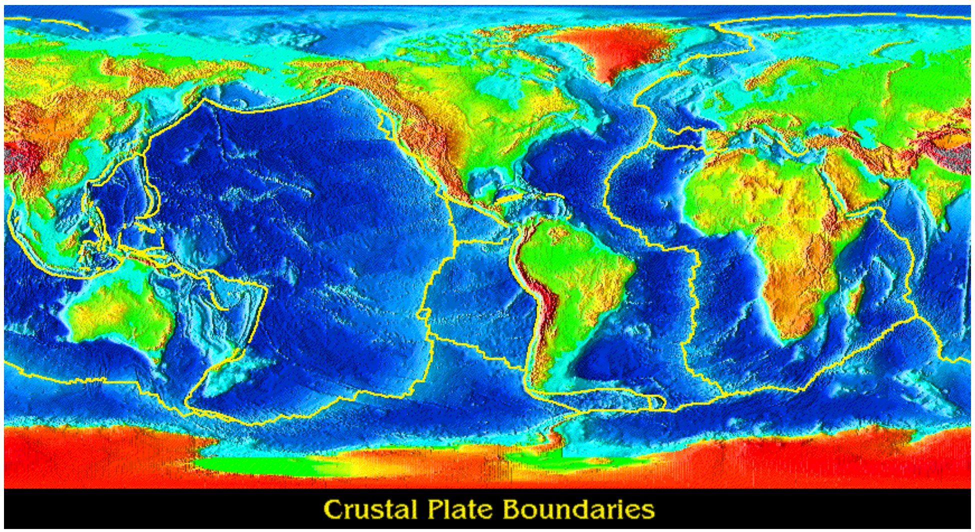


Lower friction in subduction channels filled with sediments (Lamb and Davies, 2003)

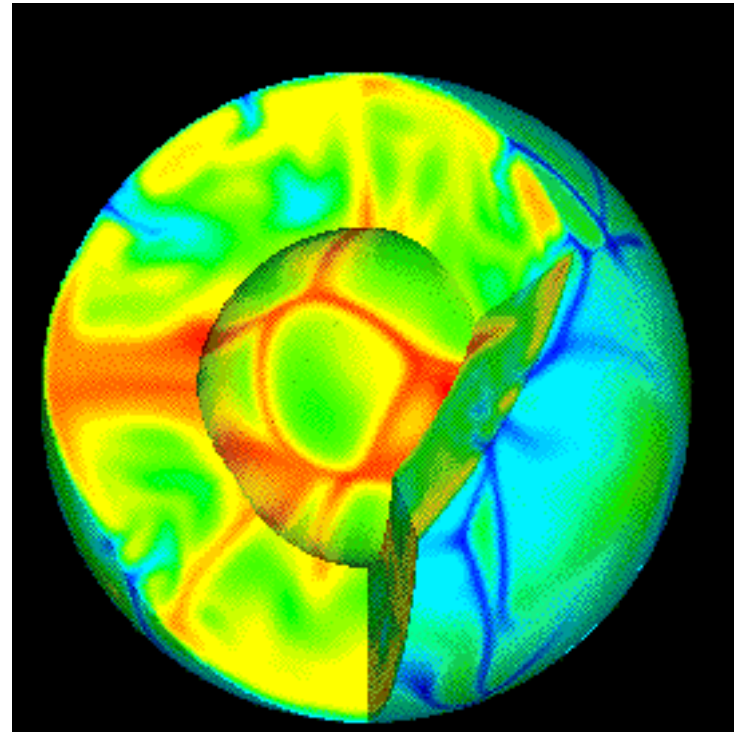
Sobolev and Babeyko, 2005, Sobolev et al., 2006

Conditions for plate tectonics

Convection



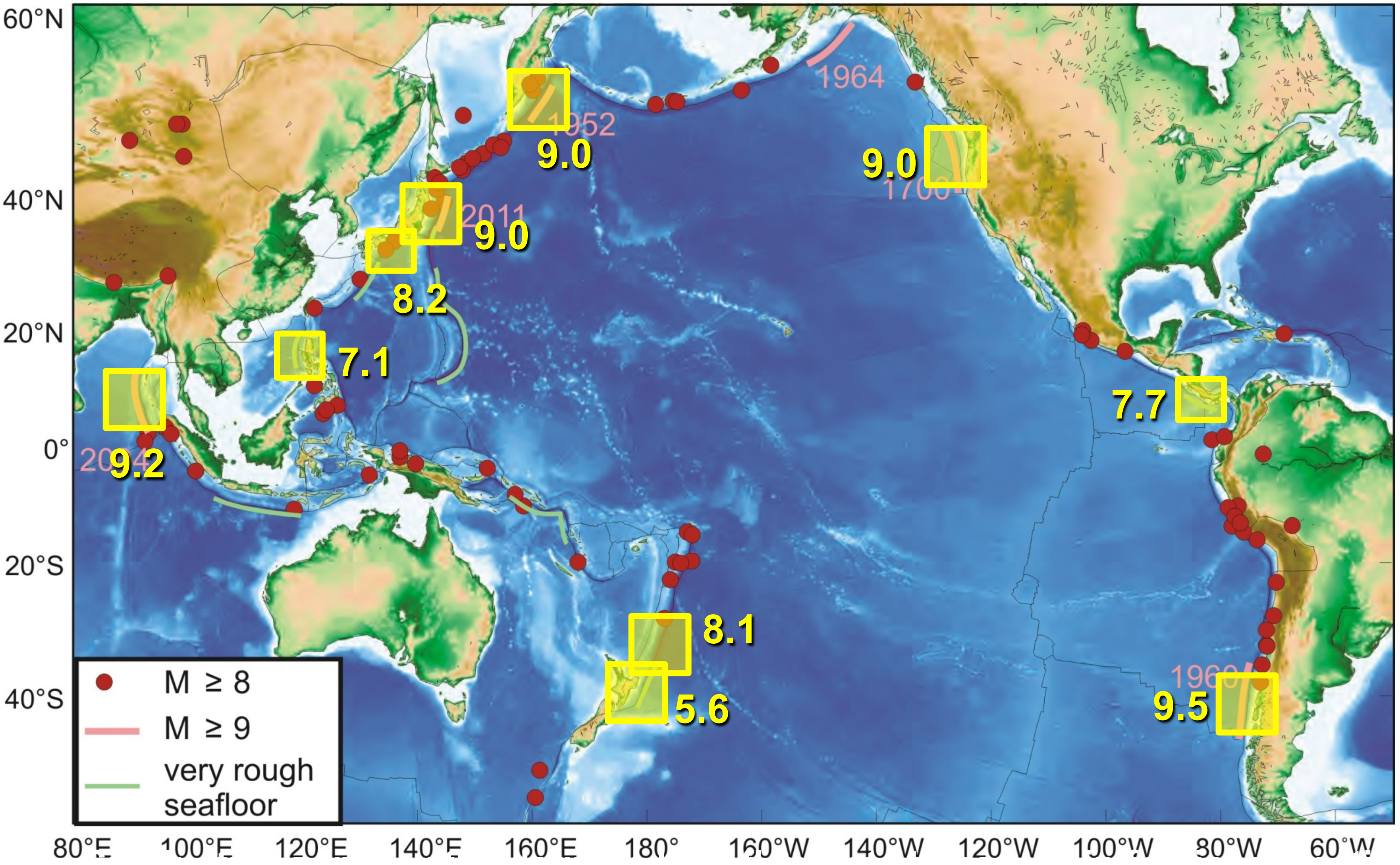
Weak plate boundaries



Ricard and Vigny, 1989; Fowler, 1993; Bercovici, 1993; Bird, 1998; Moresi and Solomatov, 1998; Tackley, 1998, Zhong et al, 1998; Trompert and Hansen, 1998; Gurnis et al., 2000….

Global model (Sobolev et al., 2009, Osei Tutu et al. G3 under review)

Friction from heat flow



Gao and Wang, 2014

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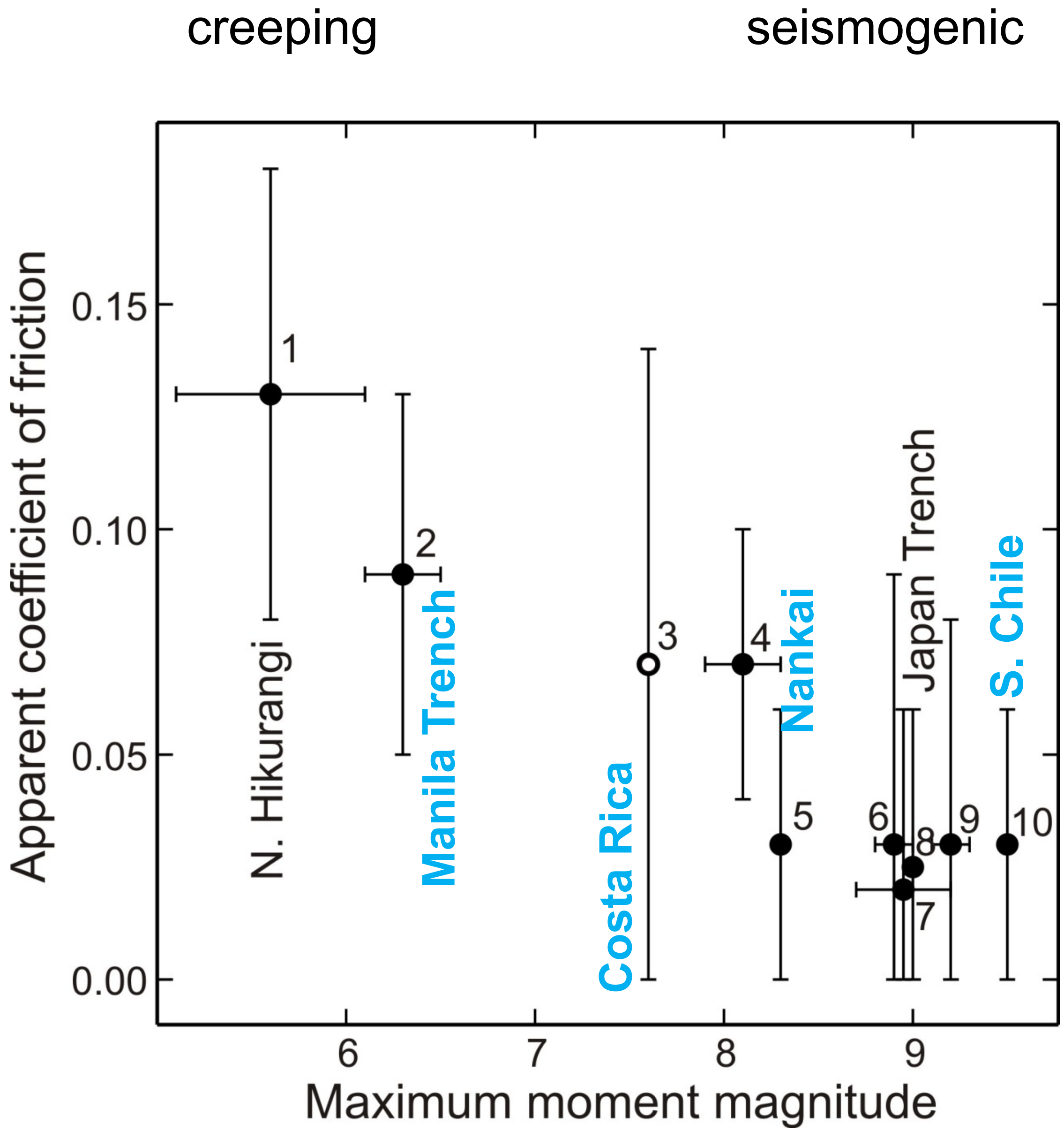

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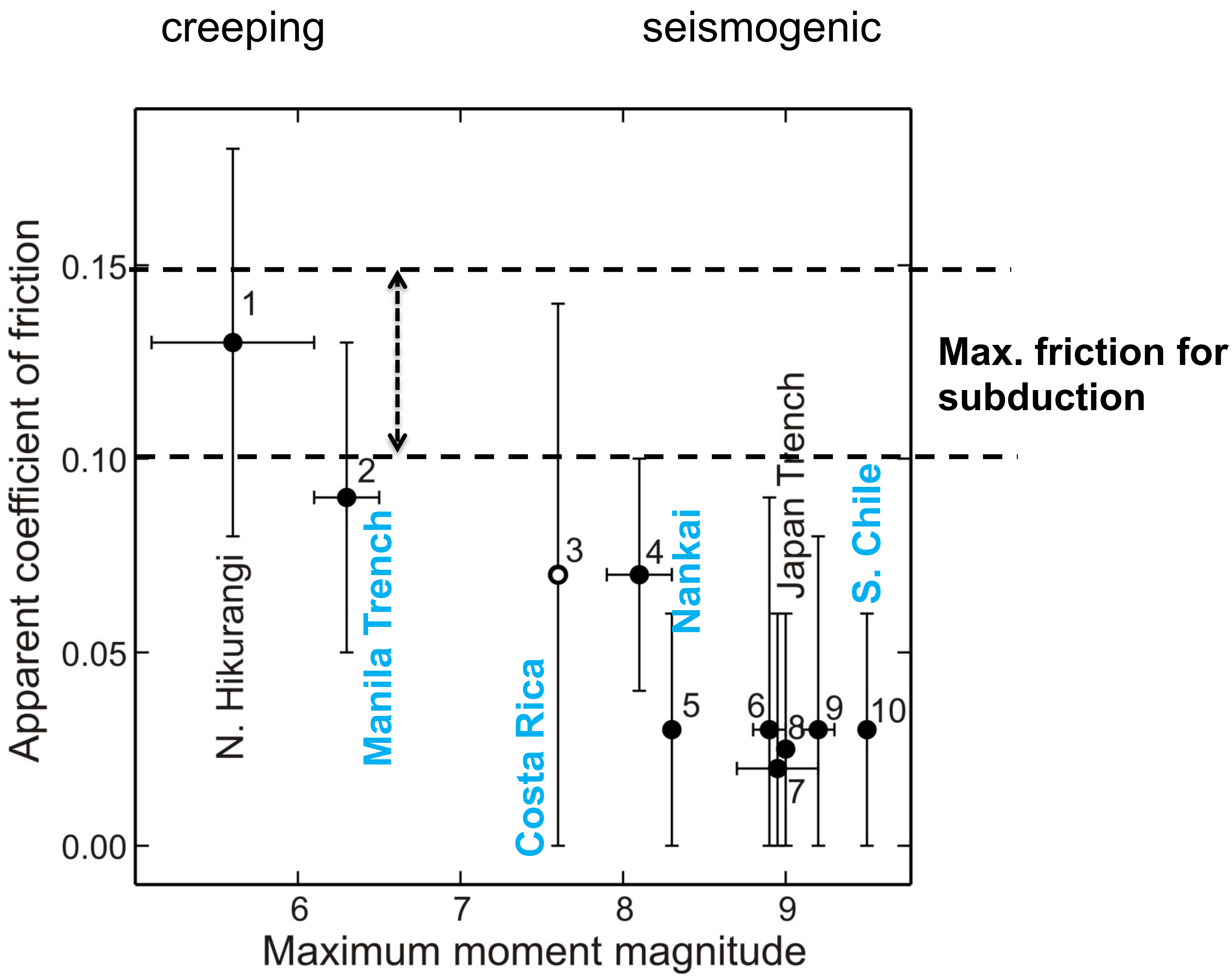
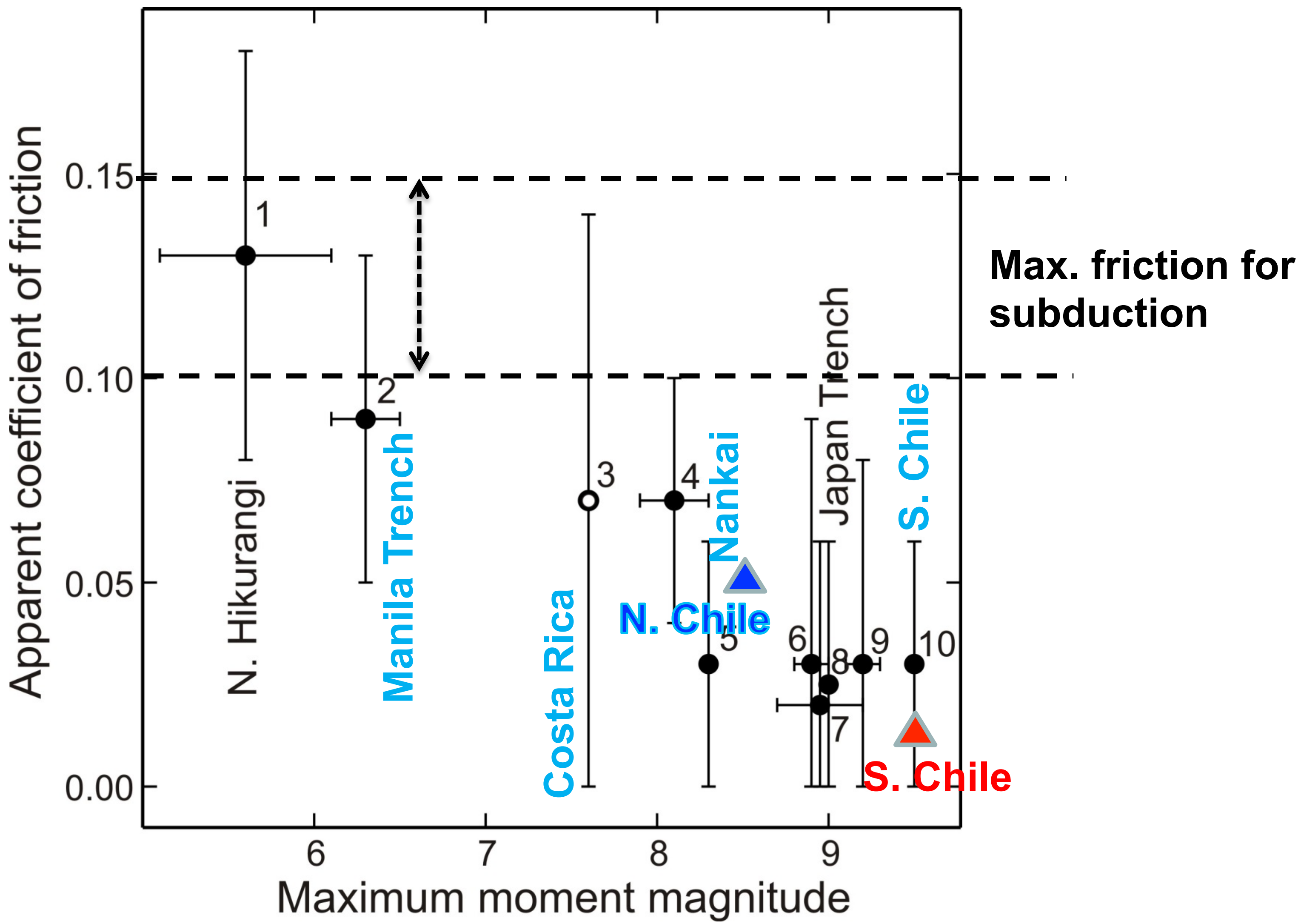


Gao and Wang, 2014

Friction from heat flow

creeping seismogenic



Gao and Wang, 2014

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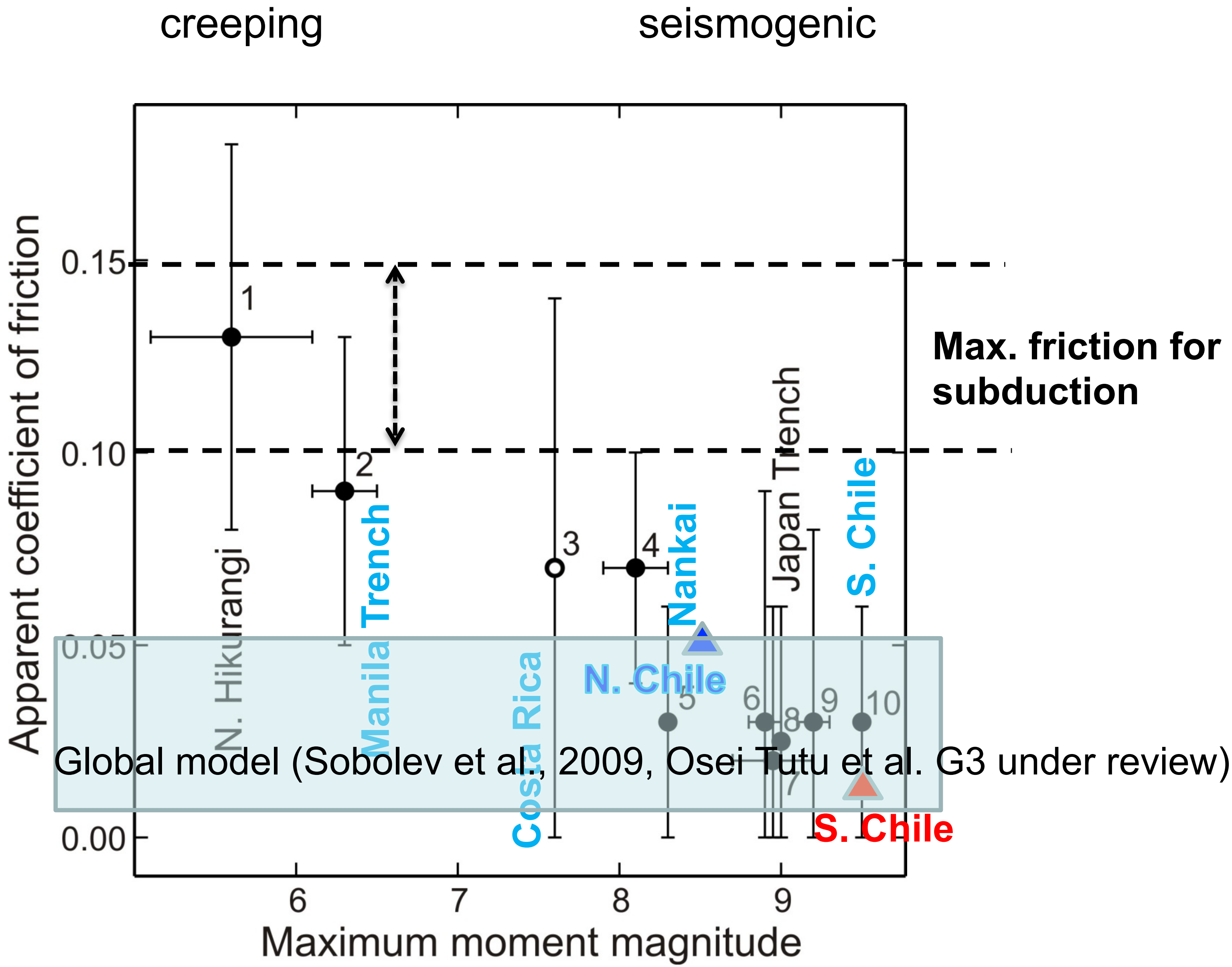


Gao and Wang, 2014

How to make friction so low?

$$\tau = c + \mu \cdot (\sigma_n - P_f)$$

$$\tau = c + \mu_{eff} \cdot \sigma_n$$

$$\mu_{eff} = \mu \cdot (1 - P_f / \sigma_n)$$

Assume μ = 0.6, P_f=0.95σ_n

<u>then μ_{eff} = 0.03</u>

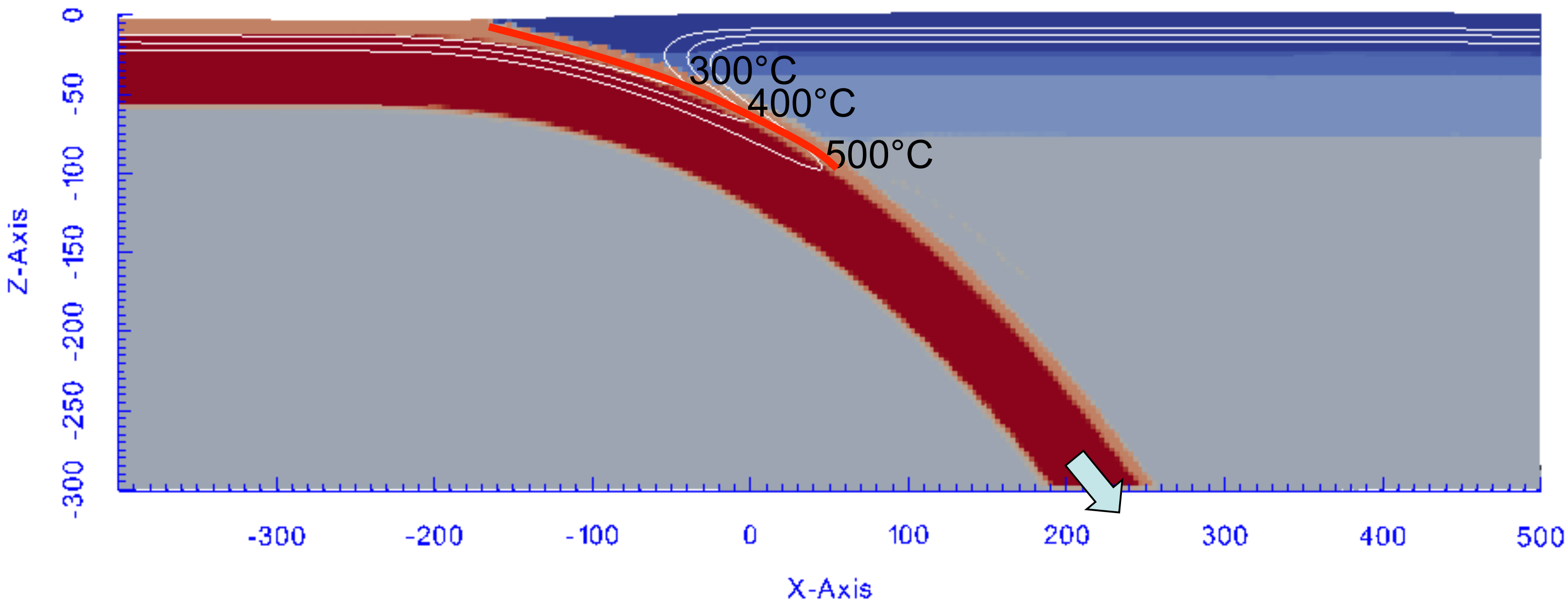
How to make friction so low?

How to make friction so low?

Subducting slabs are aquaplaning deep into the mantle!

Cross-scale Modeling of Seismic Cycle

SLIM3D code; 10 Mln. years evolution, η(T,P,σ), static friction



Rate and State Friction Law

$$\tau = \sigma_n (1 - \frac{P_f}{\sigma_n})(\mu^* + a \ln\left(\frac{V}{V^*}\right) + b \ln\left(\frac{\theta V^*}{L}\right))$$

and

$$\frac{d\theta}{dt} = 1 - \frac{\theta V}{L}$$

were:

- V and θ are sliding speed and contact state, respectively.
- a, b are non-dimensional empirical parameters.
- *L* is a characteristic sliding distance.
- The * stands for a reference value.

Seismic Cycle Model

Adaptive time-step gradually increasing from **40 sec** at earthquake to **5 years** in interseismic period, following decreasing strain rate

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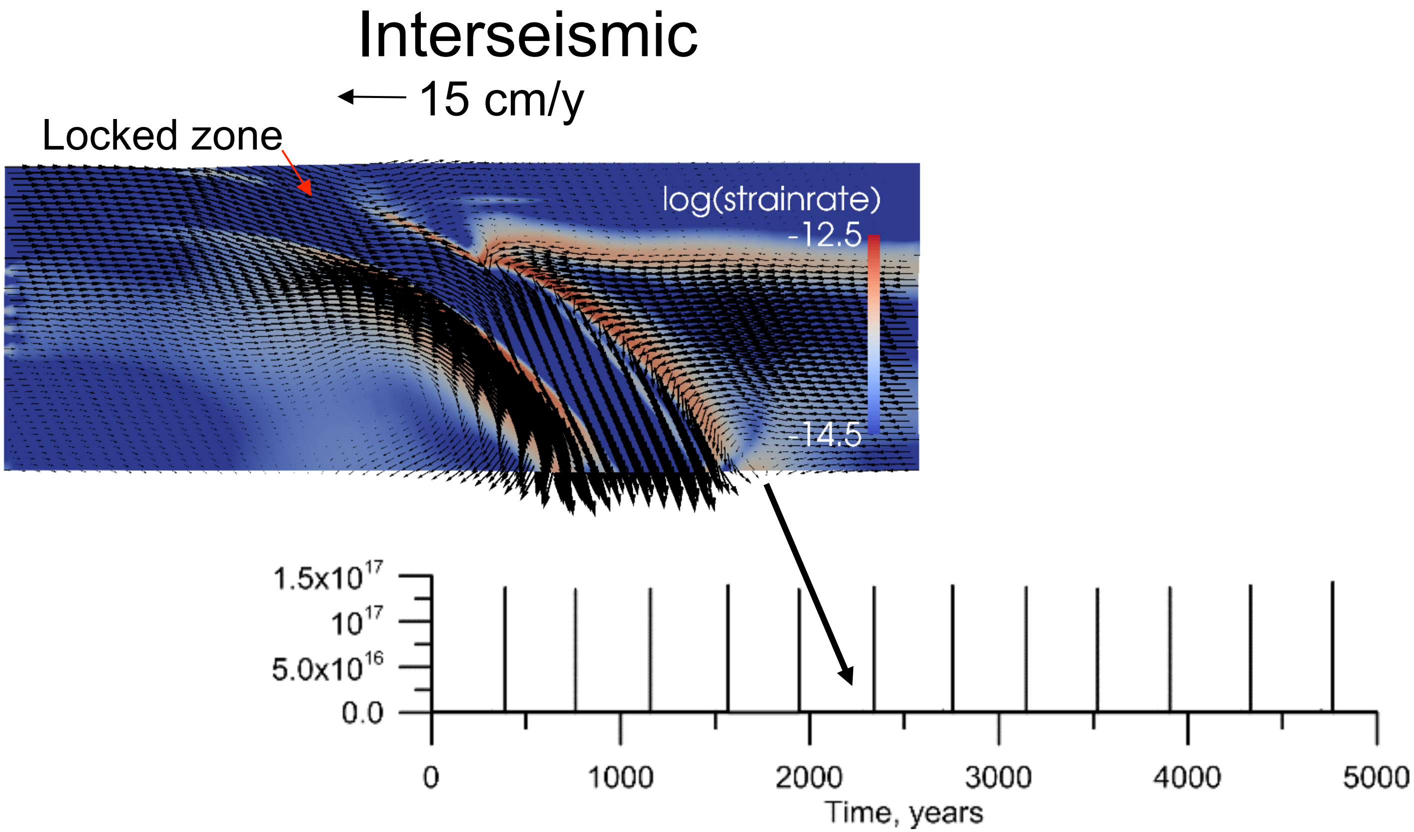

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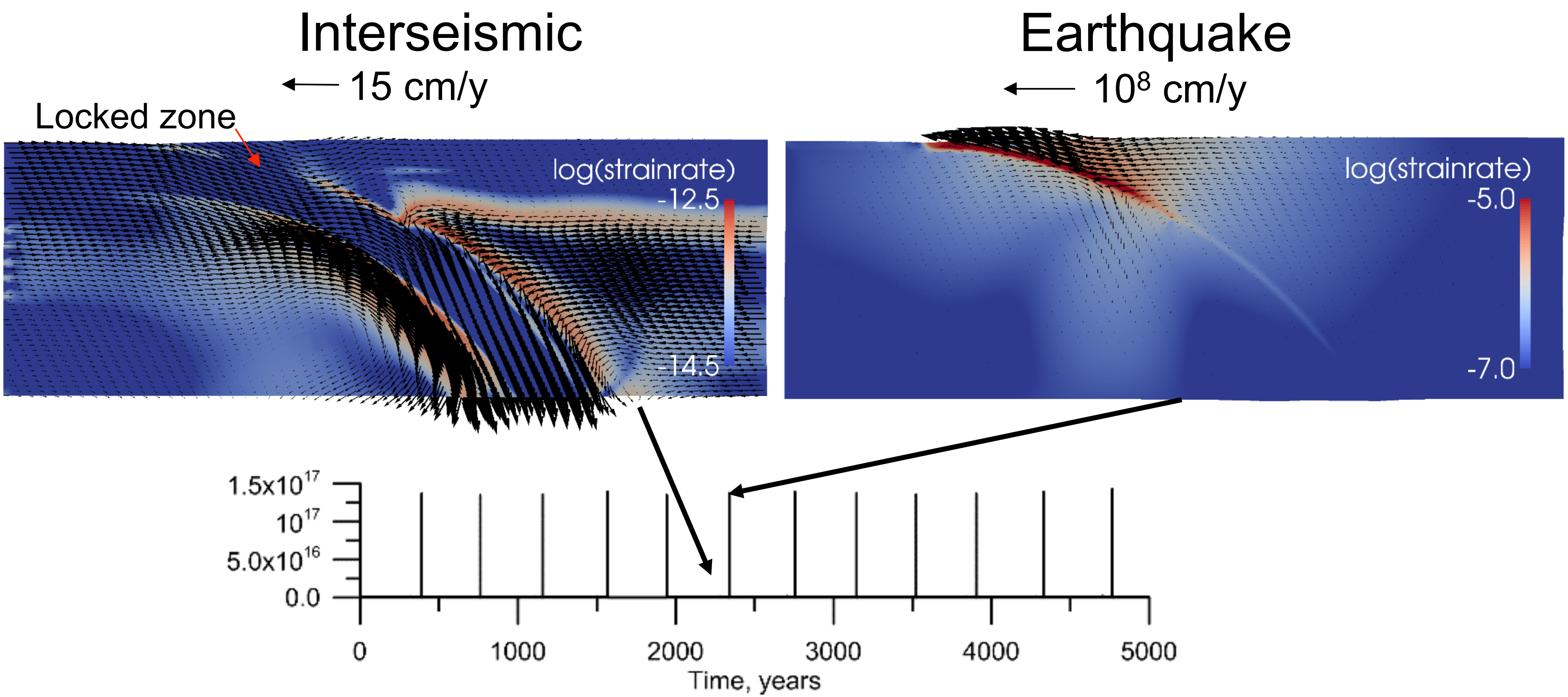
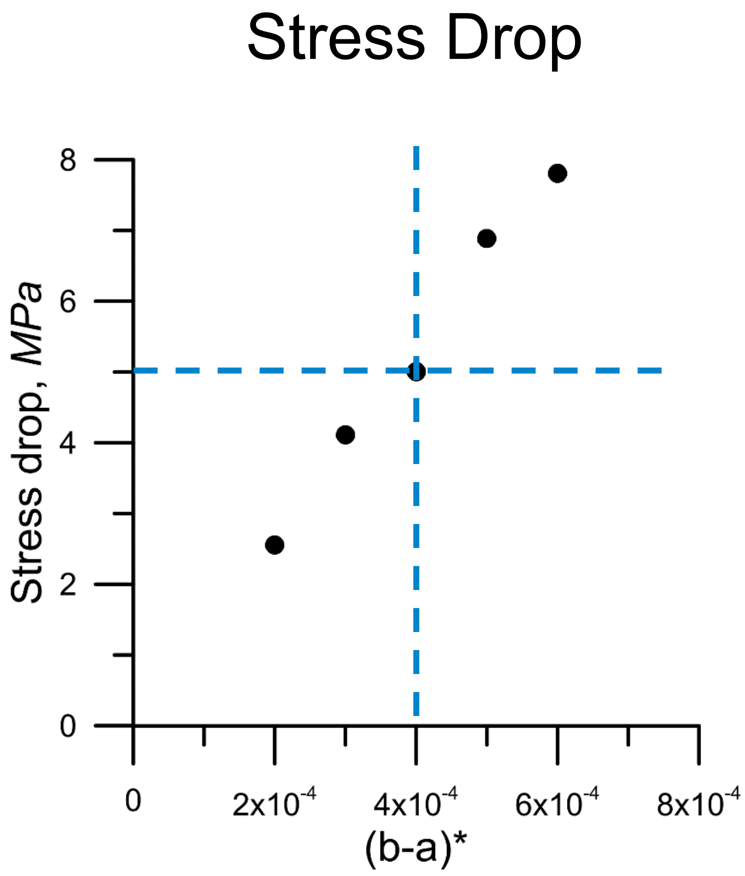
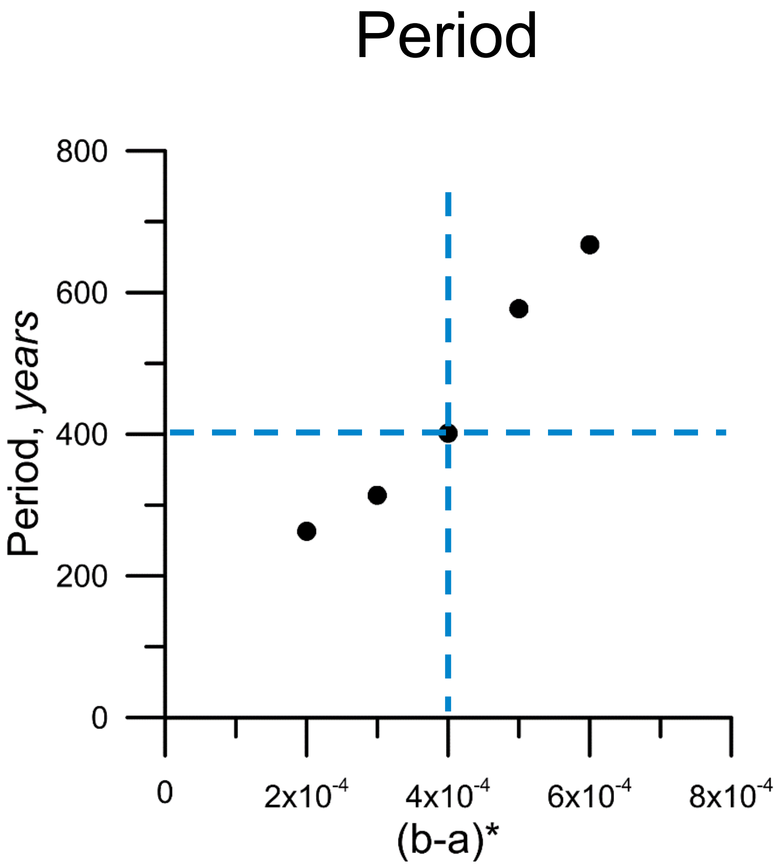


Sobolev and Muldashev, G-cubed, 2017 (Accepted online)

Calibration of Parameters (Chile 1960)

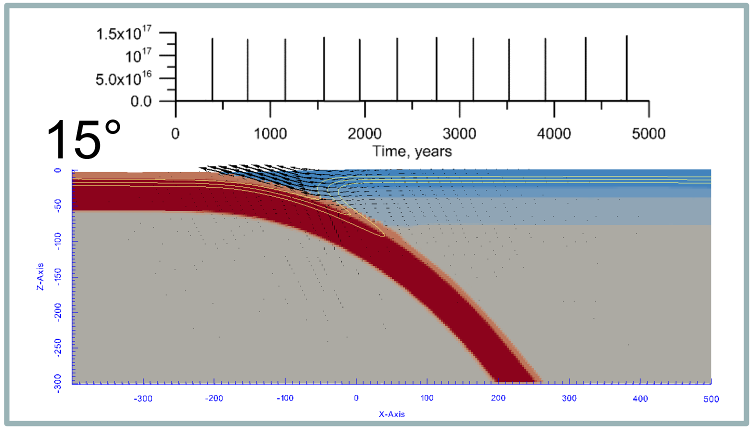
Should be stress drop about 5 MPa (Seno, 2014) and period about 400 years (Cisternas, 2005)

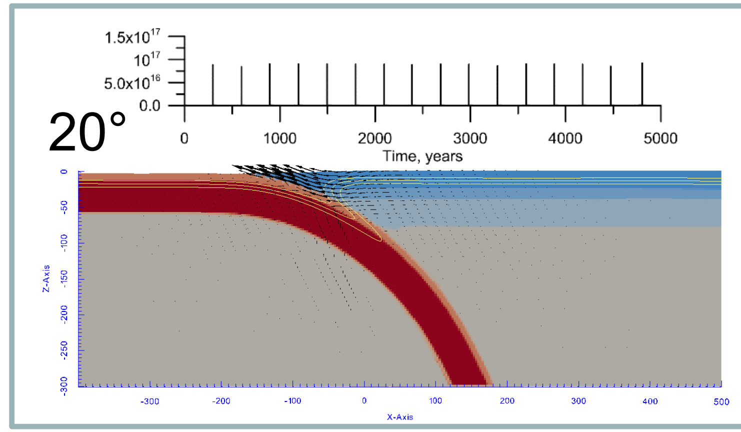


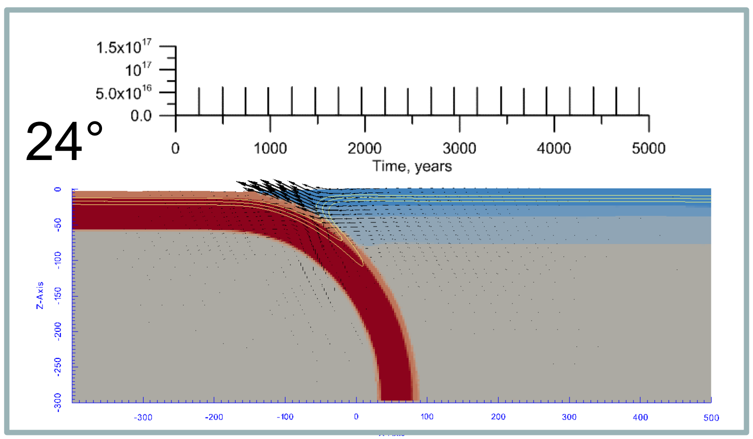


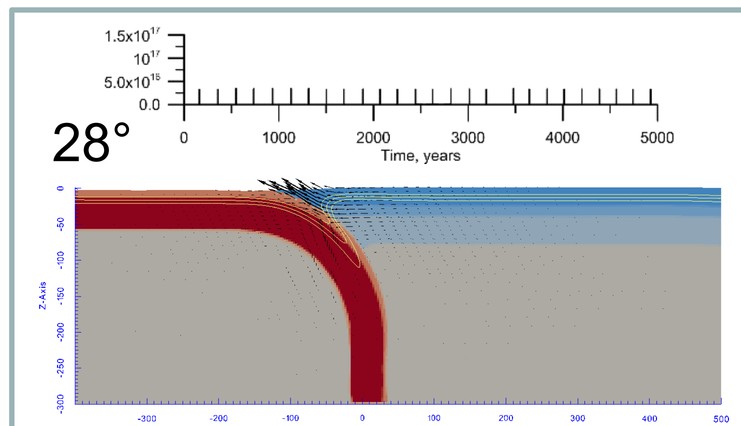
Parameter's Sensitivity

(dipping angle, static friction, subduction velocity)







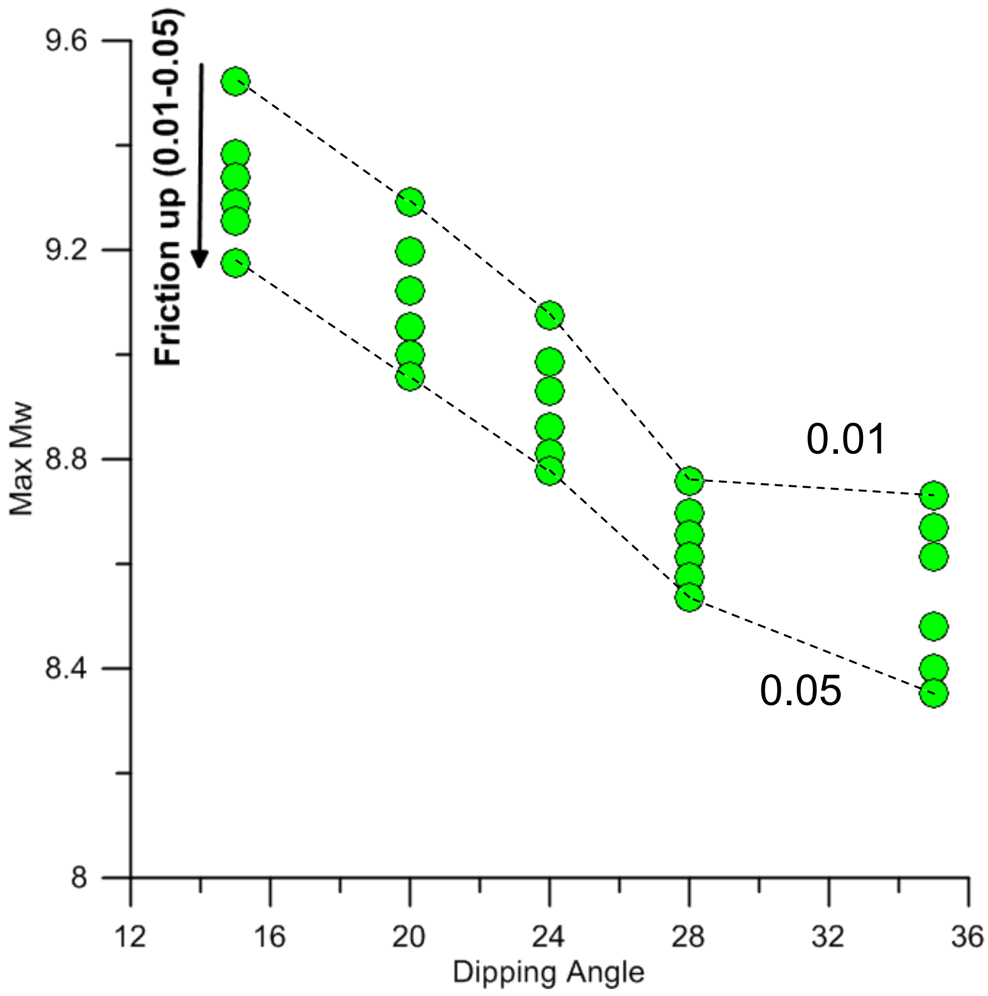


Scaling to 3D

Scaling to 3D (rupture length) by Strasser et al. (2010)

Assumption of lateral coherence to at least 3 rupture widths

Effects of Parameters



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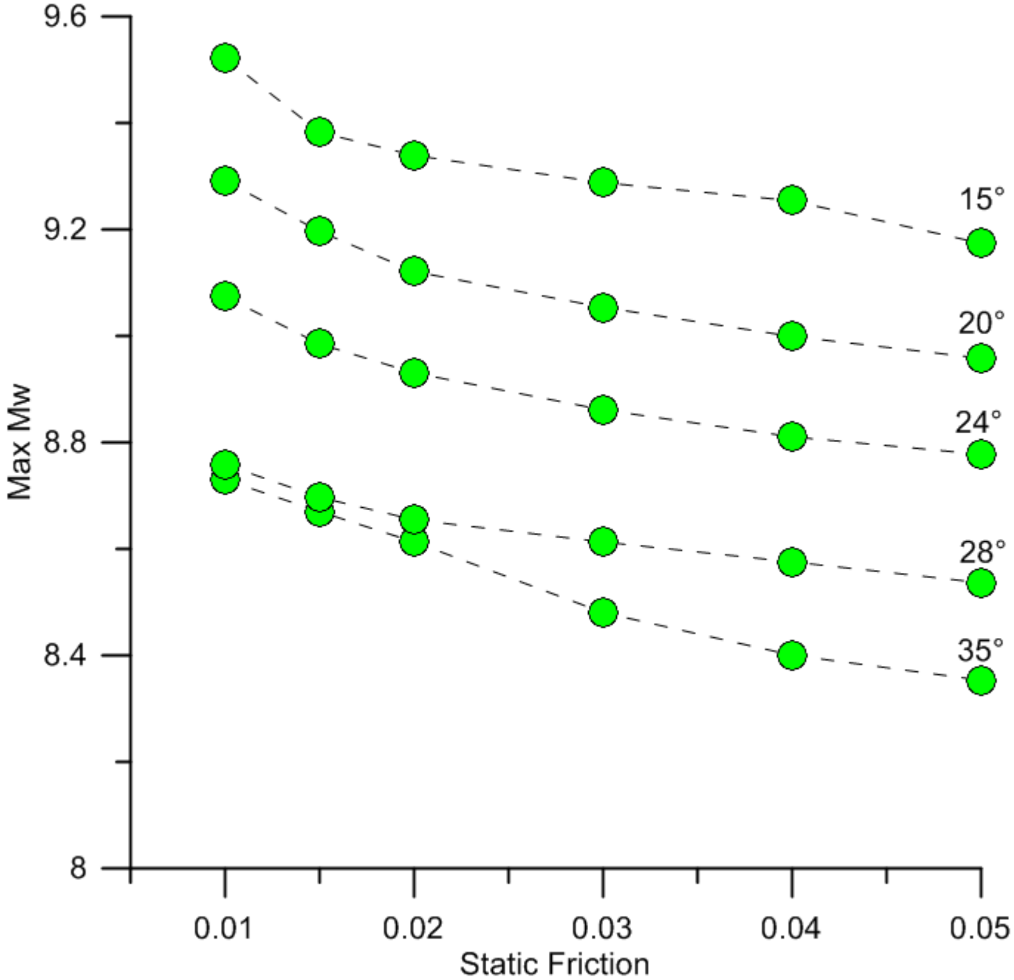

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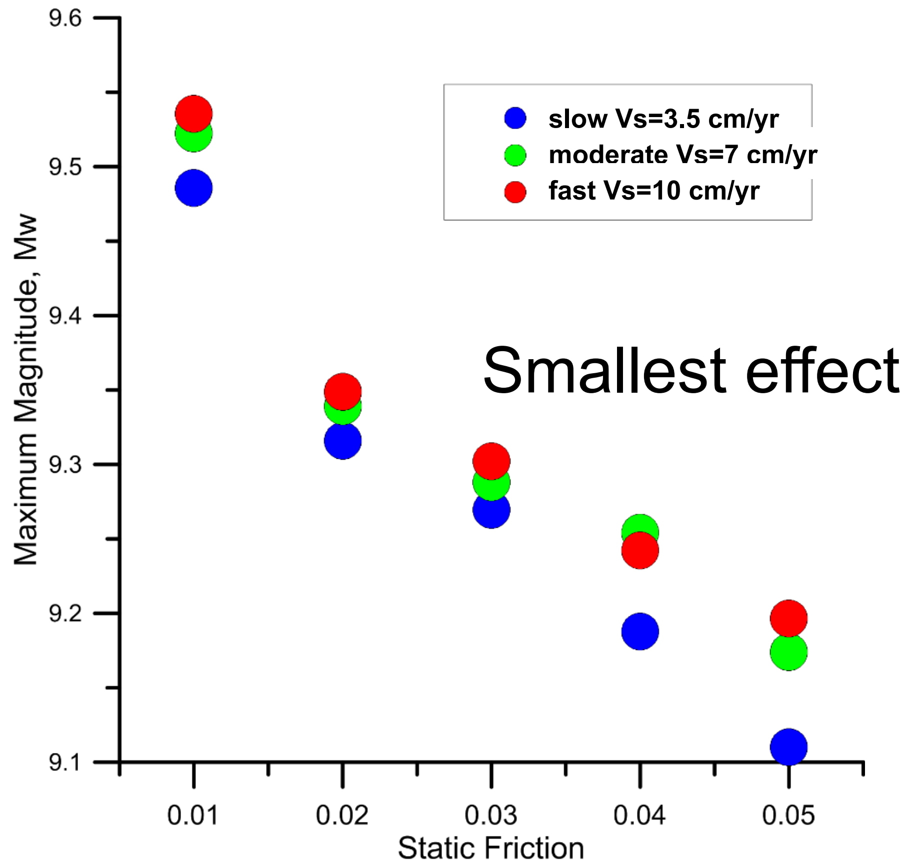
Effect of Subduction Velocity



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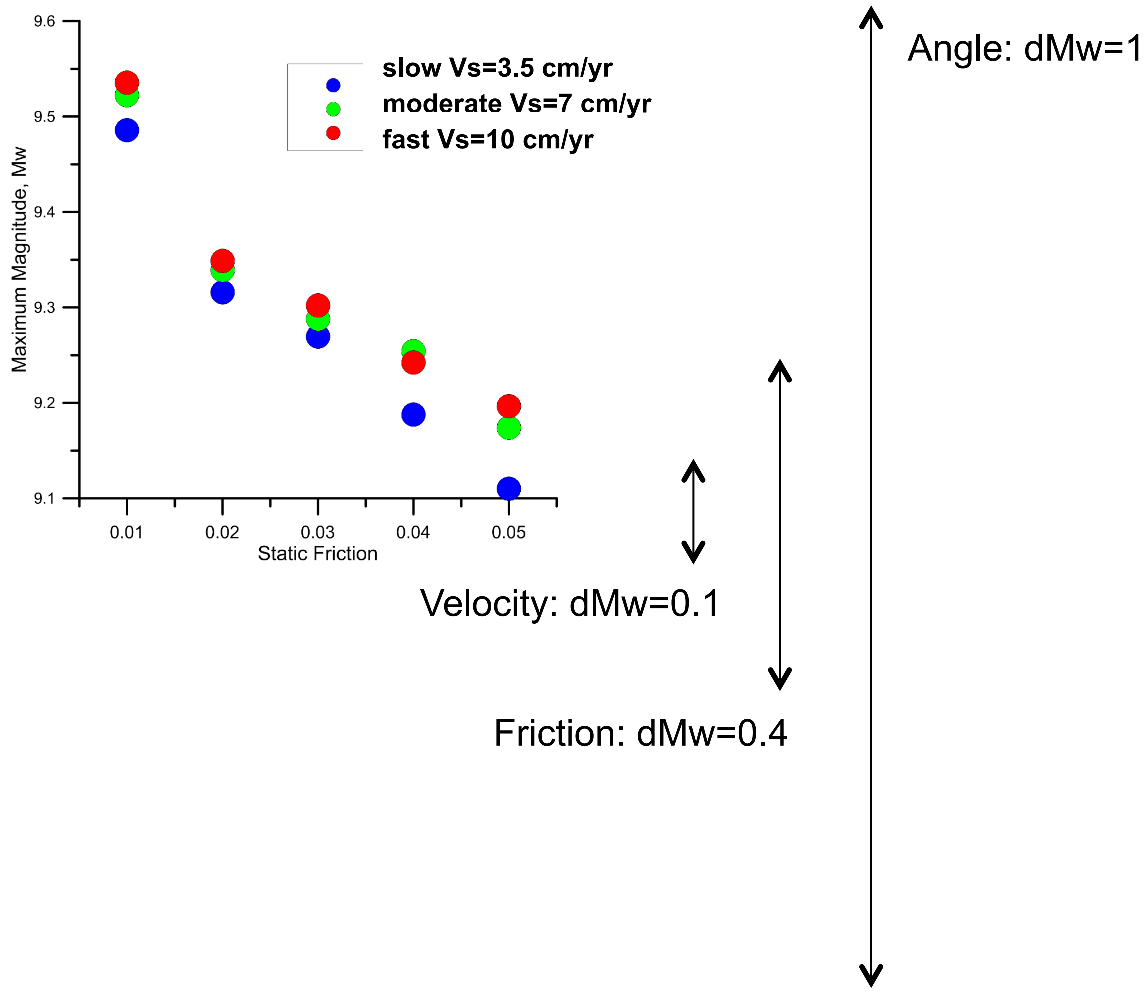
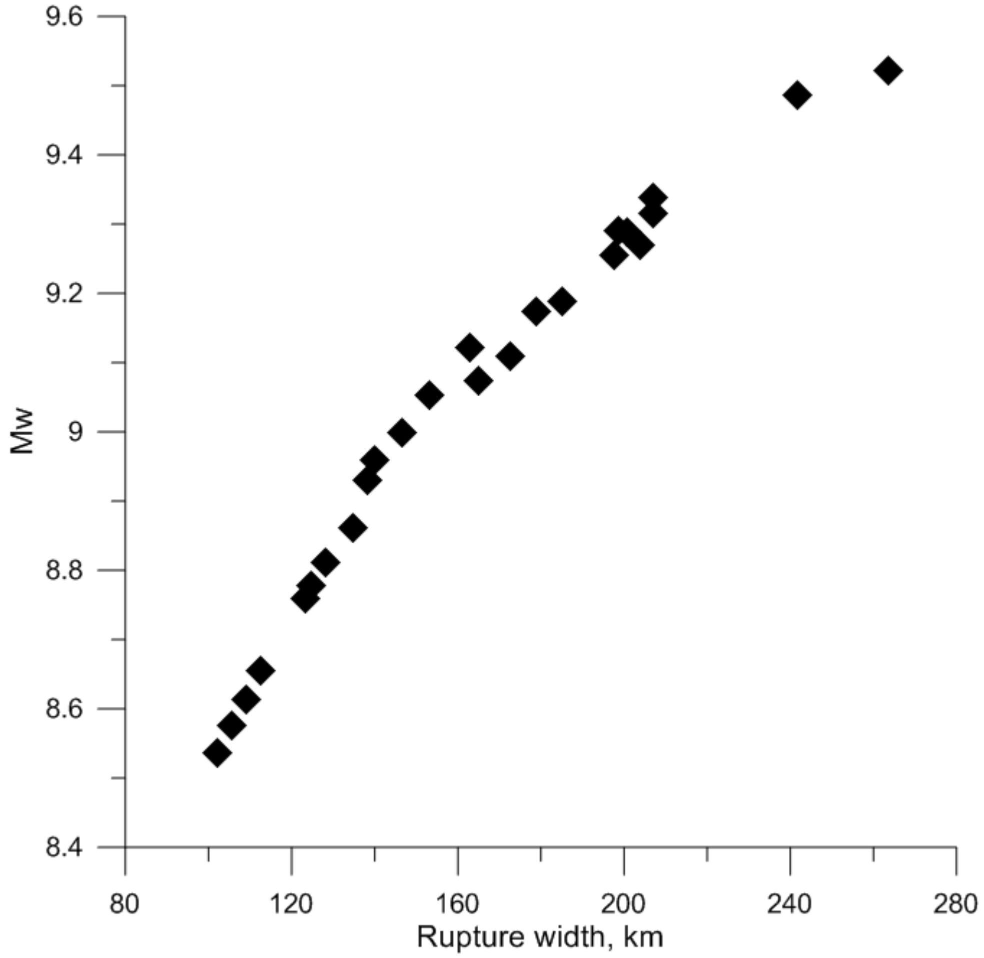


Effect of Rupture Width



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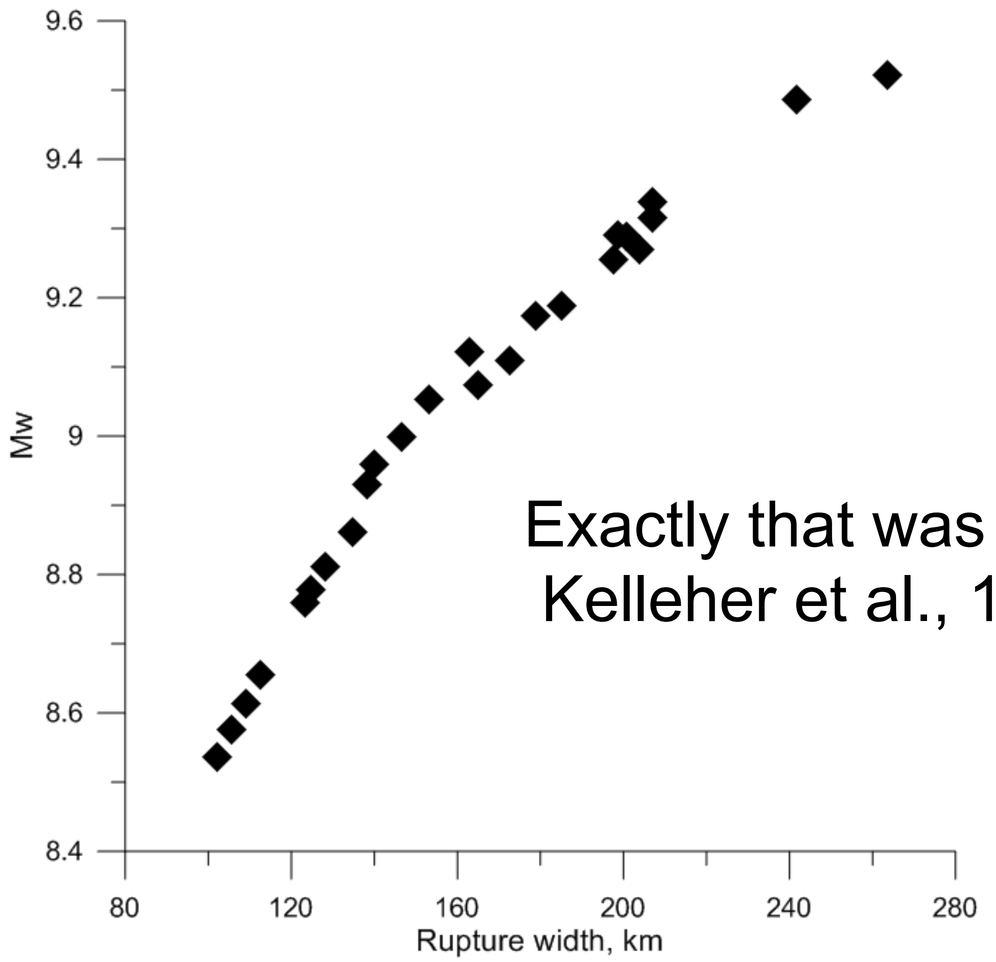
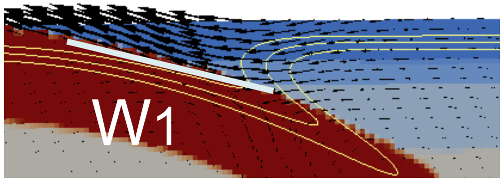
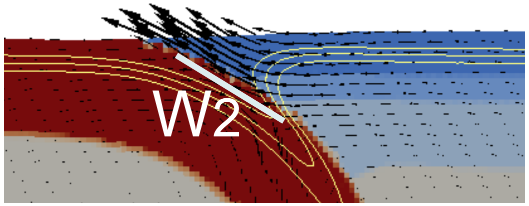


Exactly that was suggested by
Kelleher et al., 1974 !

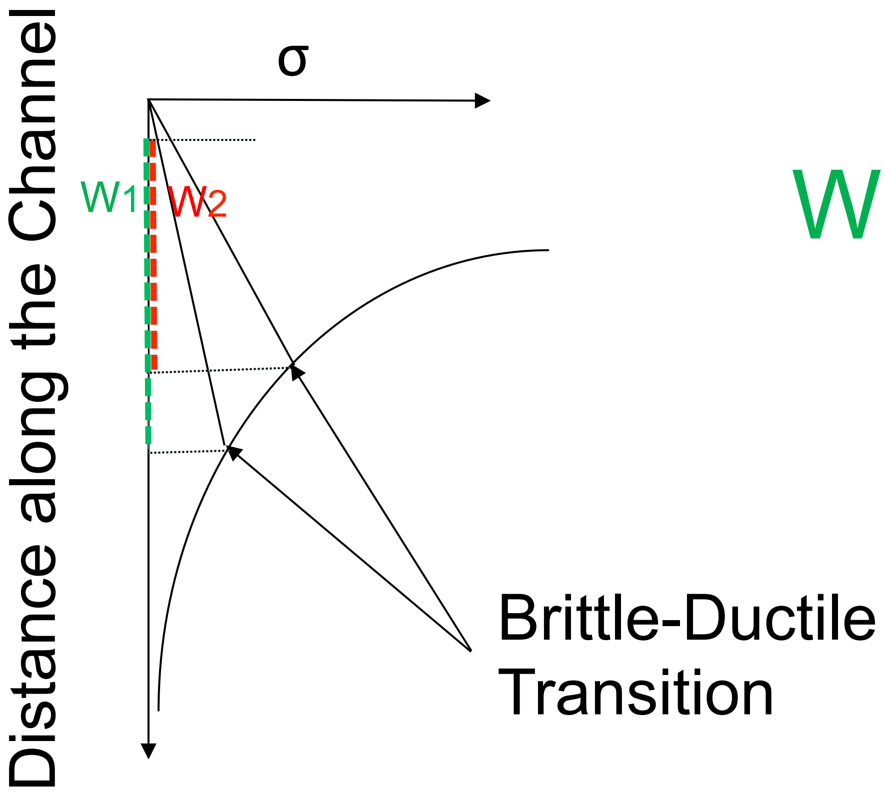
Effect of Dipping Angle on Seismogenic Zone Width





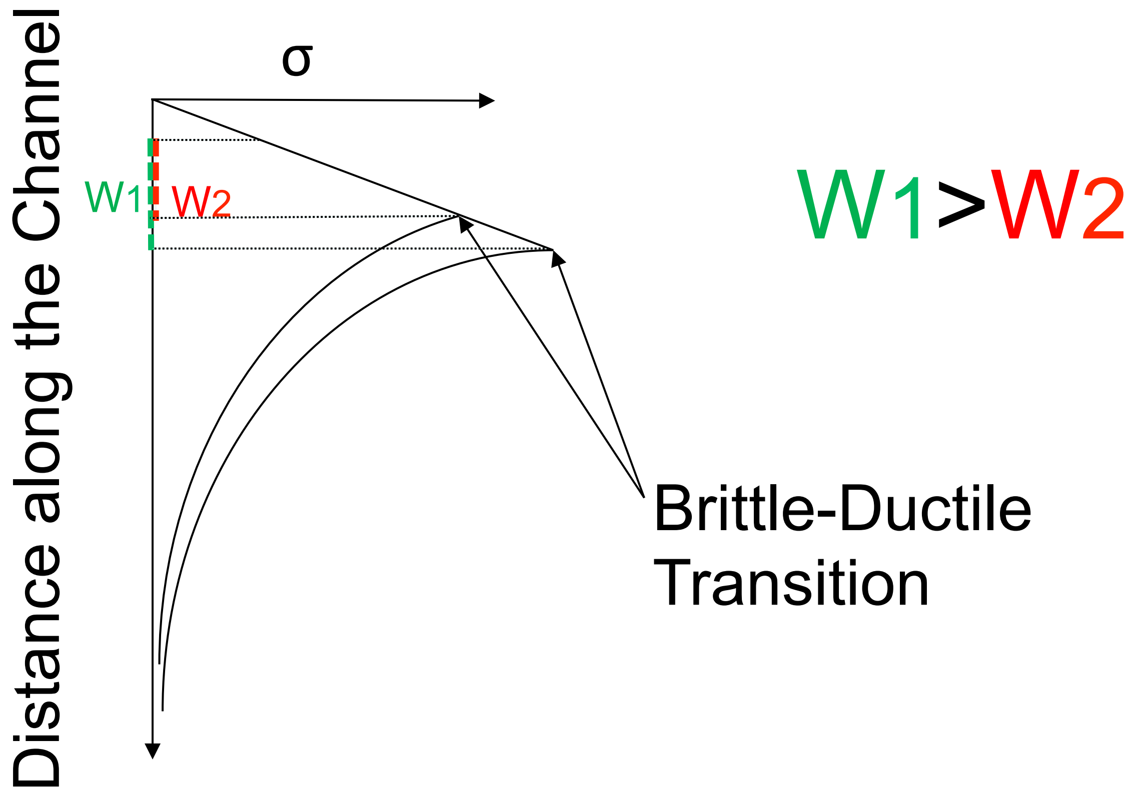
$W_1 > W_2$

Effect of Static Friction on Seismogenic Zone Width



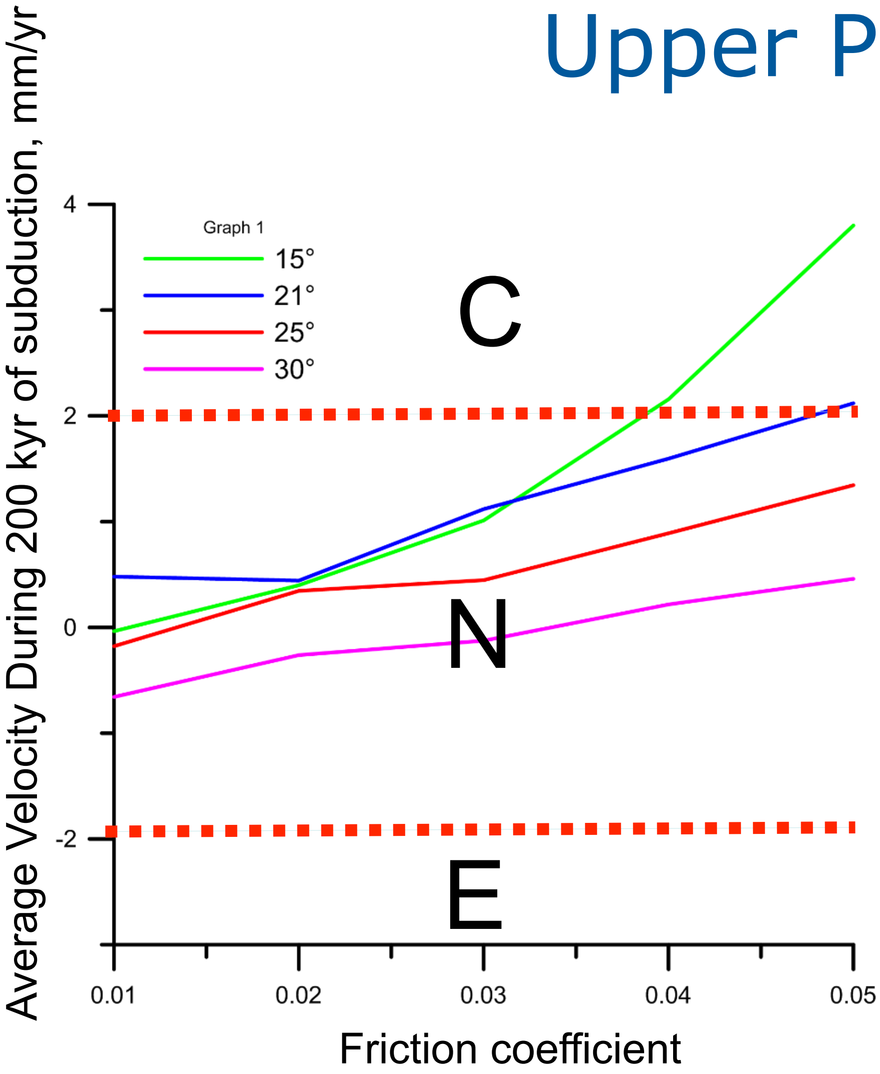
W1>W2

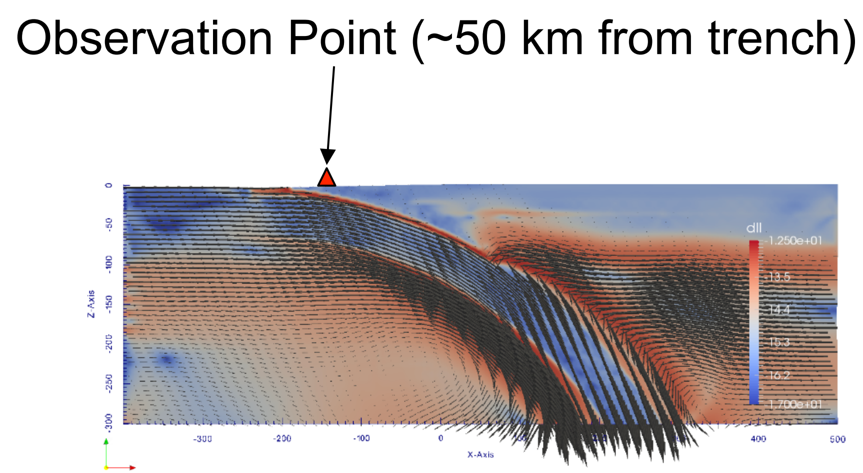
Effect of Subduction Velocity



Testing Models: Consequences for the Upper Plate Deformation

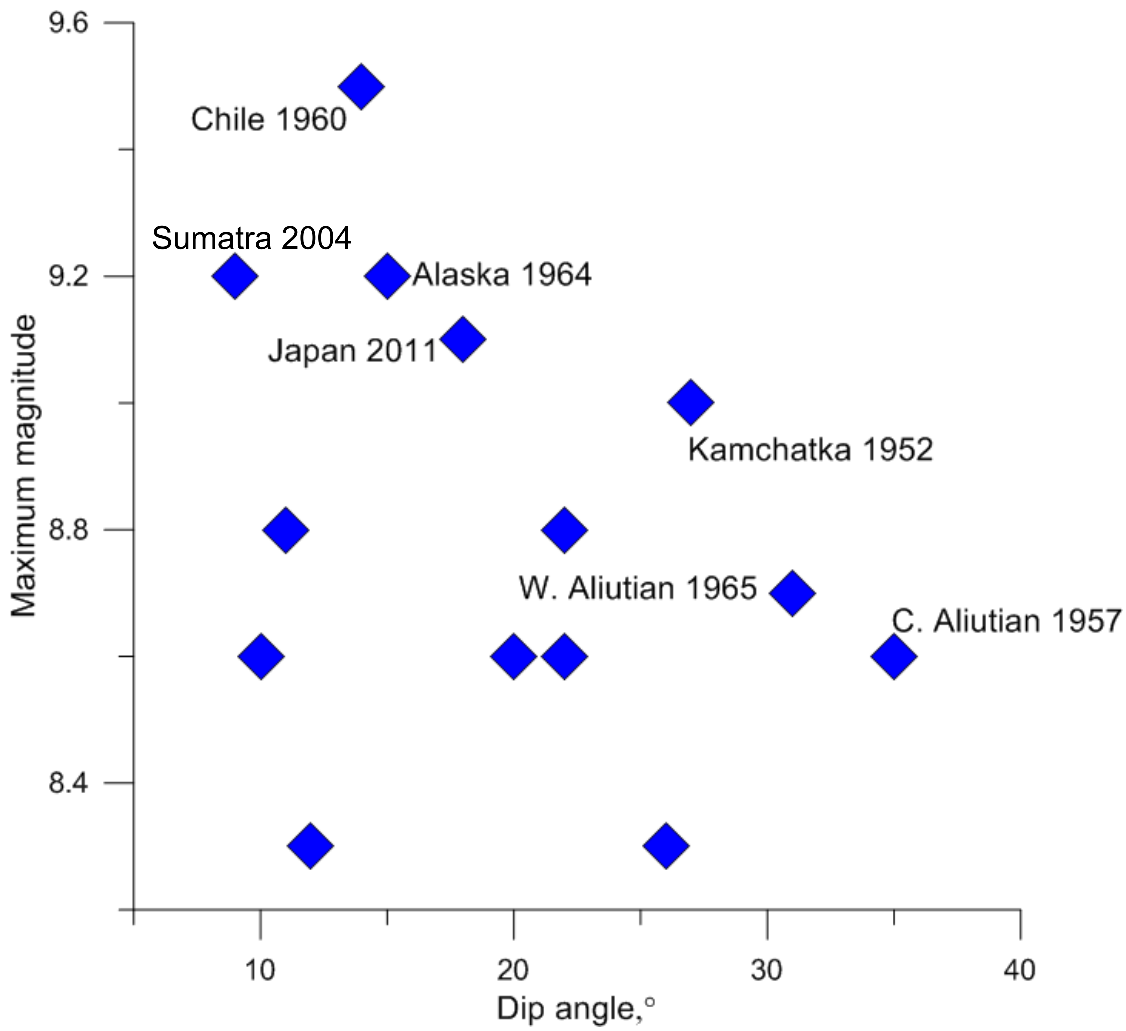
Upper Plate Strain





Testing Models: Predicted Maximum Magnitudes versus Observations

Largest Observed Earthquakes vs Model Predictions



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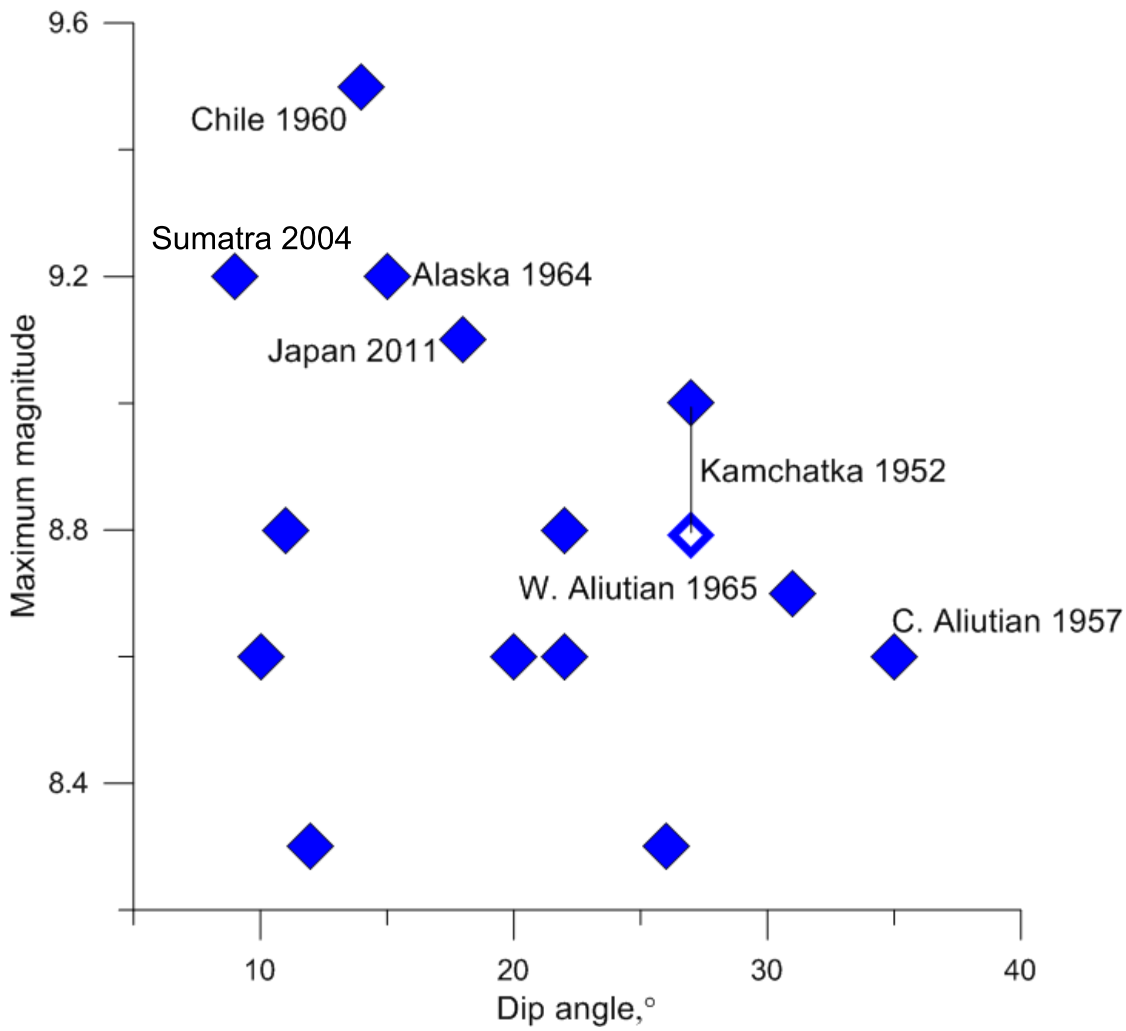

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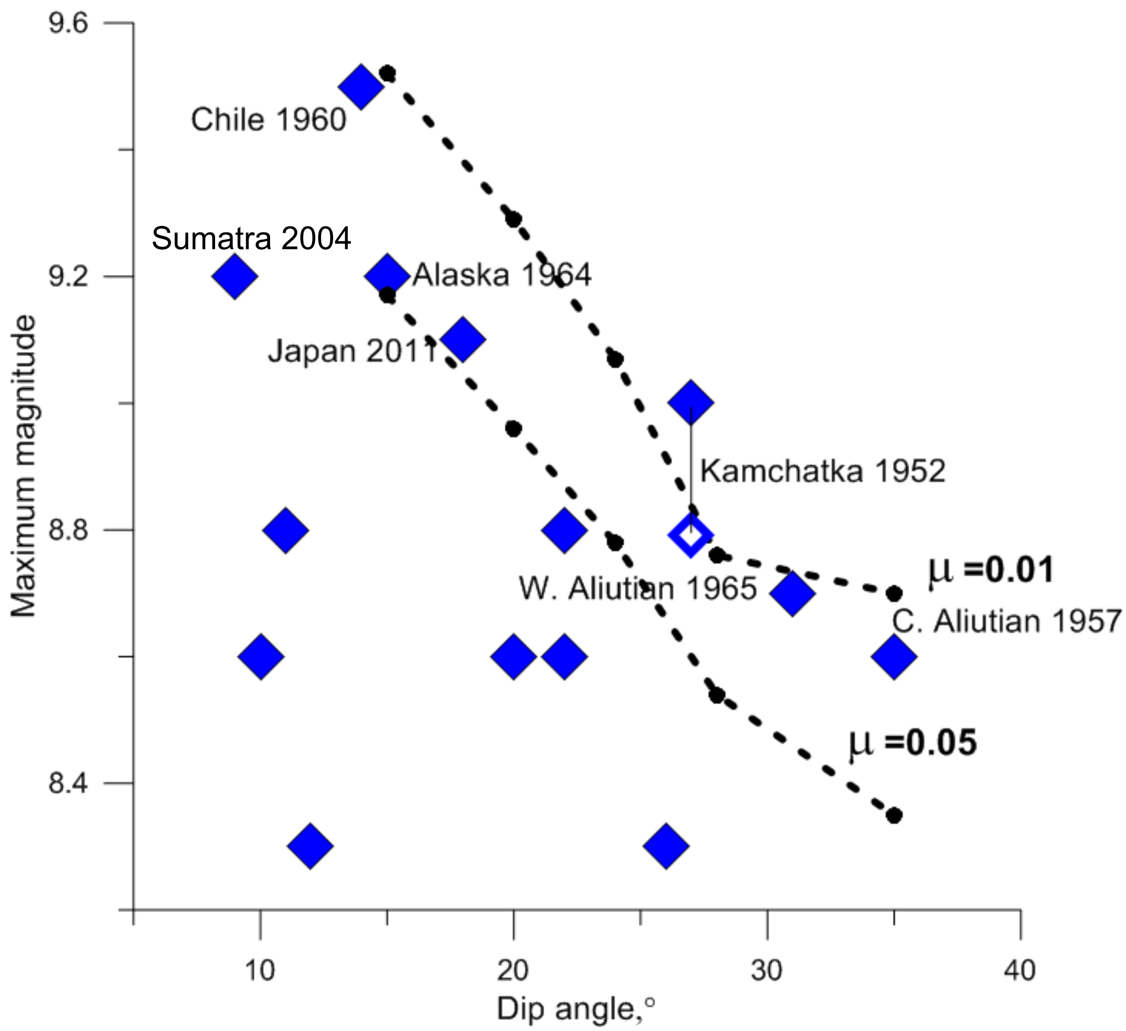
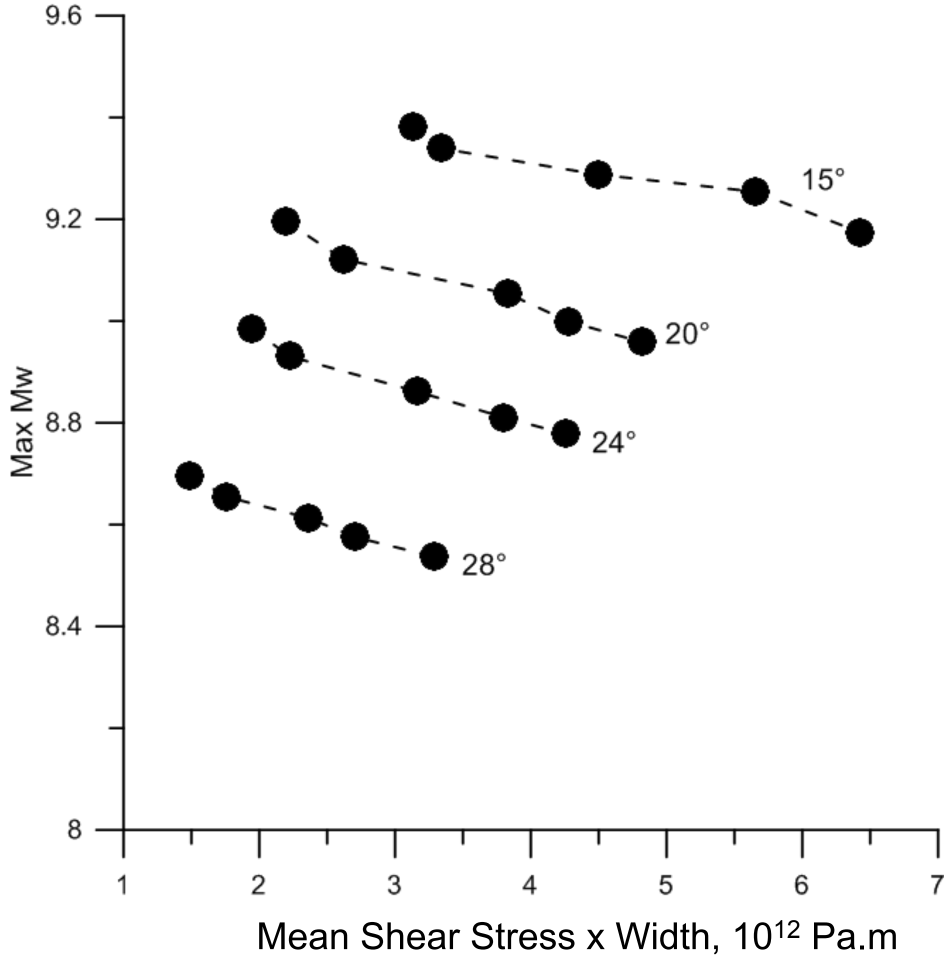
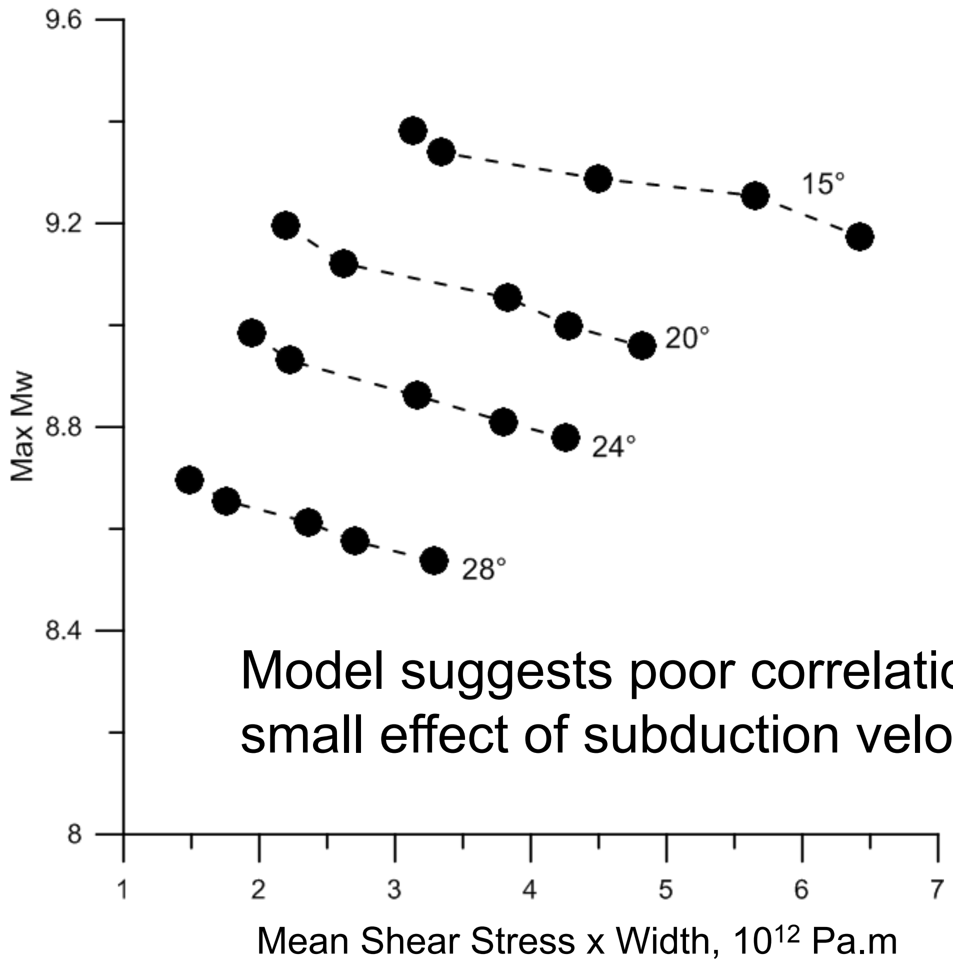


Maximum Magnitude vs. Strength of Mechanical Coupling



Maximum Magnitude vs. Strength of Mechanical Coupling



Model suggests poor correlation and small effect of subduction velocity

Conclusions

- Long-term (static) effective friction at subduction interface is very law, typically below 0.05.

- Maximum magnitudes of the earthquakes are exclusively controlled by the factors that increase rupture width and length. These factors are: lateral coherency of subduction channels (probably enabled by thick, >0.5km sediment's layer at the trench), low slab's dipping angle and low static friction.

  Effects of mechanical coupling and subduction rate are minor.

- Low friction in subduction channel results in neutral or compressive deformation in the overriding plate for low-angle subduction zones.

- These modeling results agree well with observations for the largest earthquakes and allow predicting largest possible earthquakes for subduction zones.