Lecture 8. Physics of Earthquakes

Outline

- Some basic facts and questions
- Recent great earthquakes in Chili (2010, Mw=8.8) and in Japan (2011, Mw=9.0)
- Megathrust earthquakes and structure of the upper plate
- Cross-scale dynamic models

Some basic facts

The cause of larger earthquakes is the plate tectonics and most of them happen at plate boundaries

About 80% of relative plate motion on continental boundaries is accommodated in rapid earthquakes

With few exceptions, earthquakes do not generally occur at regular intervals in time or space.

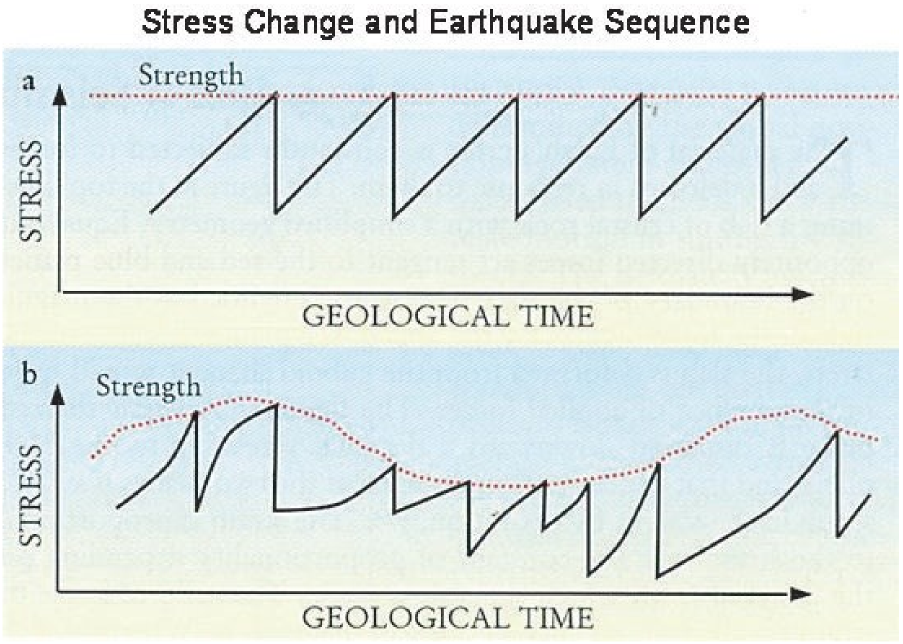
Some basic facts

The shear strain change associated with large earthquakes (*i.e. coseismic strain drop*) is of the order of 10^{-5}– 10^{-4}. This corresponds to a change in shear stress *(i.e. static* stress drop) of about 1–10 MPa.

The repeat times of major earthquakes at a given place are about 100–1000 years on plate boundaries, and 1000–10 000 years within plates.

The rupture velocity for large earthquakes is typically 75–95% of the S-wave velocity

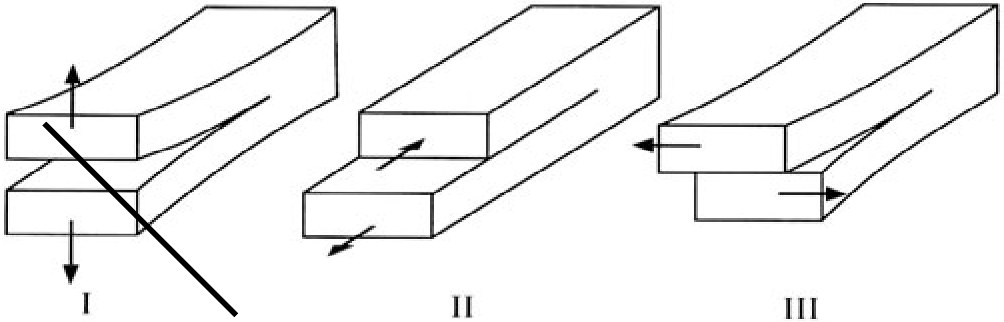
Some basic facts



Ideal

Real

Deformation modes



rare

Some basic facts

Definitions and scaling

Seismic moment: $M_0 = G \cdot D \cdot S$, G-shear modulus, D-average displacement, S-rupture area

Average stress drop $$\overline{\Delta\sigma_s} = \frac{1}{S} \int_S \Delta\sigma_s \, dS.$$

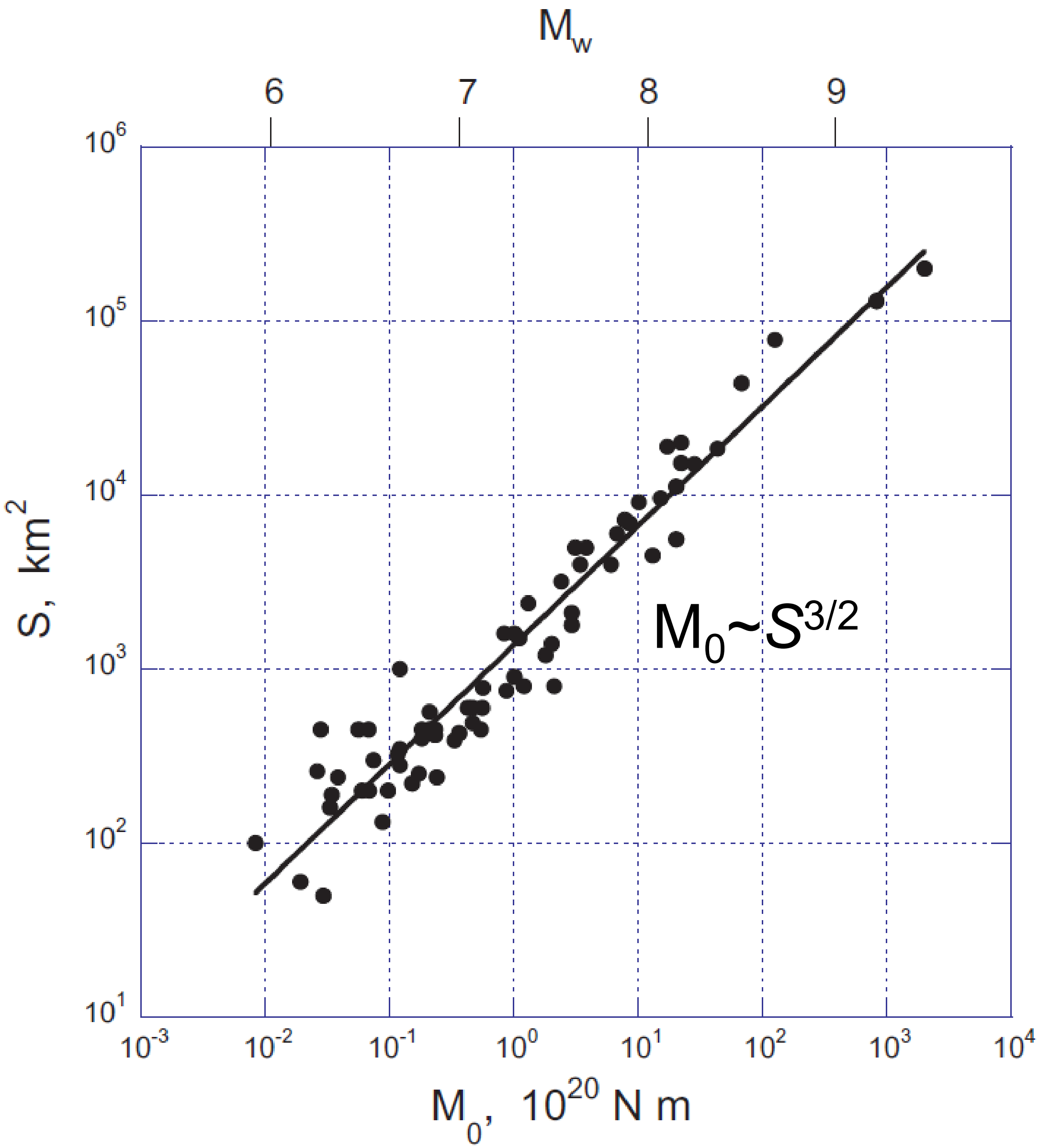
$\overline{\Delta\sigma_s} \approx C \cdot G \cdot D / L$, L-characteristic rupture length $L \approx S^{1/2}$

$\overline{\Delta\sigma_s} \approx C \cdot M_0 \cdot S^{-3/2}$ or

$M_0 \approx \overline{\Delta\sigma_s} \cdot S^{3/2}$; $D \approx S^{1/2} \, \overline{\Delta\sigma_s} / G$

Moment magnitude: $M_w = 2/3 \log_{10}(M_0) - 6.07$

Some basic facts



Kanamori and Brodsky, 2004

That means

$$\overline{\Delta\sigma_S} \approx const$$

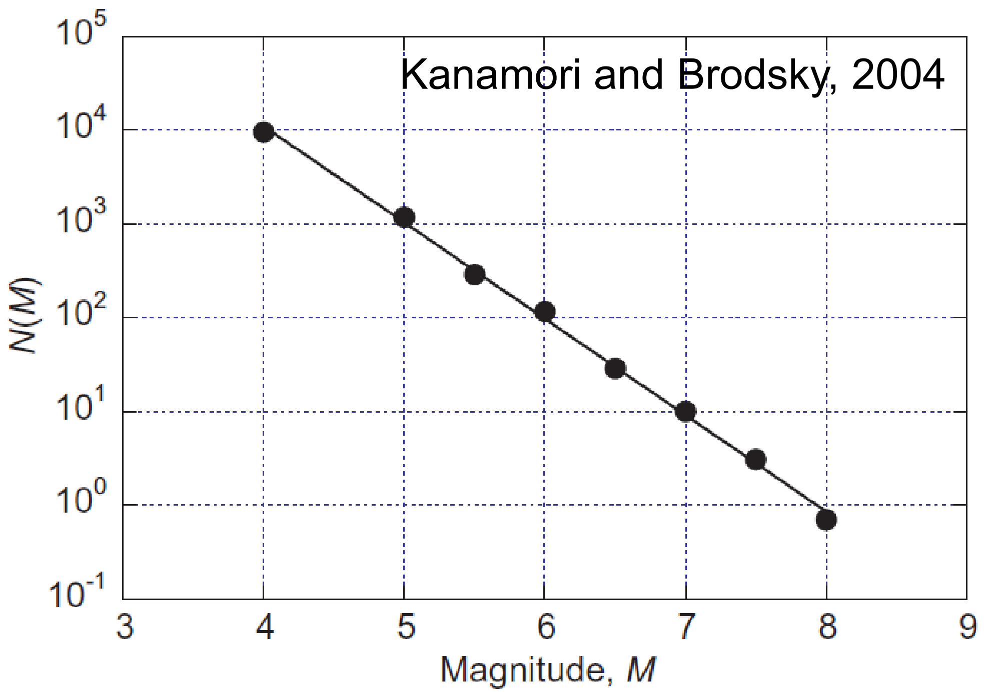
Mean value of $\overline{\Delta\sigma_S}$ is about 3 MPa

$$M_0 \approx \overline{\Delta\sigma_S} \cdot S^{3/2};$$

$$D \approx S^{1/2}\, \overline{\Delta\sigma_S}\, /G$$

Some basic facts

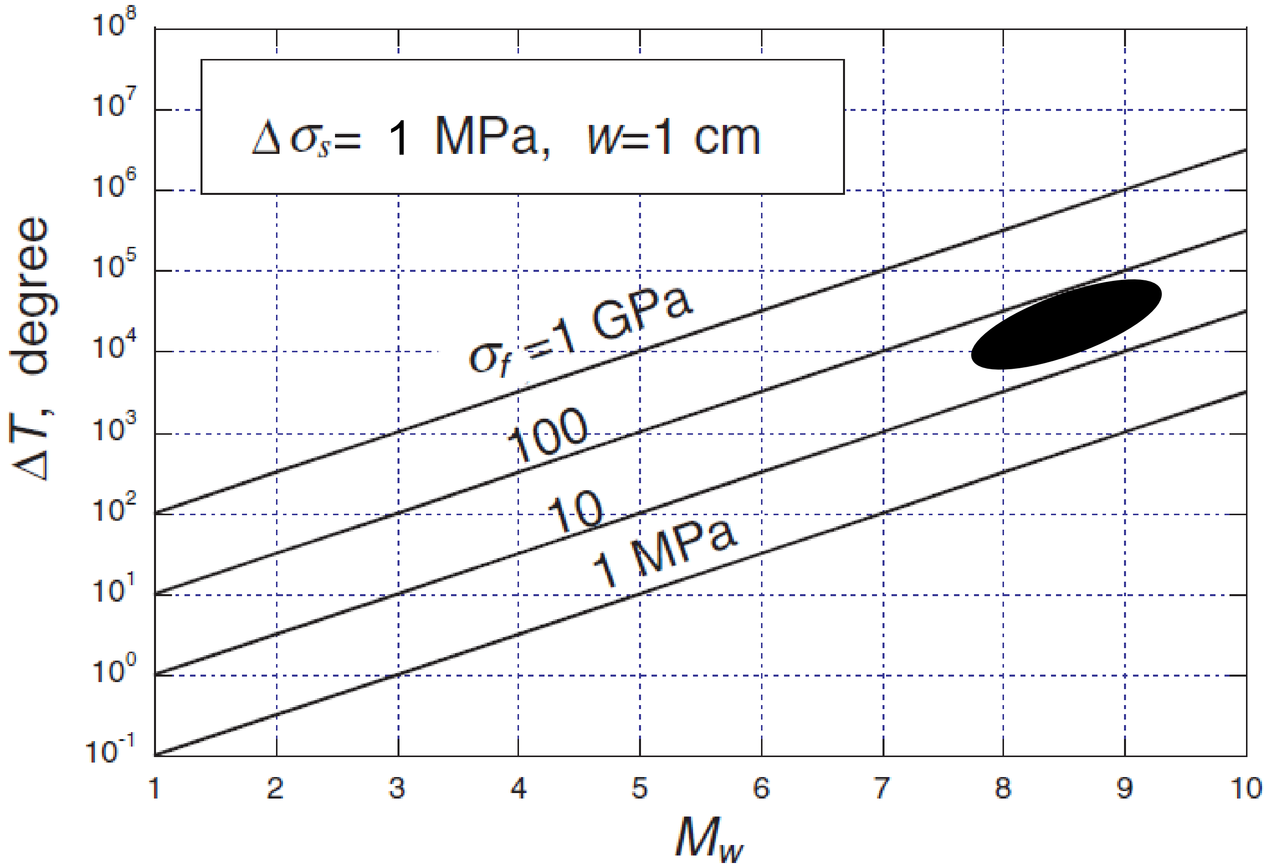
The magnitude–frequency relationship (the Gutenberg–Richter relation)



$$\log N(M) = a - bM,\ b \text{ is about } 1$$

Thermal effect of Eq.

$$\Delta T = \frac{Q}{C\rho S w} = \frac{\sigma_{\mathrm{f}} D}{C\rho w},$$



Some basic questions

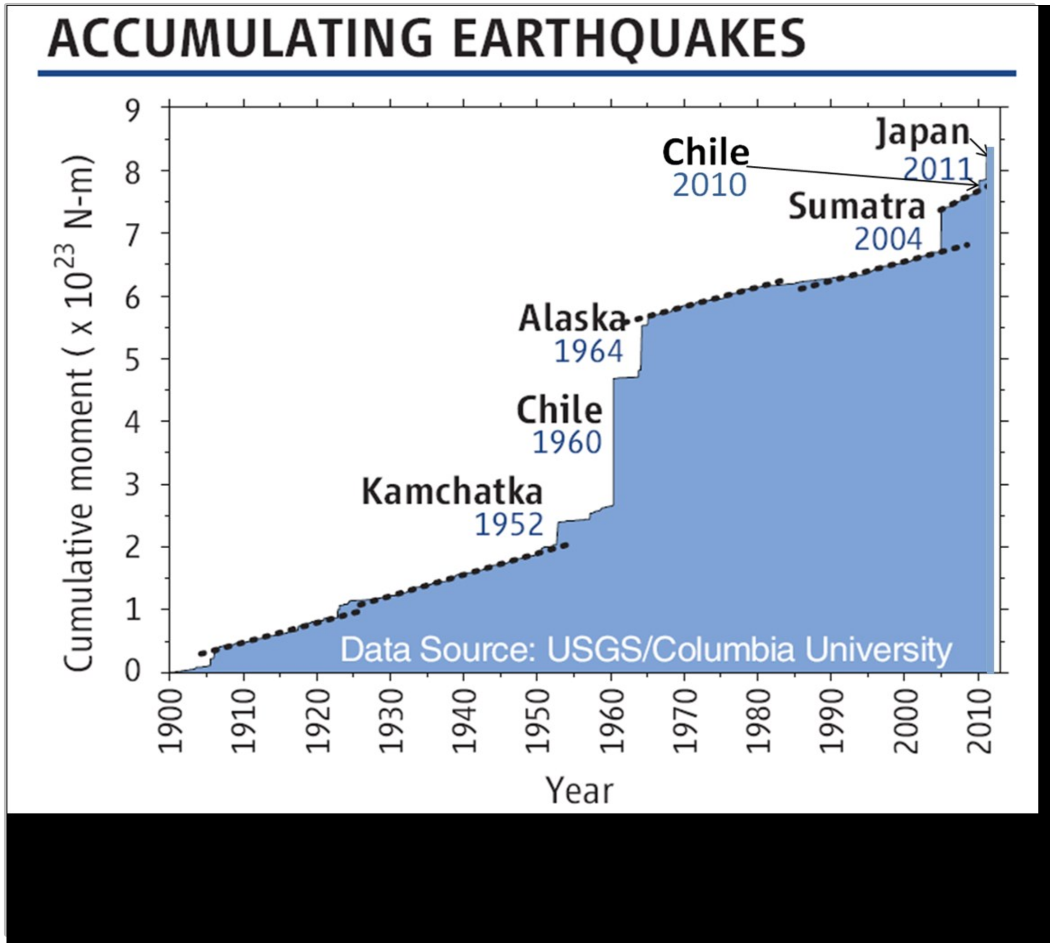
Why some plate boundaries glide past each other smoothly, while others are punctuated by catastrophic failures?

Why do some earthquakes stop after only a few hundred meters while others continue rupturing for a thousand kilometers?

How do nearby earthquakes interact?

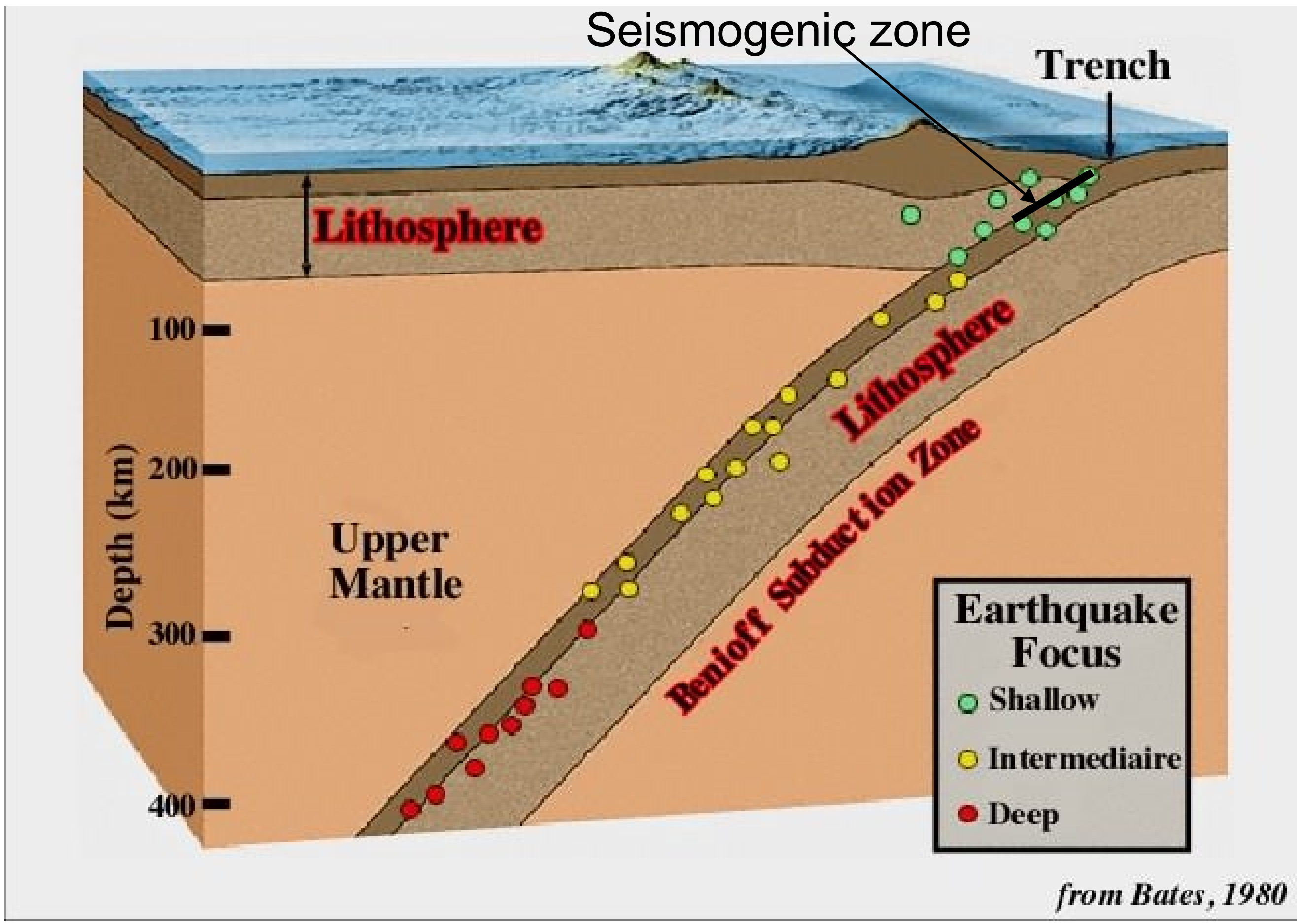
Are earthquakes sometimes triggered by other large earthquakes thousands of kilometers away or not?

Great Earthquakes challenges

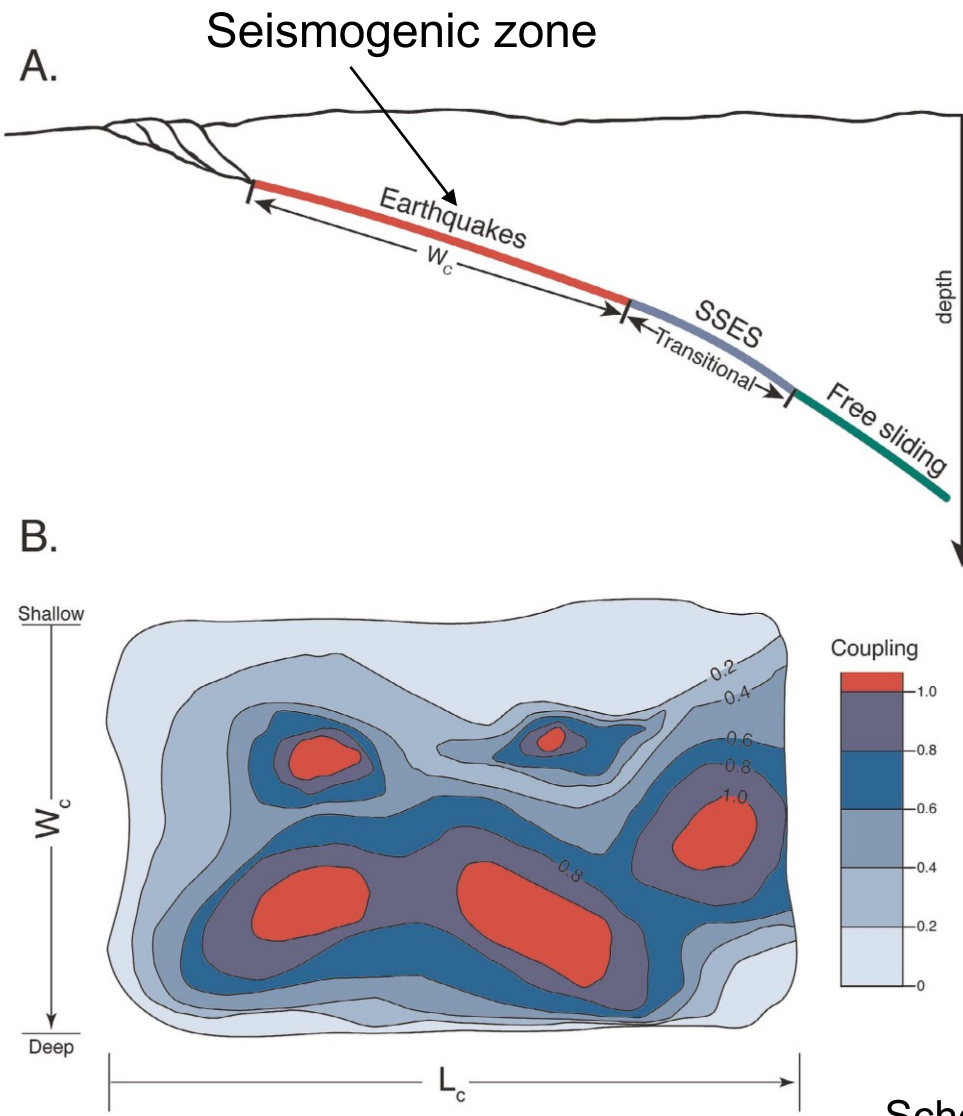


Why the greatest earthquakes occur in the weakest zones? Do they indeed cluster?

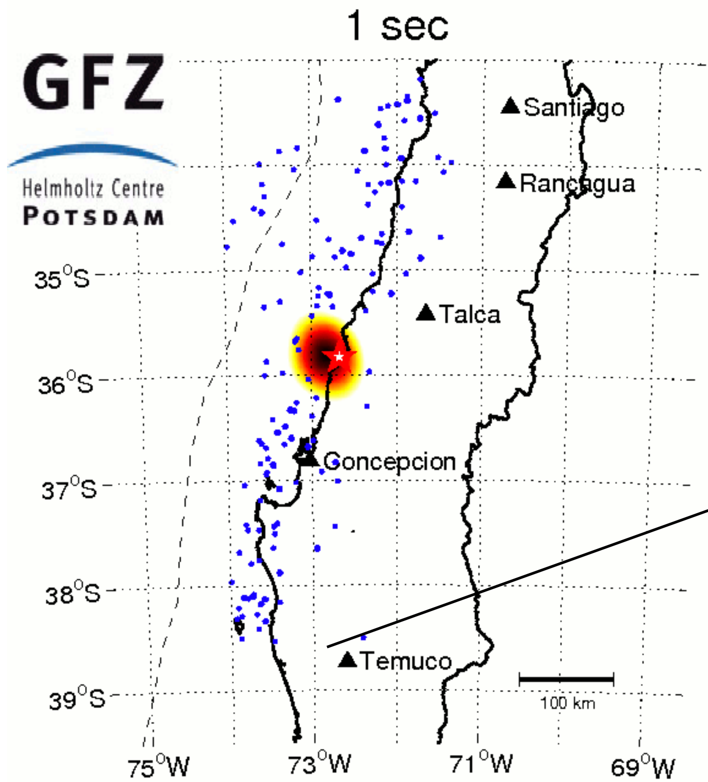
Subduction zone earthquakes



Subduction zone earthquakes



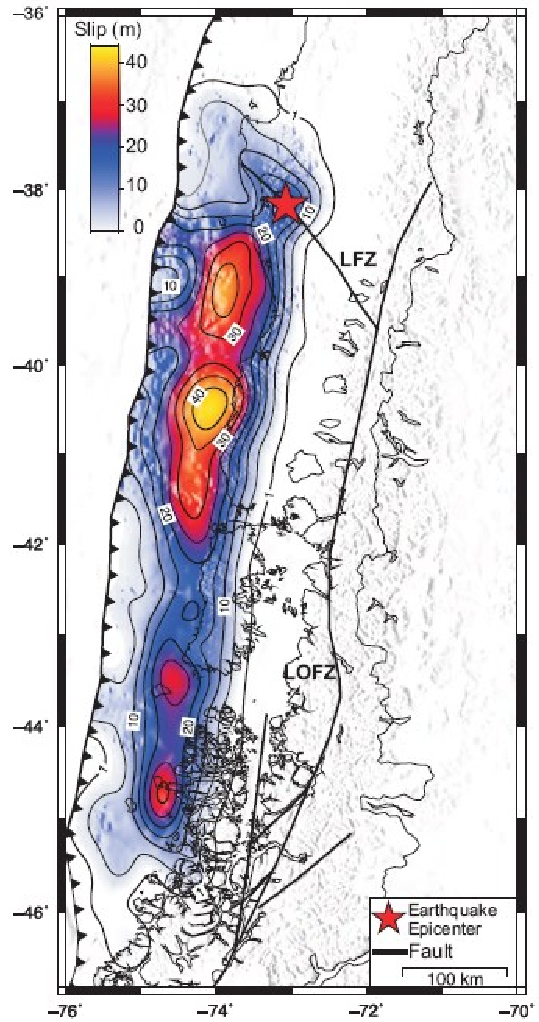
Scholz and Campos, 2012

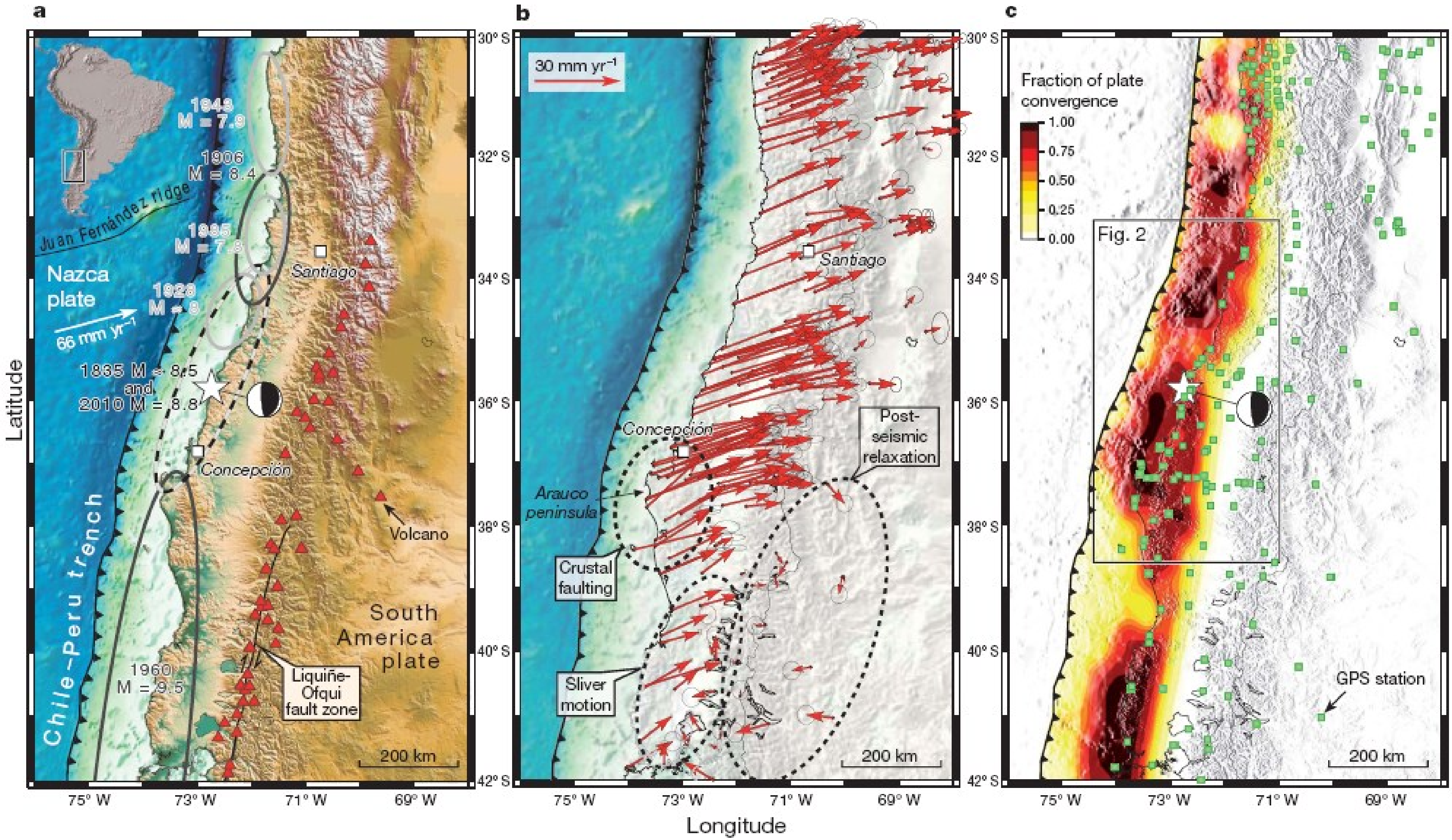


Chile earthquake (2010, Mw=8.8)

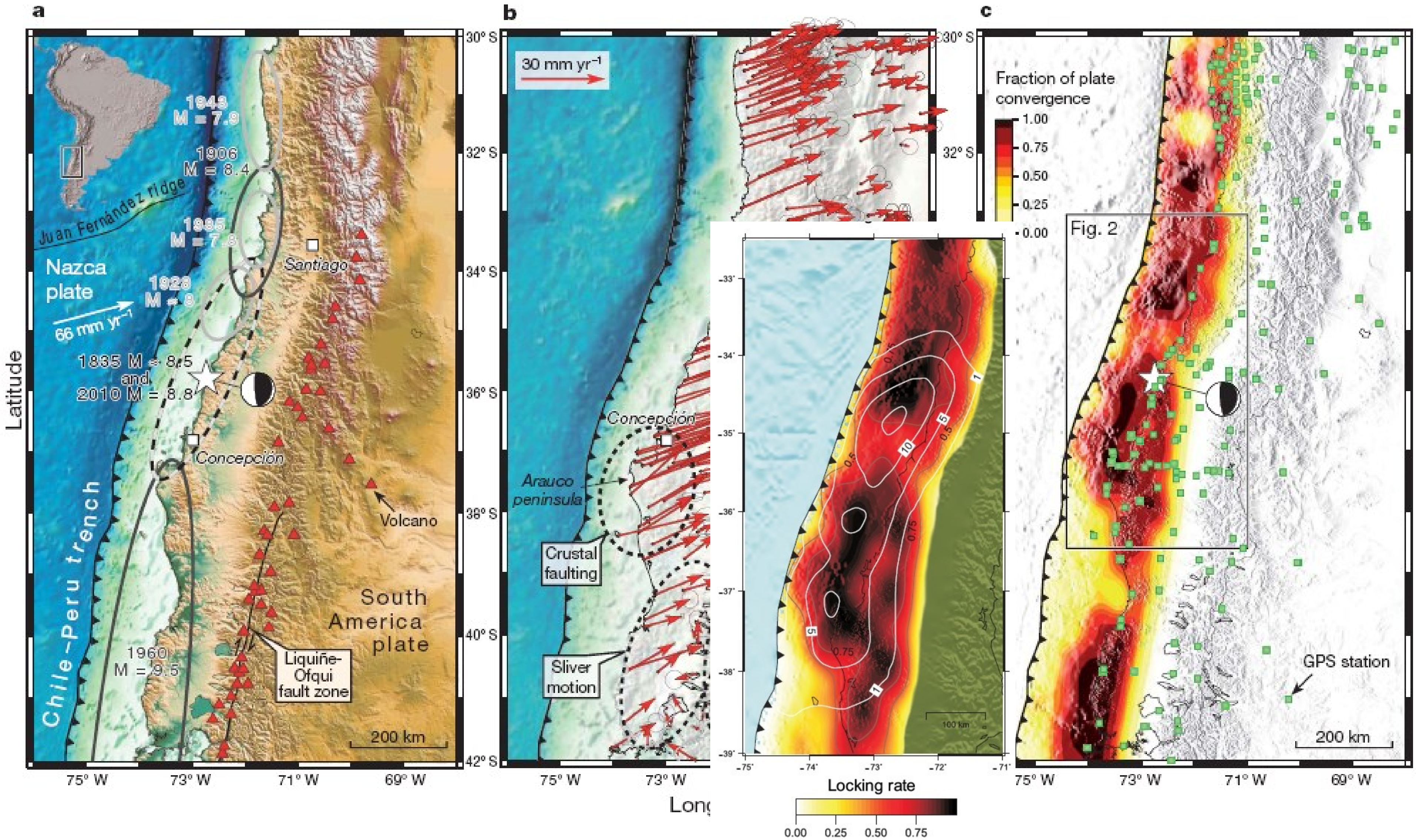
Valdivia earthquake (1960)

Slip distribution



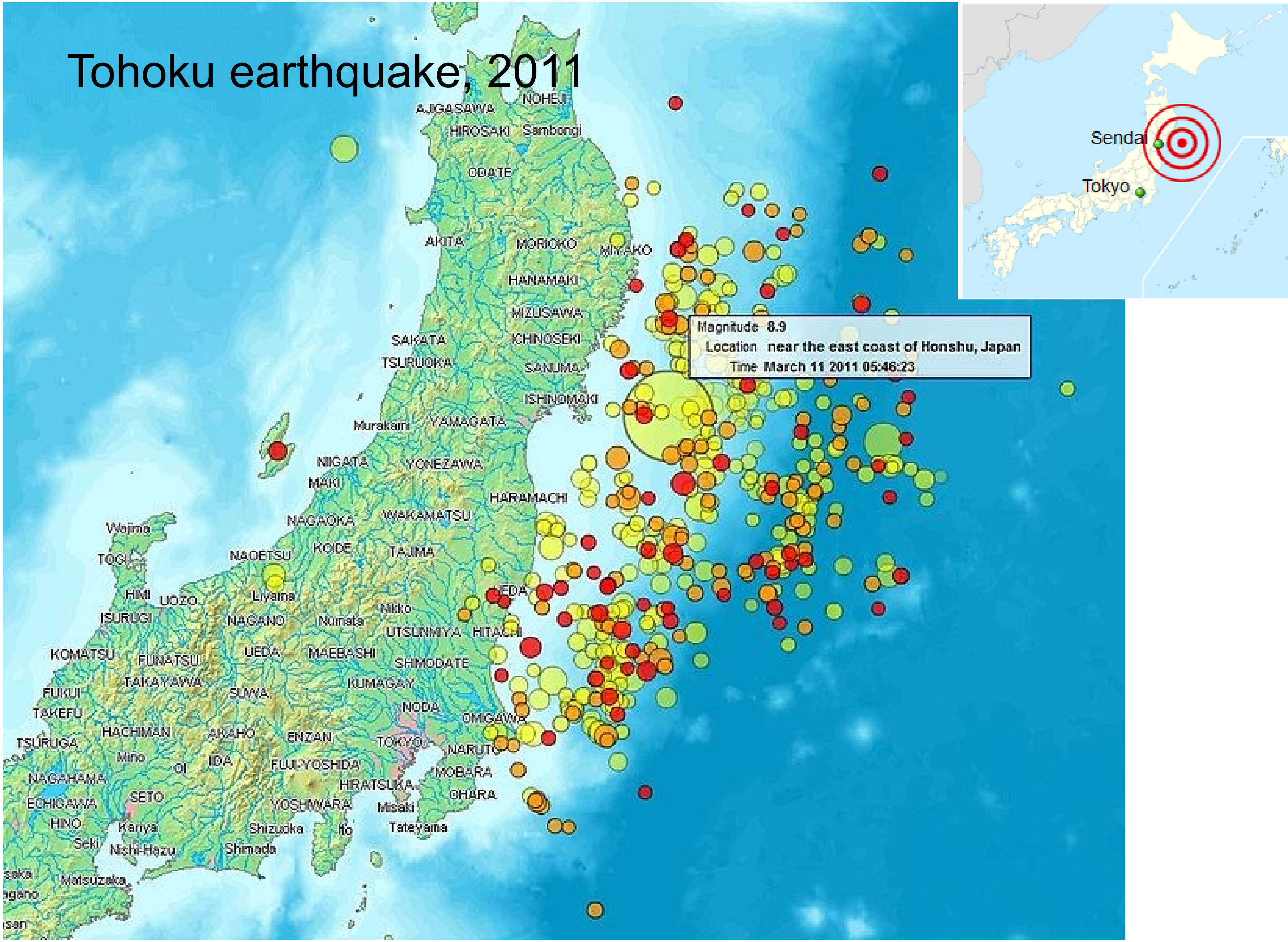


Moreno et al., 2010

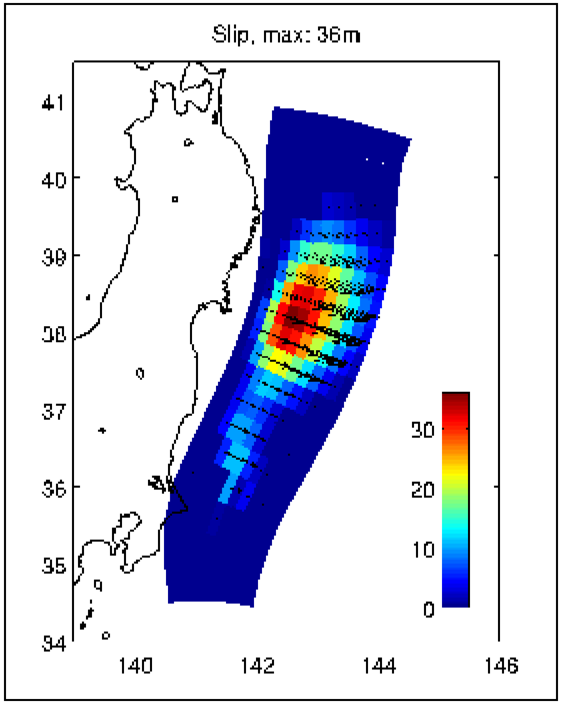


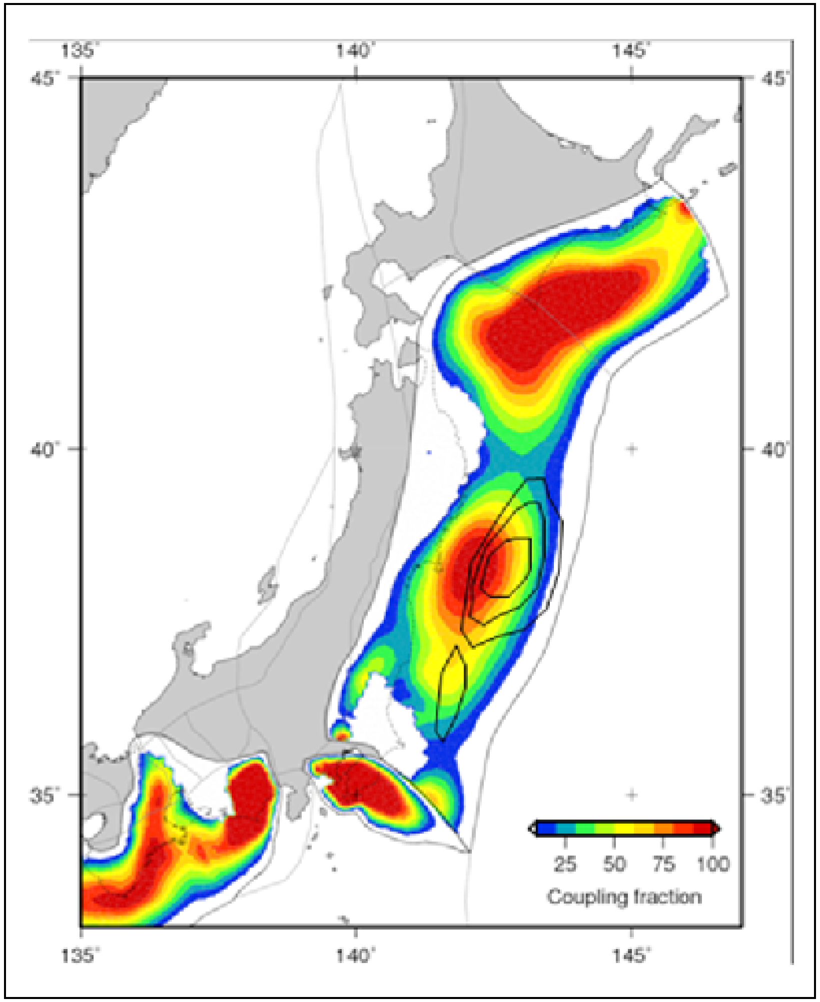
Moreno et al., 2010

Tohoku earthquake, 2011



Locking of plates





Loveless and Meade, J. Geophys. Res. 2010

Perspectives: Cross-scale dynamic models

Elastic deformation is included in our geological-time-scale (mln years) Andes model

Full set of equations

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

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

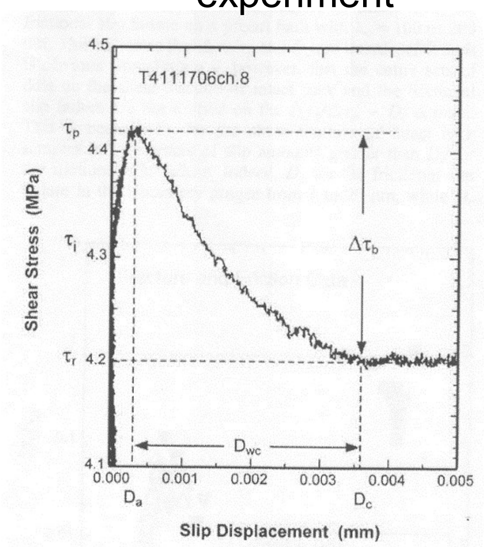
$$\rho C_p \frac{DT}{Dt} = \frac{\partial}{\partial x_i}(\lambda\frac{\partial T}{\partial x_i}) + \tau_{II}\dot{\varepsilon}_{II} + \rho A$$ energy

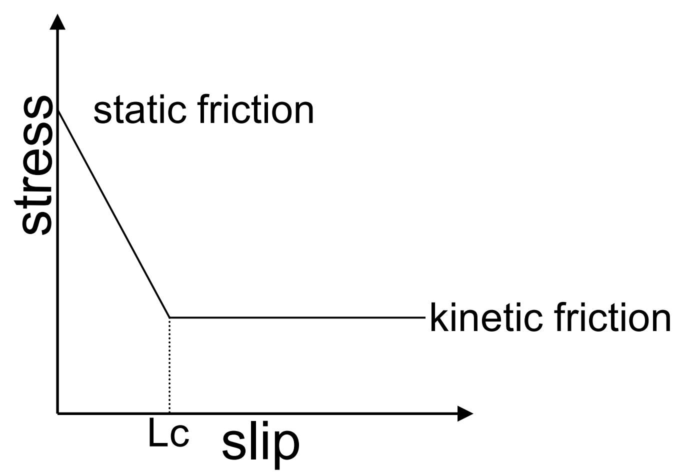
$$\dot{\varepsilon}_{ij} = \frac{1}{2}(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}) = \underline{\frac{1}{2G}\frac{D\tau_{ij}}{Dt}} + \frac{1}{2\eta_{eff}}\tau_{ij}$$

Frictional instabilities governed by static-kinetic friction

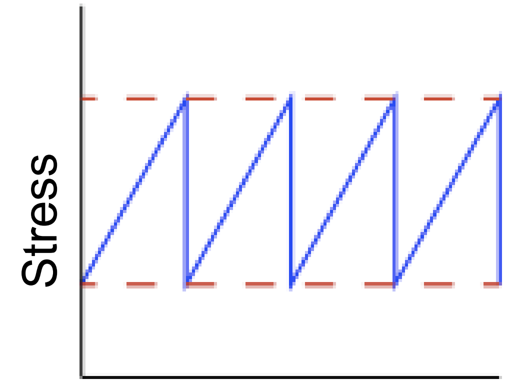
The static-kinetic (or slip-weakening) friction:

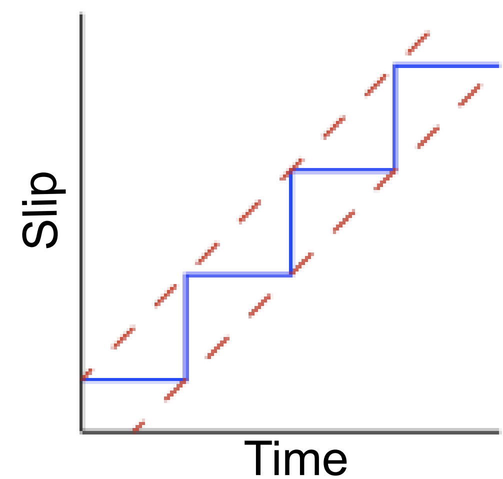
experiment → Constitutive law





Ohnaka (2003)





Frictional instabilities governed by rate- and state-dependent friction

Dieterich-Ruina friction:

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

and

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

At steady state:

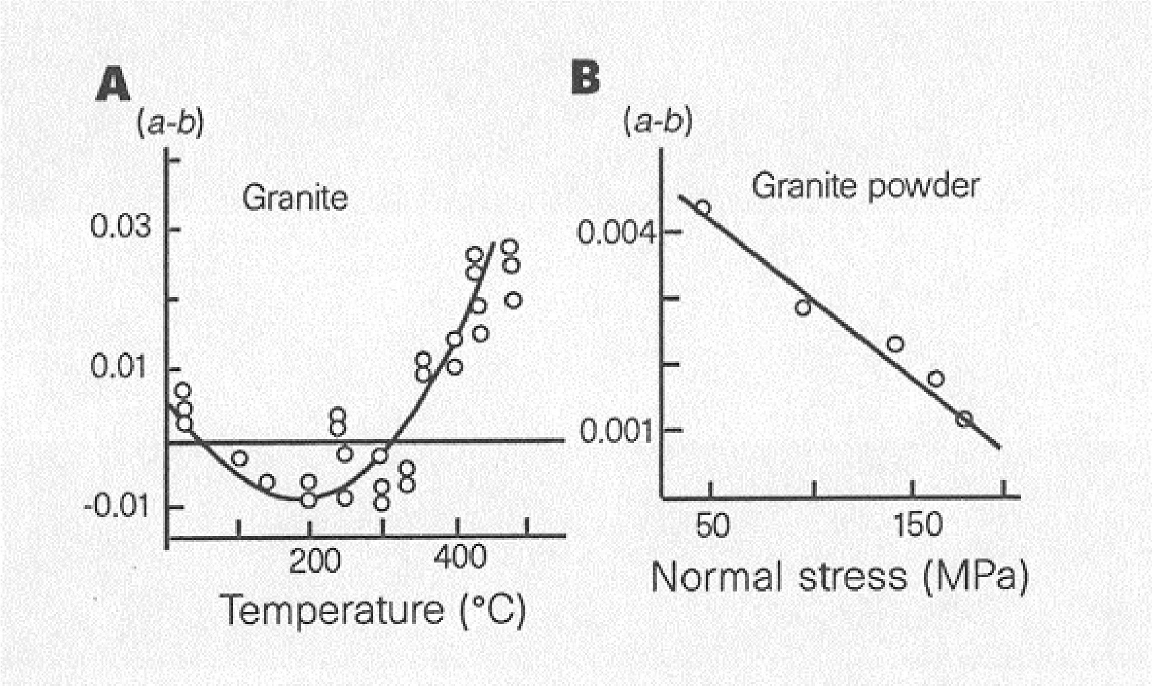
$$\mu = \mu^* + (a-b)\ln\left(\frac{V}{V^*}\right)$$

were:

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

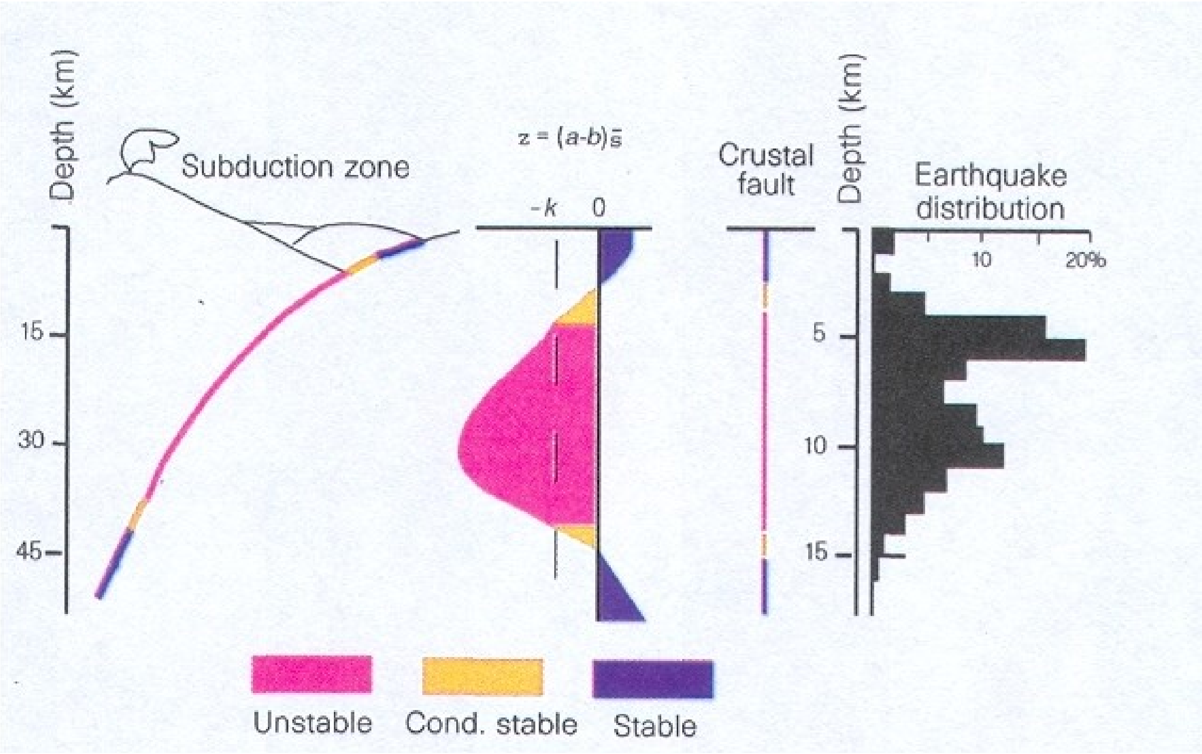
How b-a changes with depth ?

• Note the smallness of b-a.



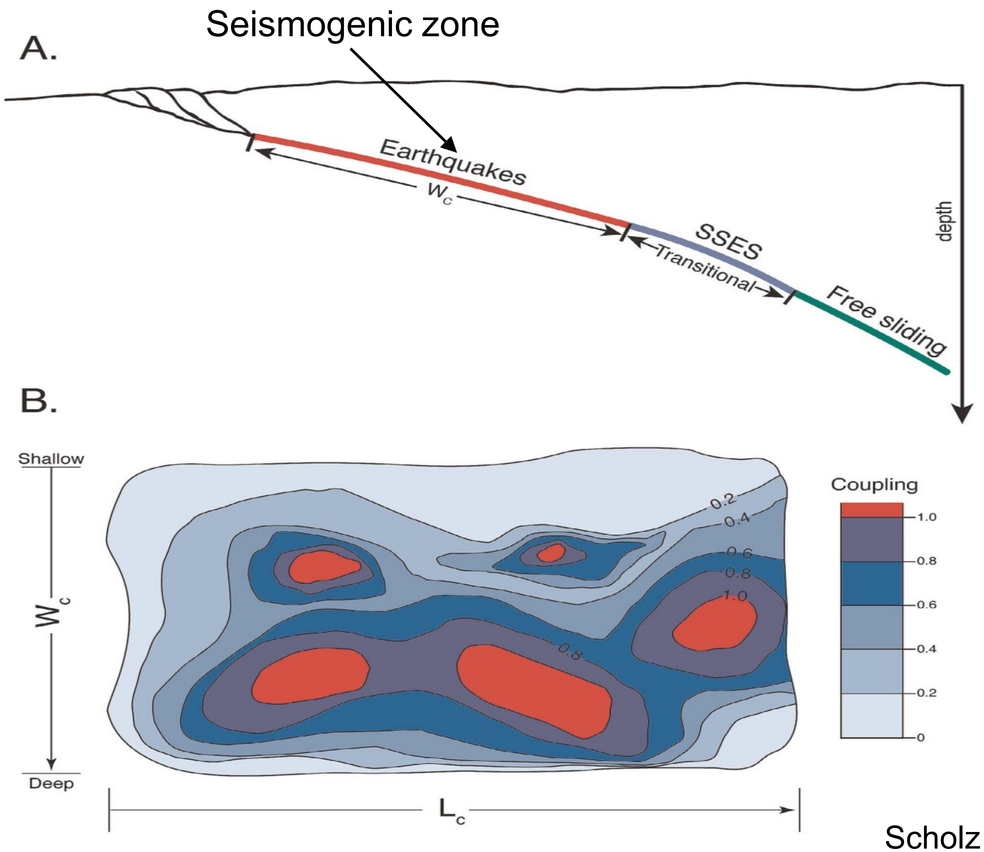
Scholz, Nature 1998 and references therein

The depth dependence of b-a may explain the seismicity depth distribution



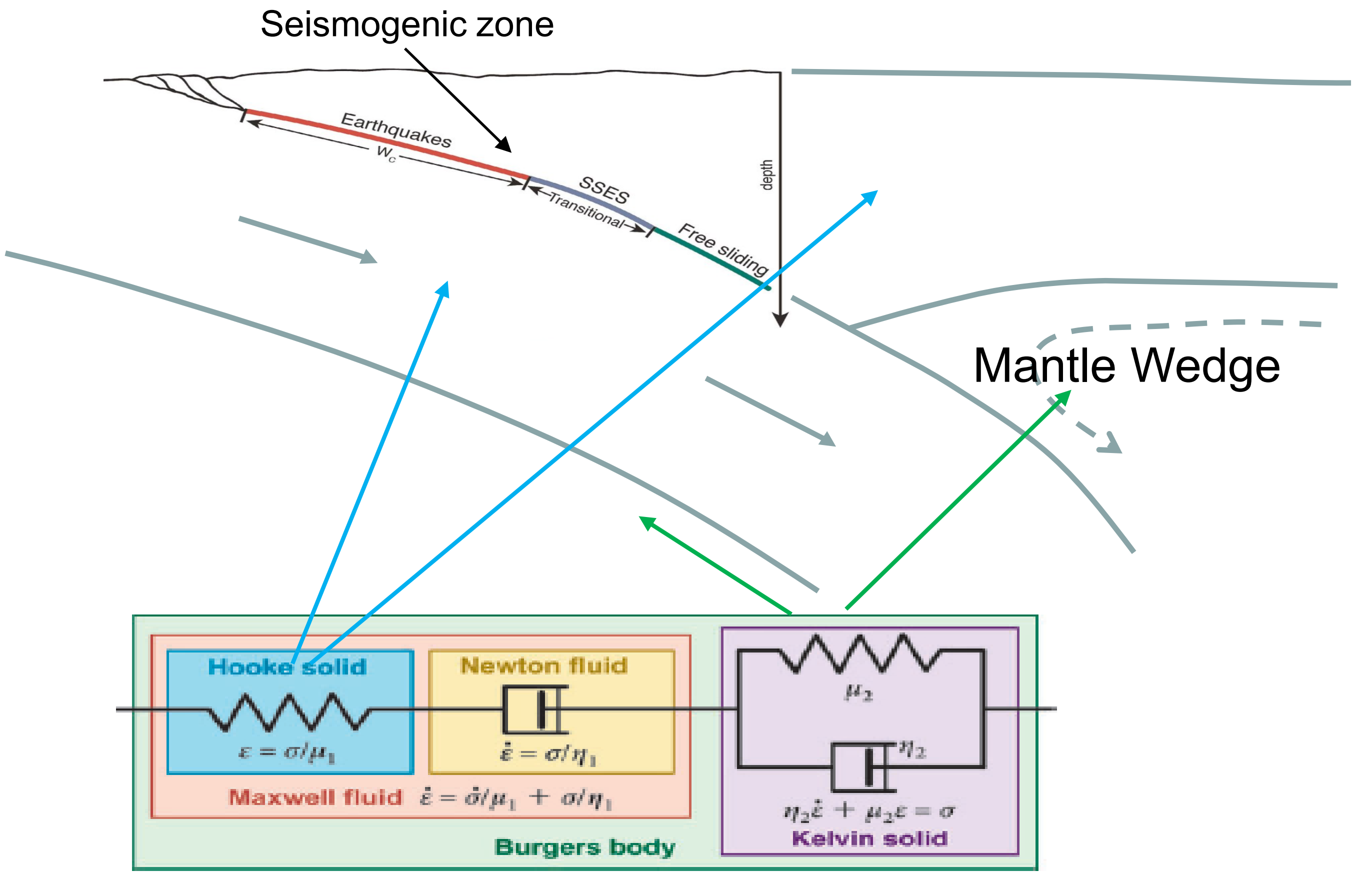
Scholz (1998)

Subduction zone earthquakes

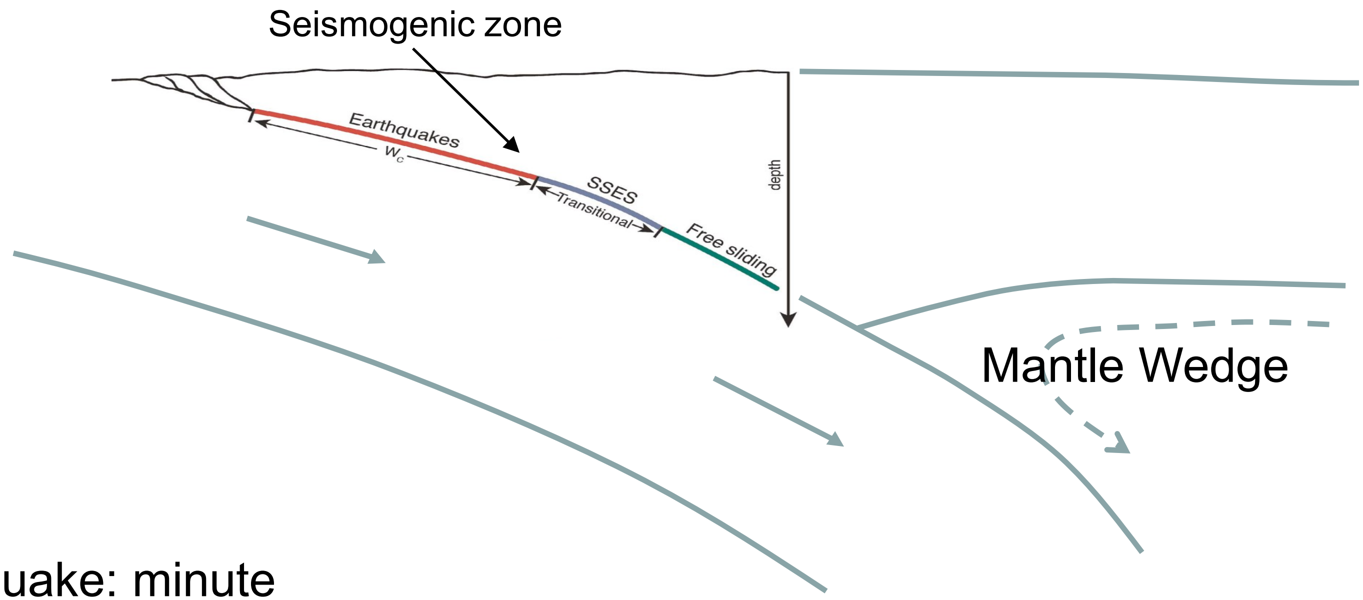


Scholz and Campos, 2012

Subduction zone earthquakes



Subduction zone earthquakes



1. Earthquake: minute
2. Aftertslip (fault control) **hours-1 year,** V ≈1/t
3. Visco-elastic relaxation (wedge control) **year-decades**

Our aim was to develop the thermo-mechanical model able to:

- Replicate long-term (10^6yr) evolution of subduction zone
- Generate earthquakes as spontaneous mechanical instabilities
- Replicate all stages of seismic cycle and multiple cycles in time scale range from minute to 10^4yr

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- Replicate long-term (10^6yr) evolution of subduction zone
- Generate earthquakes as spontaneous mechanical instabilities
- Replicate all stages of seismic cycle and multiple cycles in time scale range from minute to 10^4yr
- **And all that with mineral-physics-based rheology**

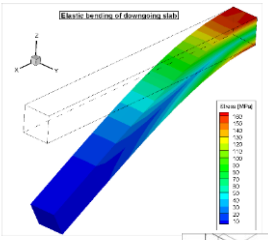
Technique

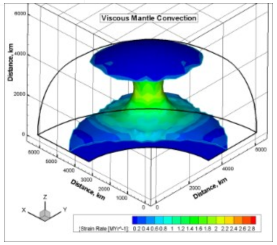
FEM code SLIM3D (Popov and Sobolev PEPI, 2008)

Balance equations

Momentum: $$\frac{\partial \sigma_{ij}}{\partial x_j} + \Delta \rho g\, z_i = 0$$

Energy: $$\frac{DU}{Dt} = -\frac{\partial q_i}{\partial x_i} + r$$





Deformation mechanisms

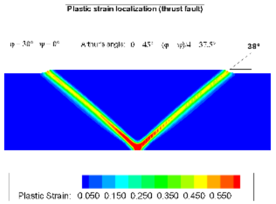
$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}_{ij}^{el} + \dot{\varepsilon}_{ij}^{vs} + \dot{\varepsilon}_{ij}^{pl}$$

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

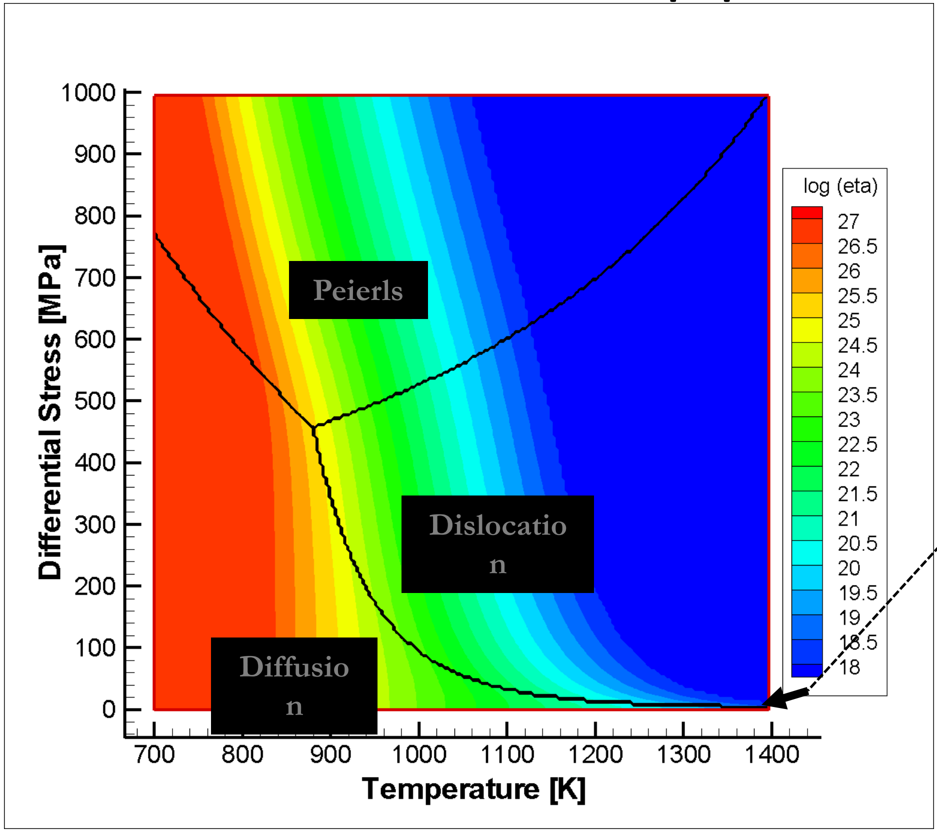
Viscous strain: $$\dot{\varepsilon}_{ij}^{vs} = \frac{1}{2\eta_{eff}}\tau_{ij}$$

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

Mohr-Coulomb



Three creep processes



$$\eta_{eff} = \frac{1}{2}\tau_{II}\left(\dot{\varepsilon}_L + \dot{\varepsilon}_N + \dot{\varepsilon}_P\right)^{-1}$$

Diffusion creep

$$\dot{\varepsilon}_L = B_L \tau_{II} \exp\left(-\frac{E_L}{RT}\right)$$

Dislocation

$$\dot{\varepsilon}_N = B_N \left(\tau_{II}\right)^n \exp\left(-\frac{E_N}{RT}\right)$$

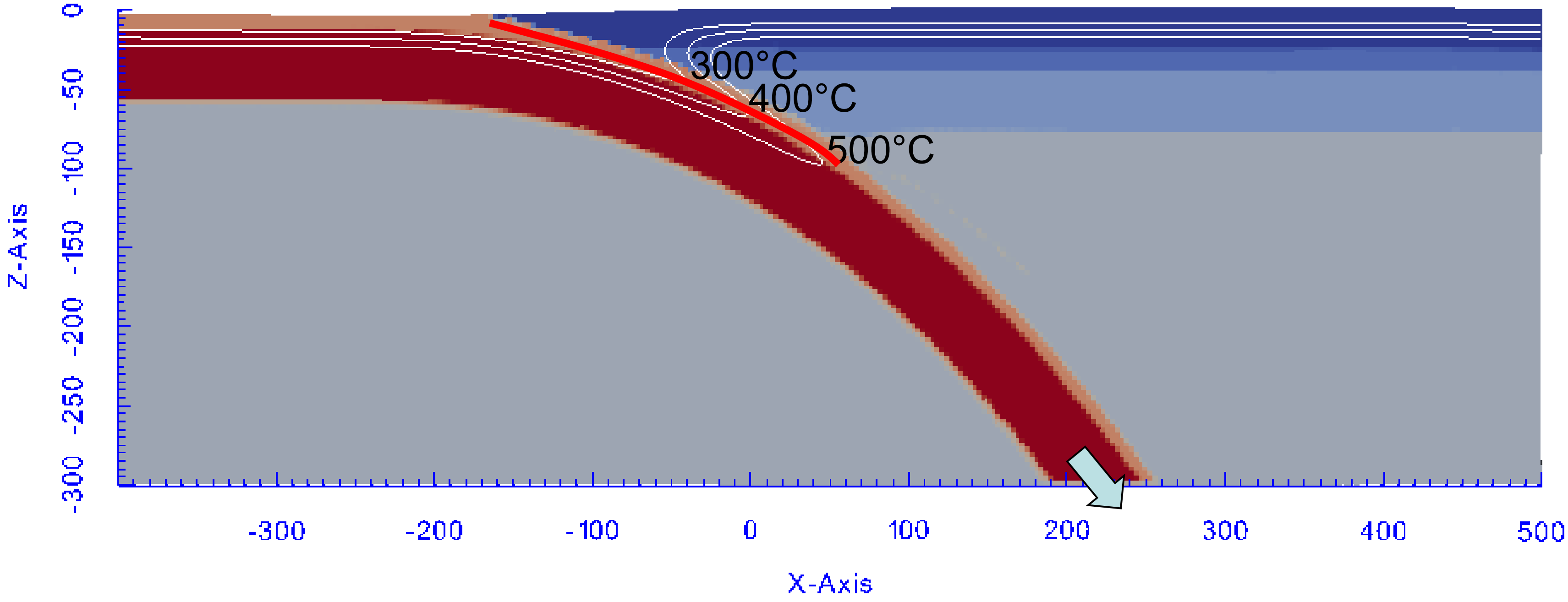
Peierls creep

$$\dot{\varepsilon}_P = B_P \exp\left[-\frac{E_P}{RT}\left(1-\frac{\tau_{II}}{\tau_P}\right)^2\right]$$

(Kameyama *et al.* 1999)

Cross-scale Modeling of Seismic Cycle

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



Rate and State Friction Law

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

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.

Transient viscous rheology

Steady power-law dislocation creep

$$\dot{\varepsilon}_{ss} = B \cdot \tau^n \exp(-H_a / RT)$$

Transient rheology (motivated by Karato (1998))

$$\dot{\varepsilon} = \dot{\varepsilon}_{ss}(1 + (\beta - 1)\exp(-\varepsilon_{ss}^{after\_eq} / \varepsilon_{el}^{eq}))$$

where:

- $\dot{\varepsilon}_{ss}$ is power-law steady state creep strain rate (lab data)
- ε_{el}^{eq} is elastic strain induced by earthquake
- $\varepsilon_{ss}^{after\_eq}$ is steady state viscous strain after the earthquake
- β is a constant about 10 for peridotite

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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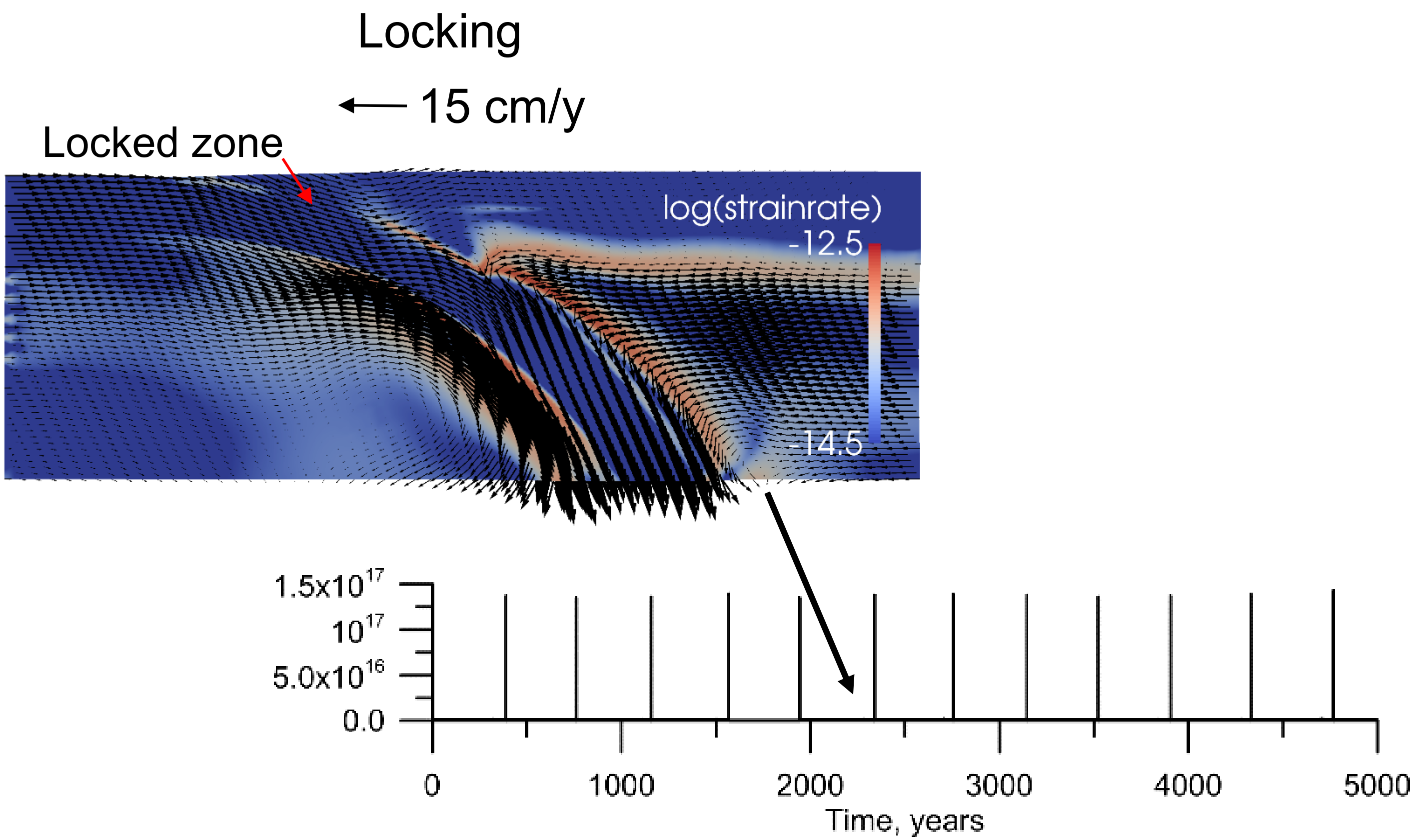

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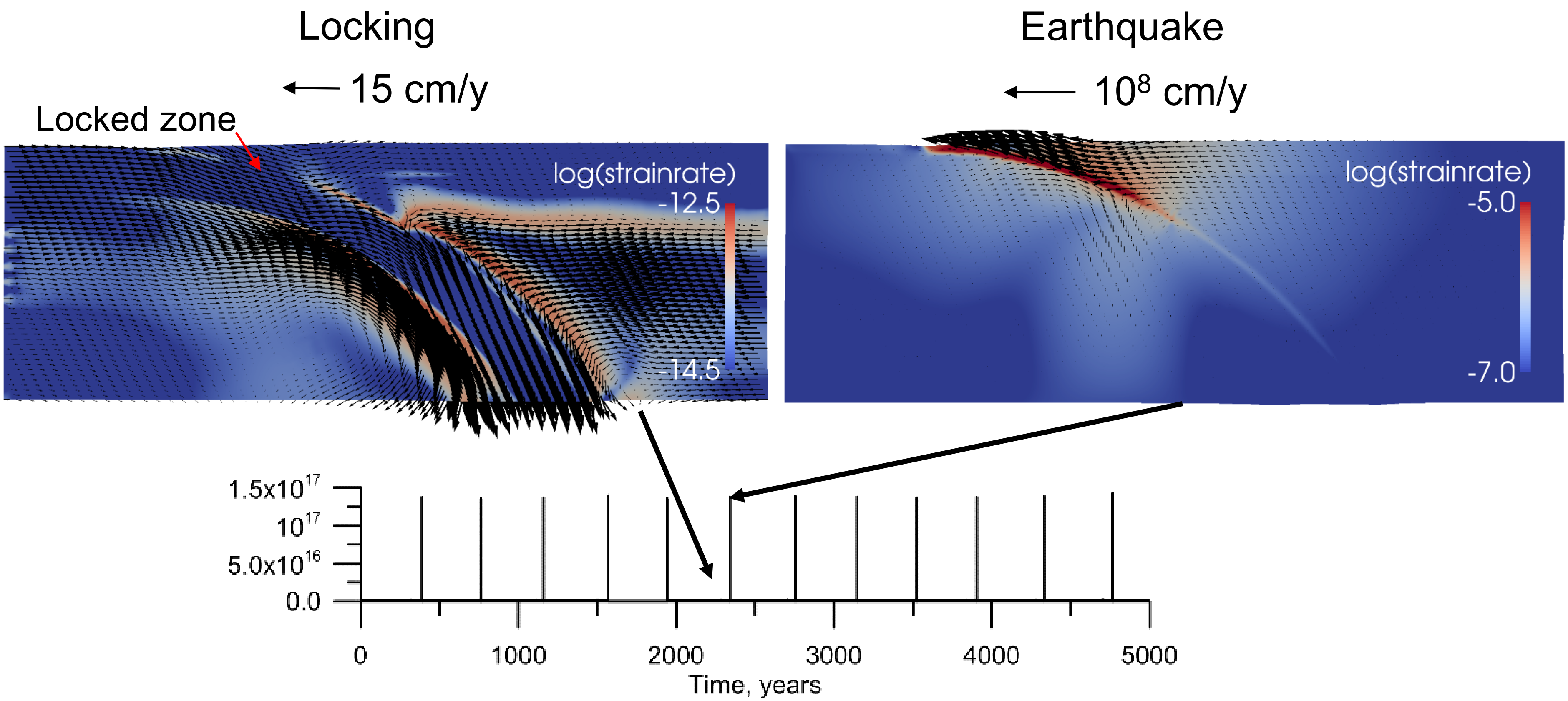
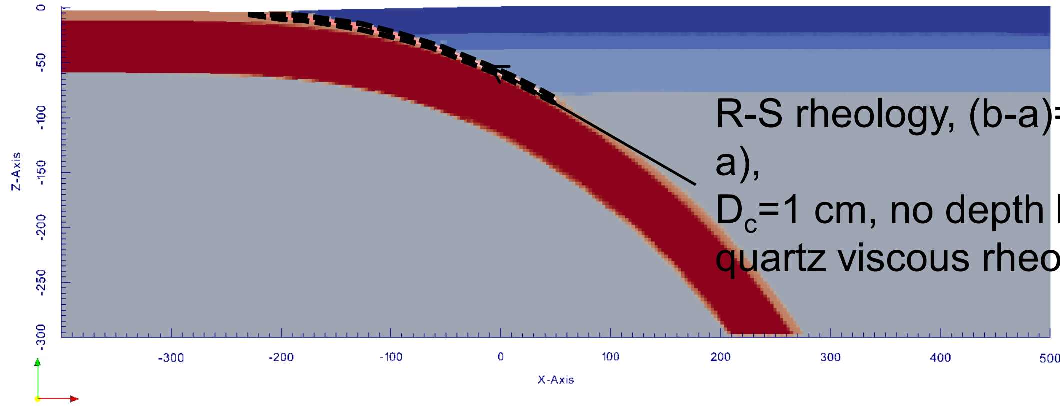
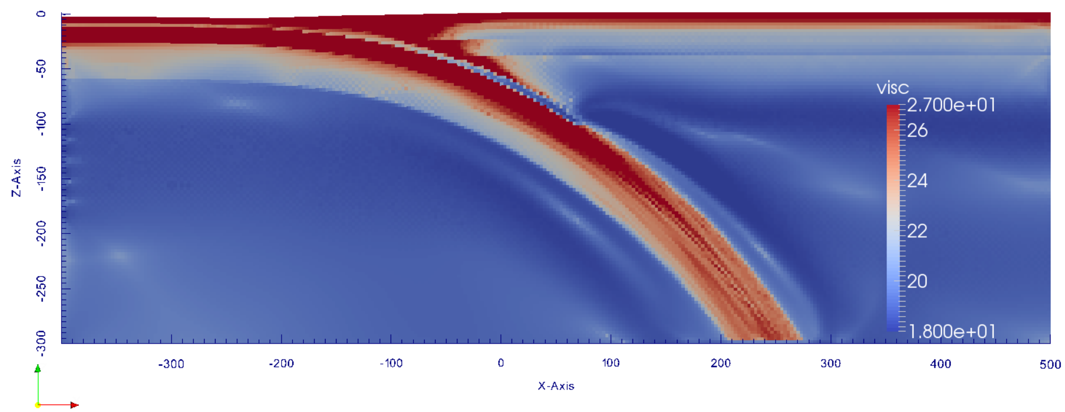


Model setup
(short time scale)

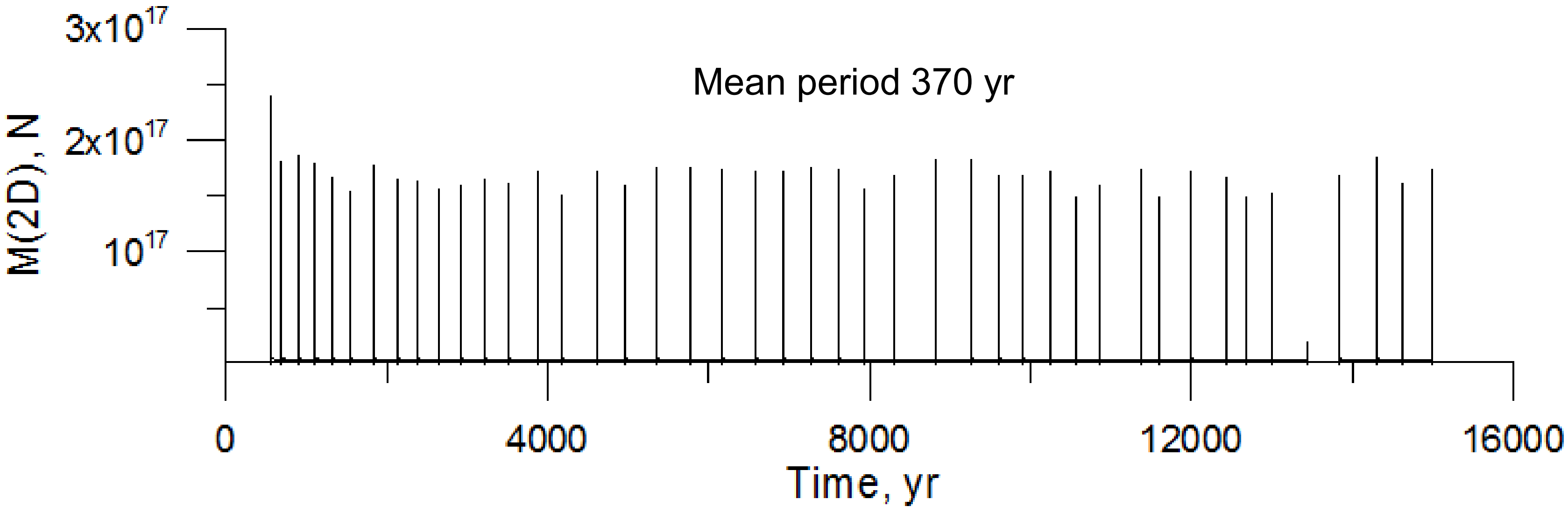


R-S rheology, (b-a)=4.10^{-4}, b=2(b-a),
D_c=1 cm, no depth limit; weak „wet" quartz viscous rheology



Earthquakes

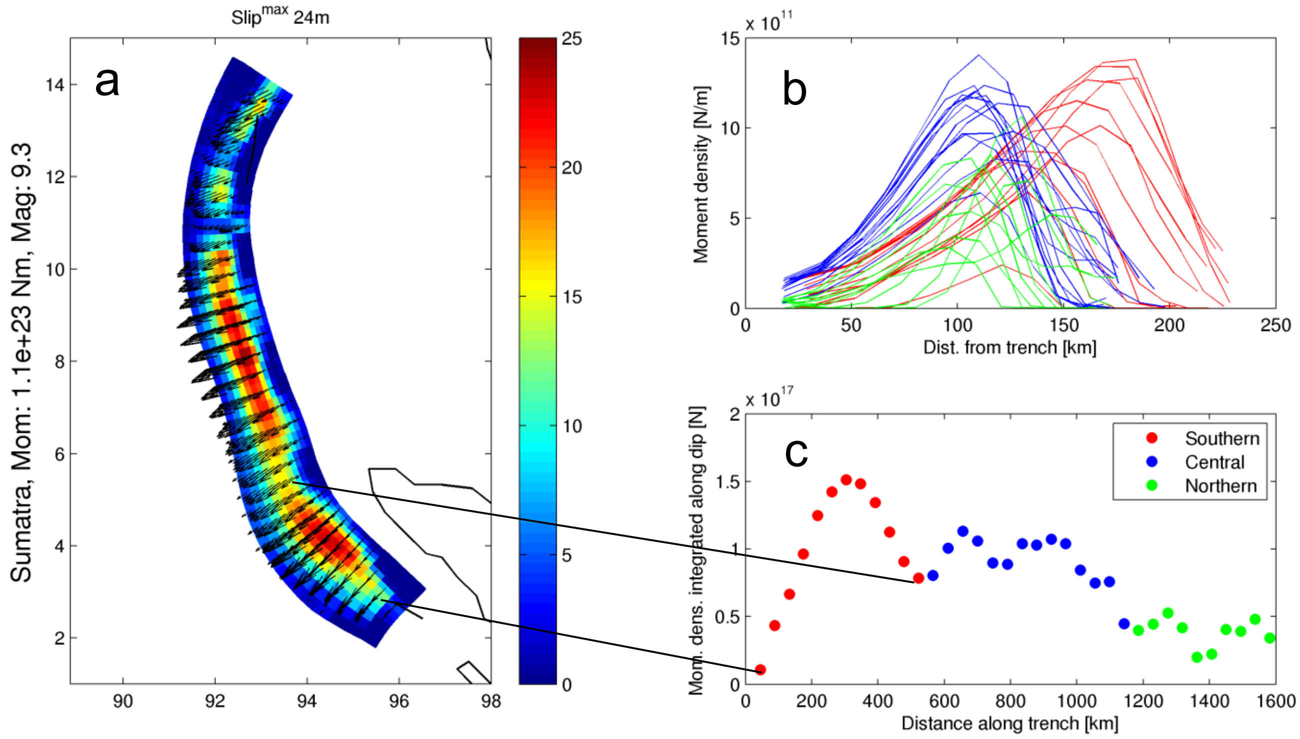
Adaptive time-step algorithm: from 5 yr step gradually multiplying by ½ to about 40 sec and back



Generated earthquakes sequence

2D Moments
Sumatra, 2004

From Andreas Hoechner, GFZ



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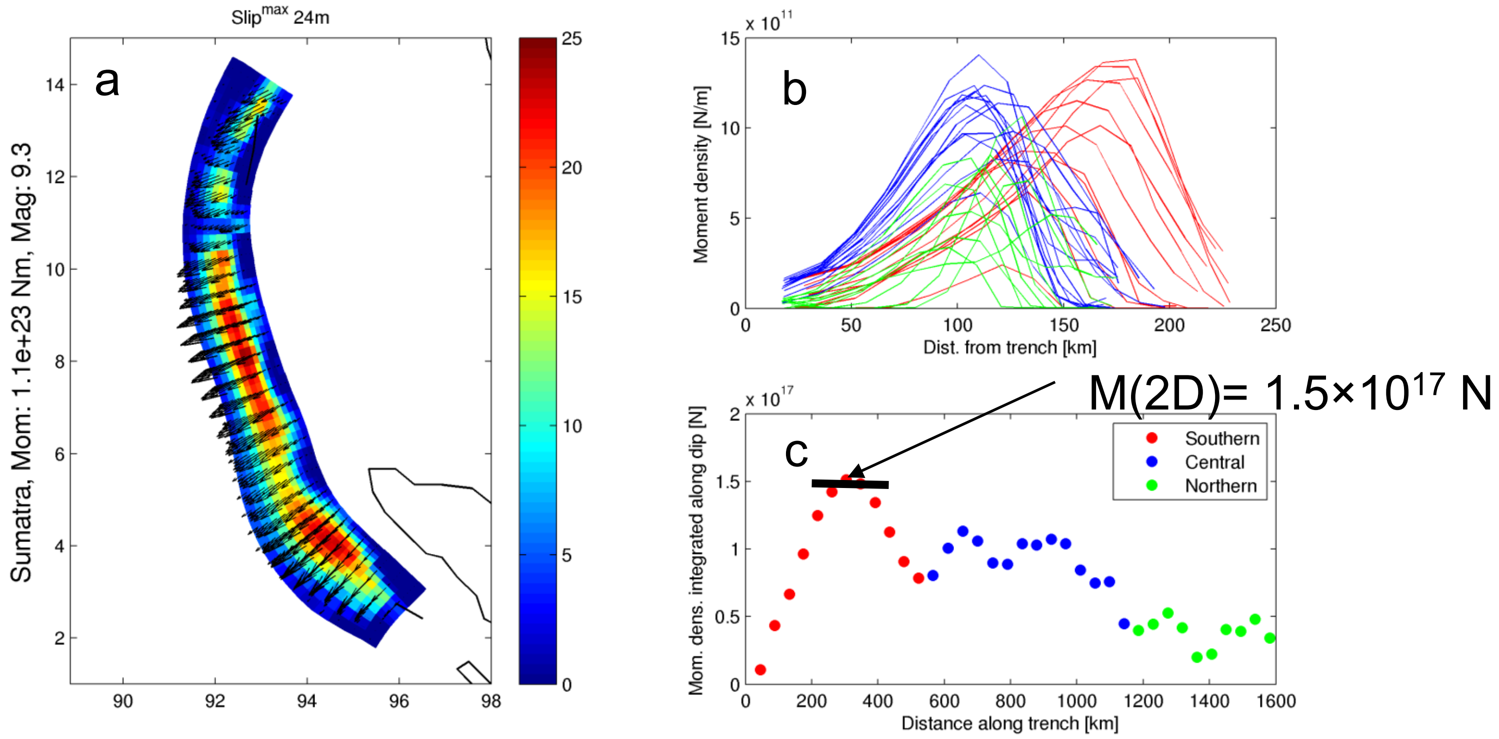

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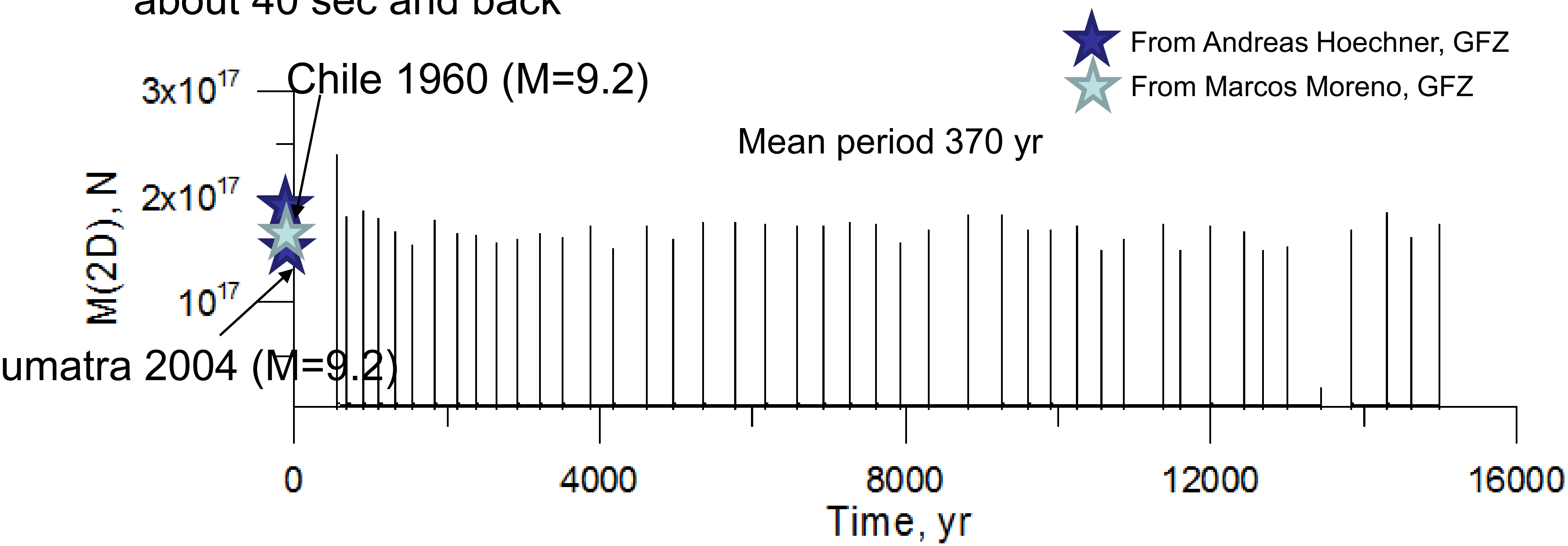
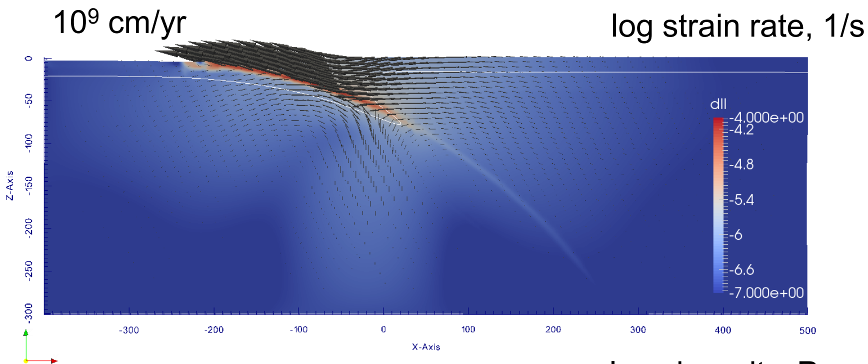
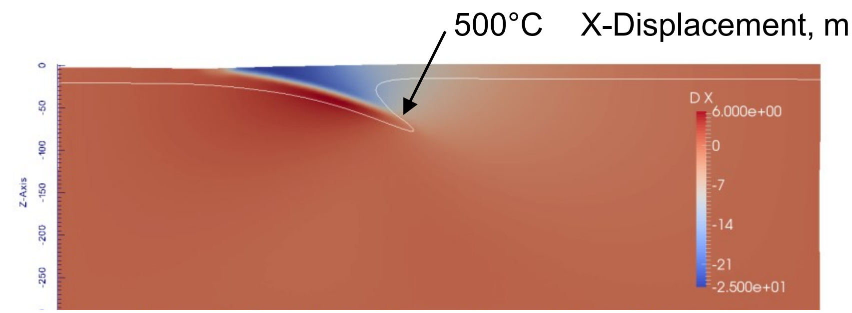


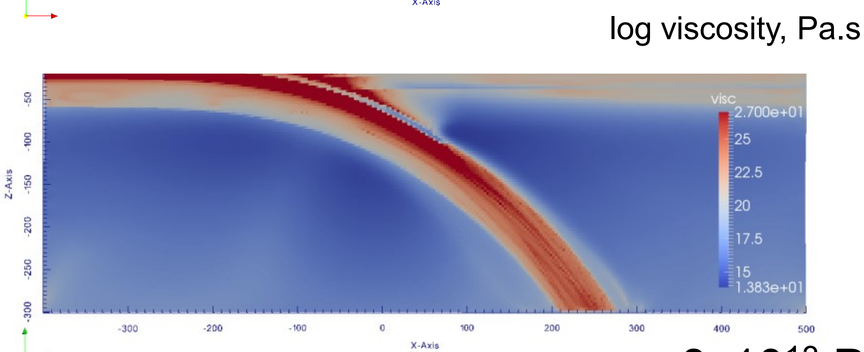
Generated earthquakes sequence

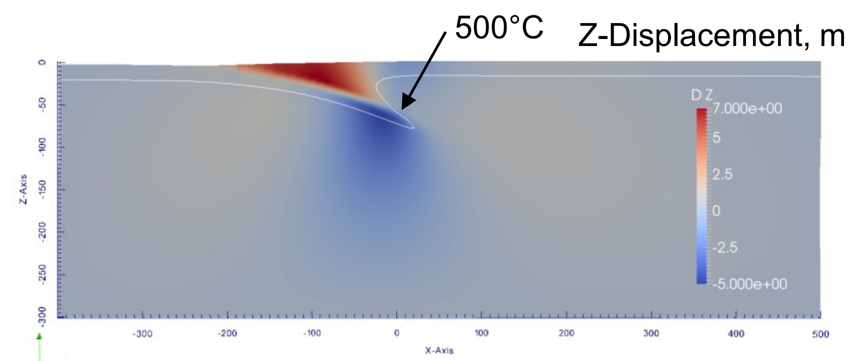
Zoom-in to earthquake

about 40 sec time-scale, M(2D)=1.8×10^{17}, mean slip at the fault 17 m, stress drop 6 MPa, rupture penetrates to about 500°C-isotherm depth









$\eta_{min}=8\text{x}10^{13}$ Pa

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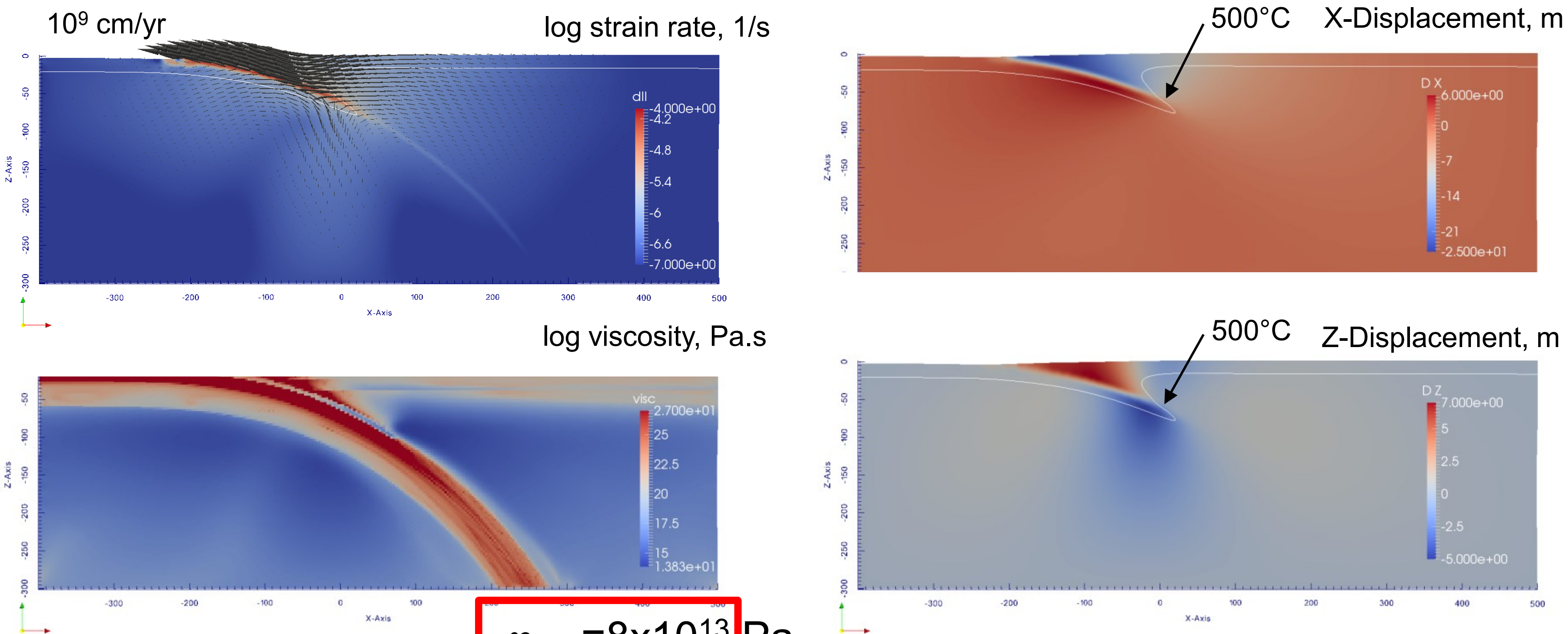
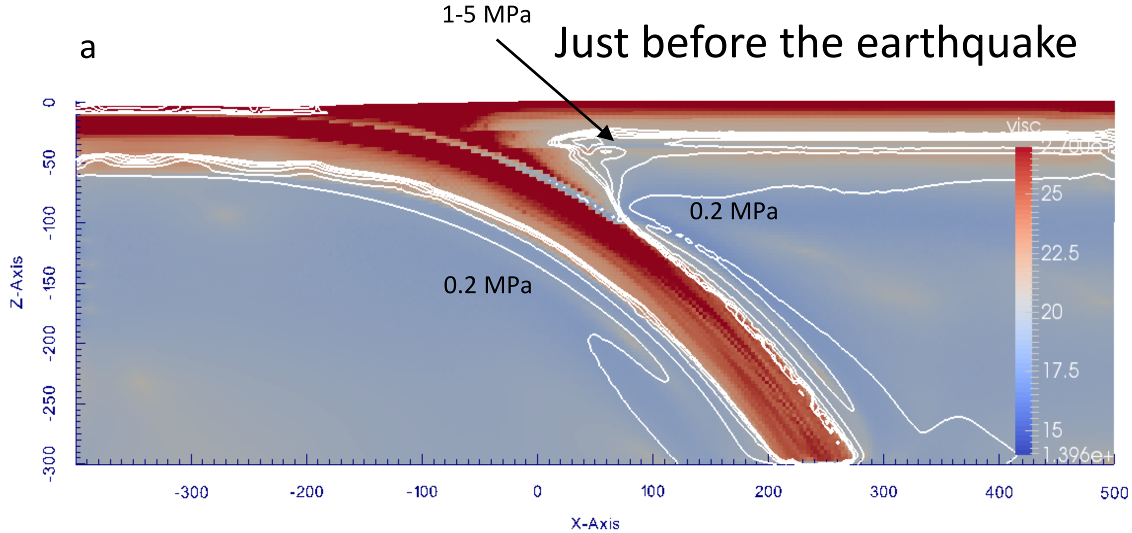


$\eta_{min}=8\times10^{13}$ Pa

Why viscosity drop?

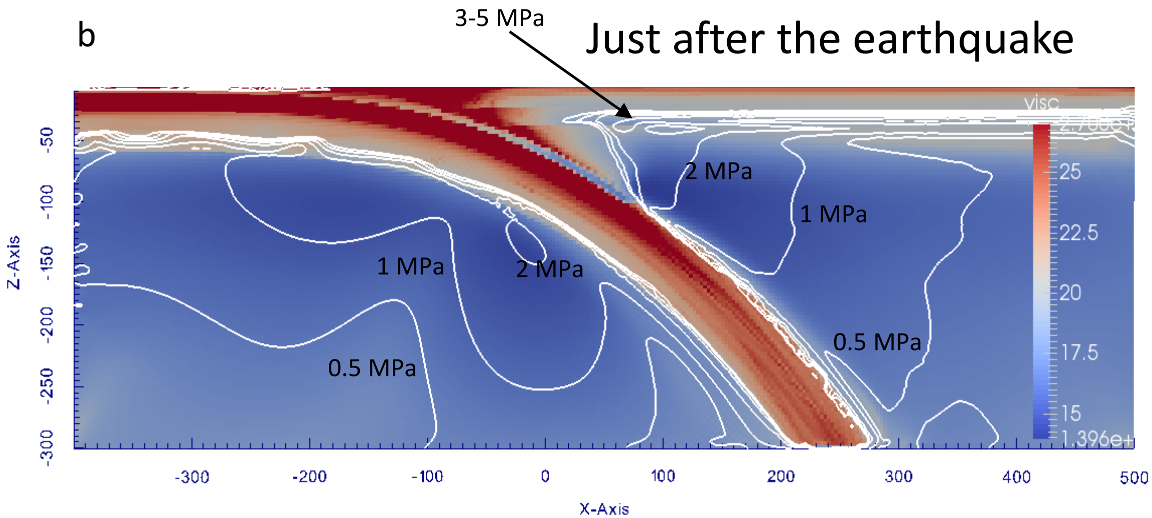
a



$$\dot{\varepsilon}_{ss} = B \cdot \tau^{n} \exp(-H_a / RT)$$

Stress in the mantle wedge changes by up to 16 times
→1000 times viscosity drop

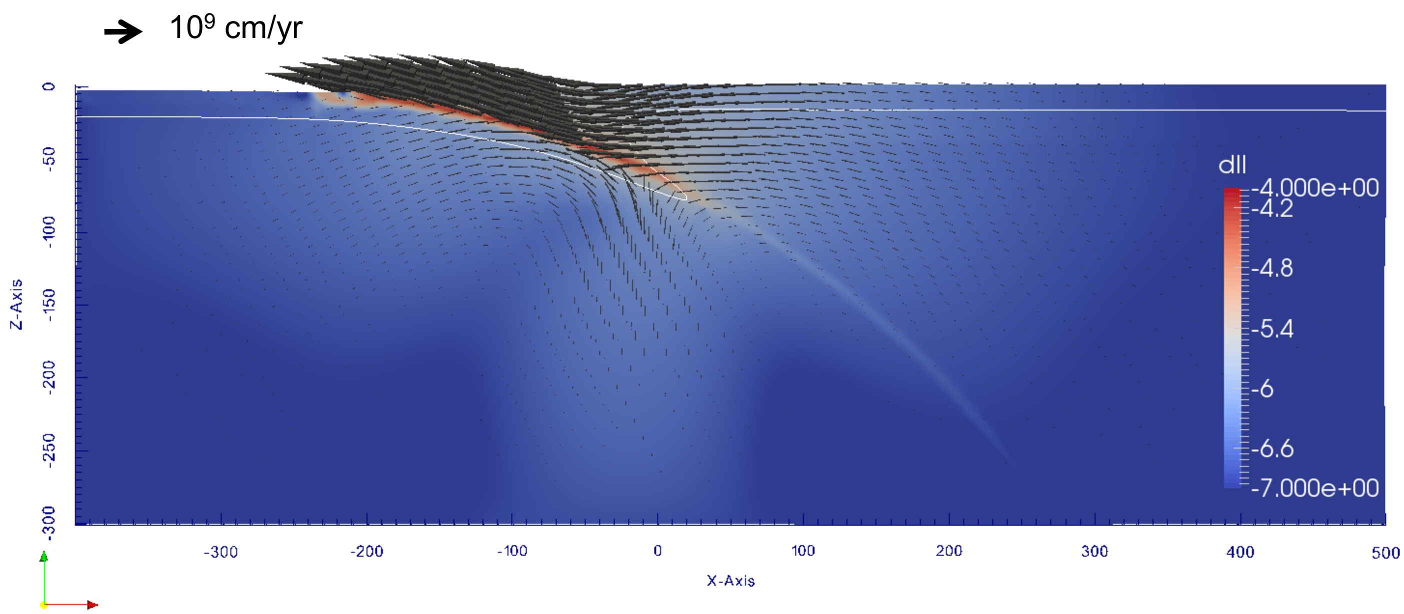
b



Additional 10 times drop is due to transient rheology

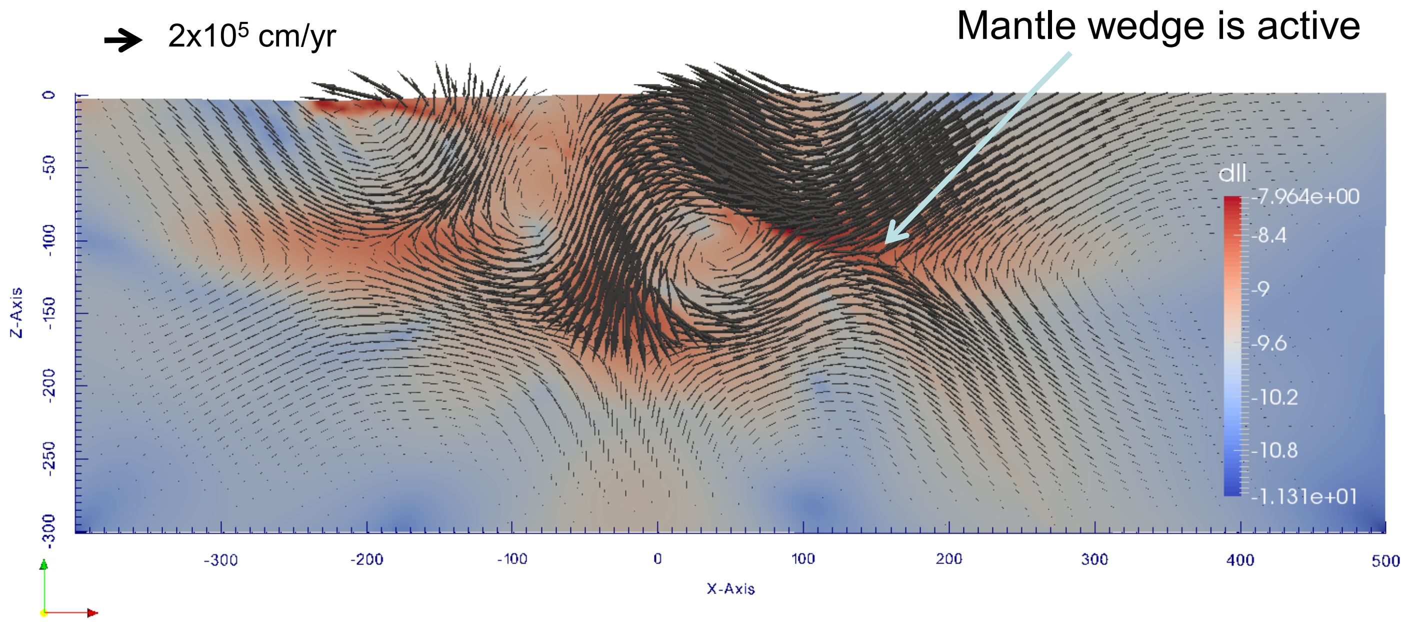
Seismic-cycle tour

40 sec

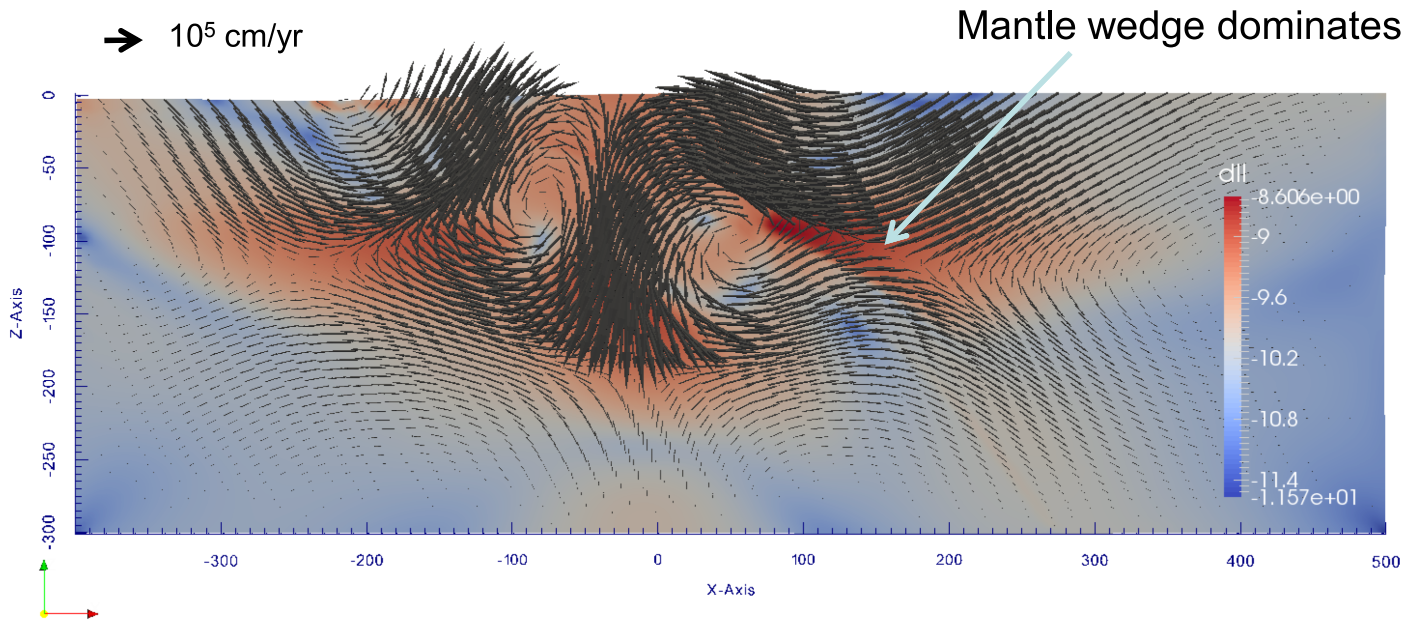


Seismic-cycle tour

7 min

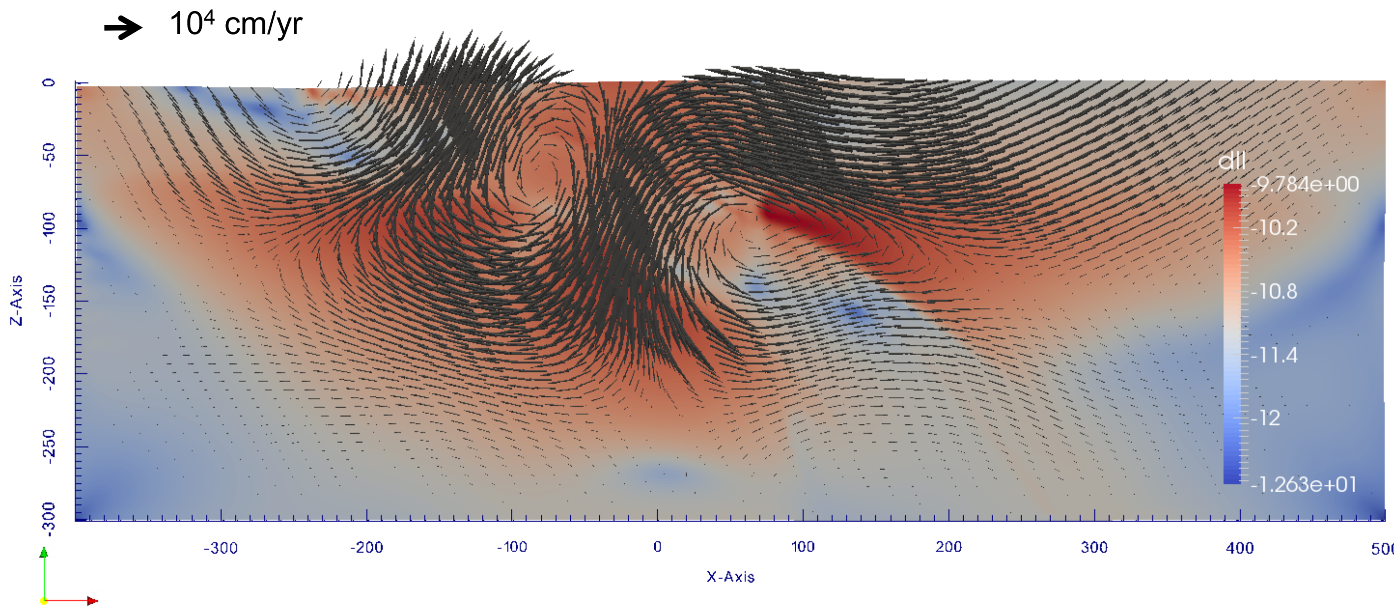


1 hour



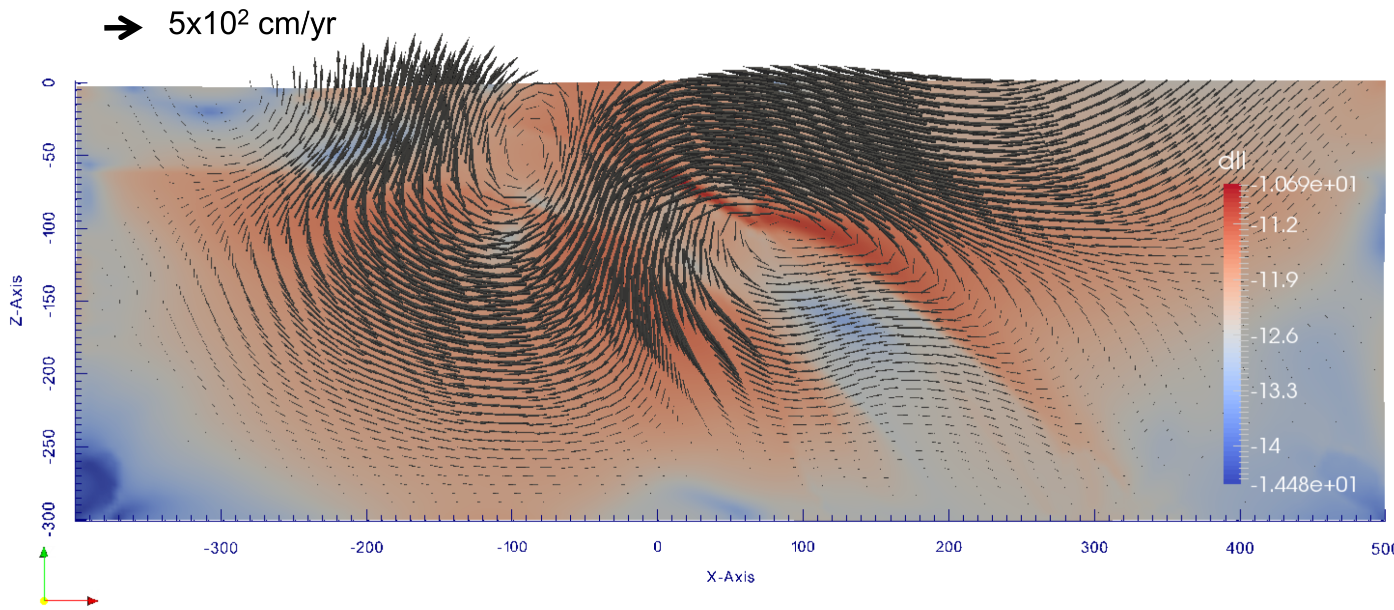
10^5 cm/yr
Mantle wedge dominates
dll
-8.606e+00
-9
-9.6
-10.2
-10.8
-11.4
-1.157e+01
Z-Axis
0
-50
-100
-150
-200
-250
-300
X-Axis
-300
-200
-100
0
100
200
300
400
500

1 day



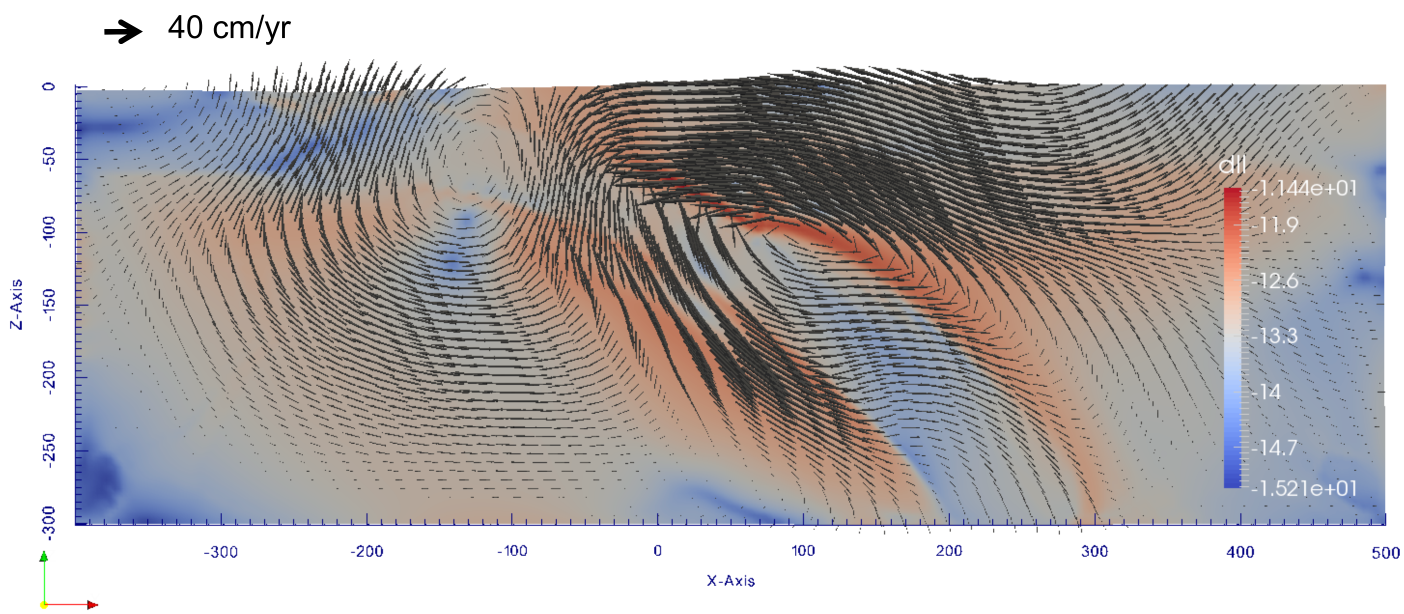
10^4 cm/yr
dll
-9.784e+00
-10.2
-10.8
-11.4
-12
-1.263e+01
Z-Axis
X-Axis
0
-50
-100
-150
-200
-250
-300
-300
-200
-100
0
100
200
300
400
500

1 month



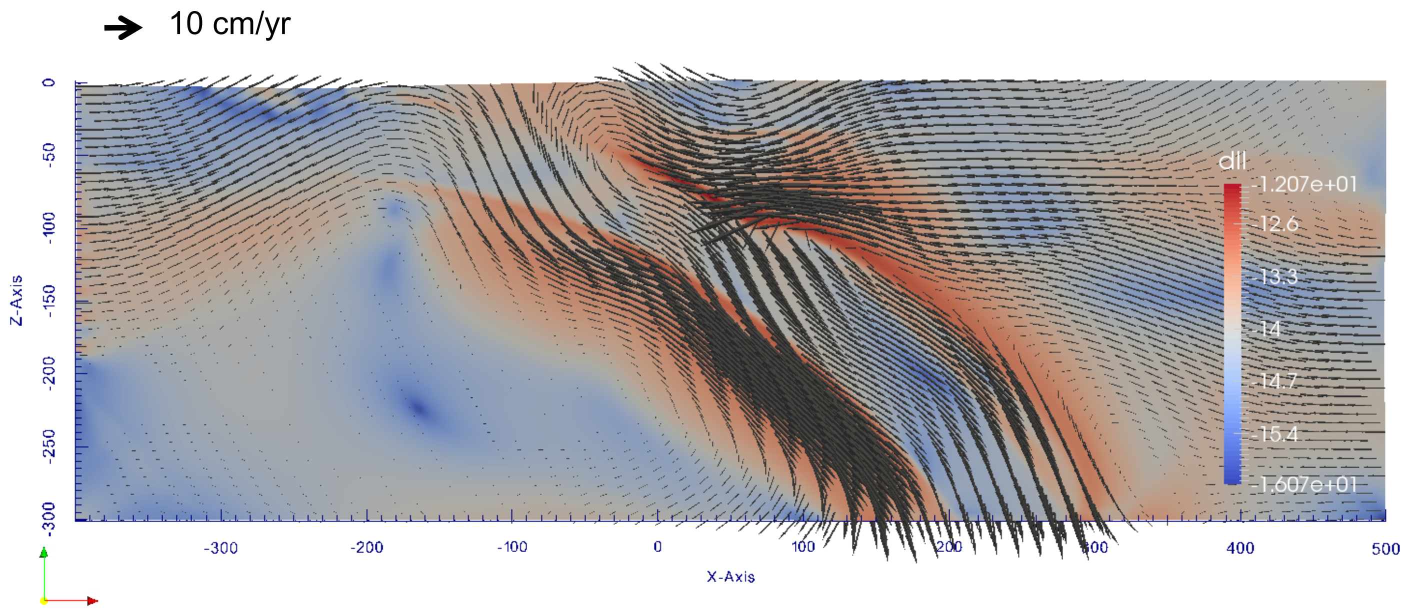
5x10^2 cm/yr
dll
-1.069e+01
-11.2
-11.9
-12.6
-13.3
-14
-1.448e+01
Z-Axis
0
-50
-100
-150
-200
-250
-300
X-Axis
-300
-200
-100
0
100
200
300
400
500

1 year



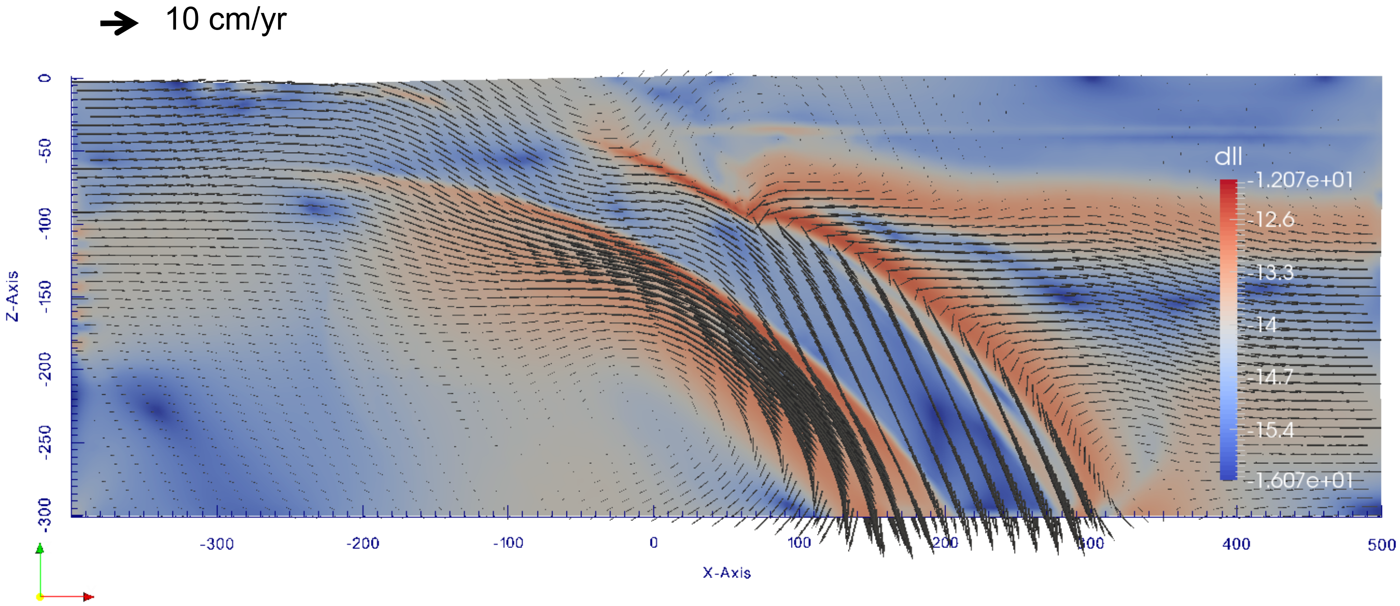
40 cm/yr
Z-Axis
X-Axis
0
-50
-100
-150
-200
-250
-300
-300
-200
-100
0
100
200
300
400
500
dll
-1.144e+01
-11.9
-12.6
-13.3
-14
-14.7
-1.521e+01

10 years



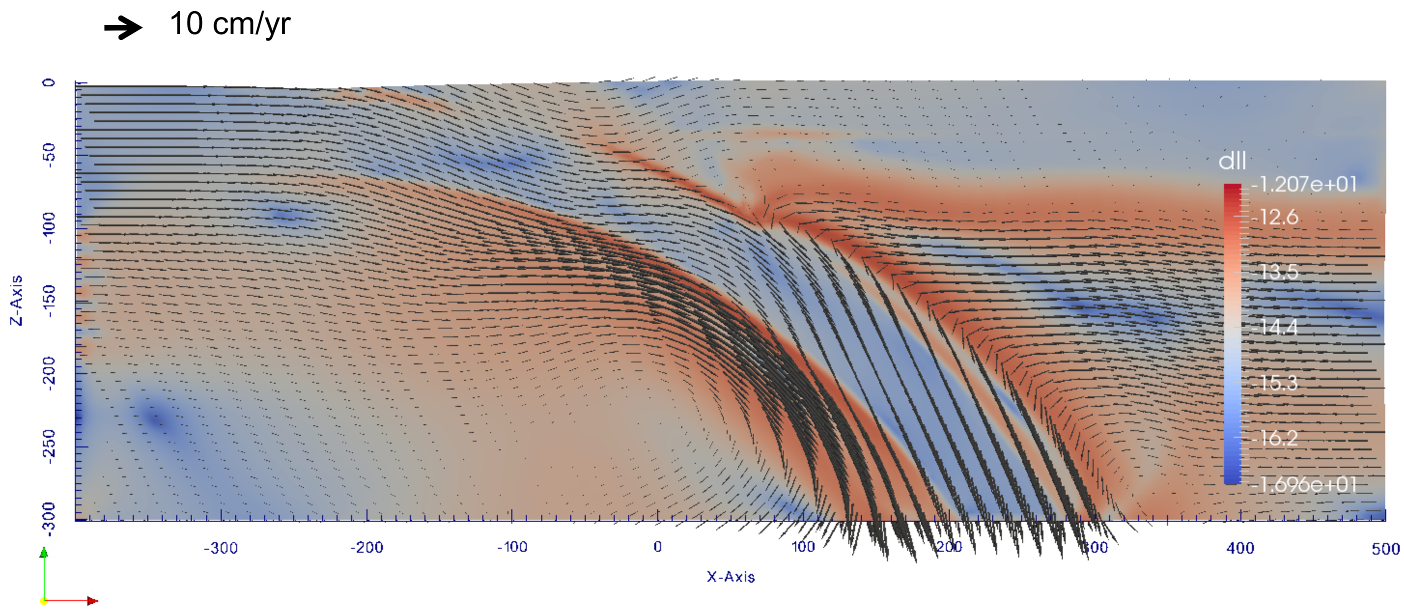
10 cm/yr
Z-Axis
X-Axis
0
-50
-100
-150
-200
-250
-300
-300
-200
-100
0
100
200
300
400
500
dll
-1.207e+01
-12.6
-13.3
-14
-14.7
-15.4
-1.607e+01

50 years

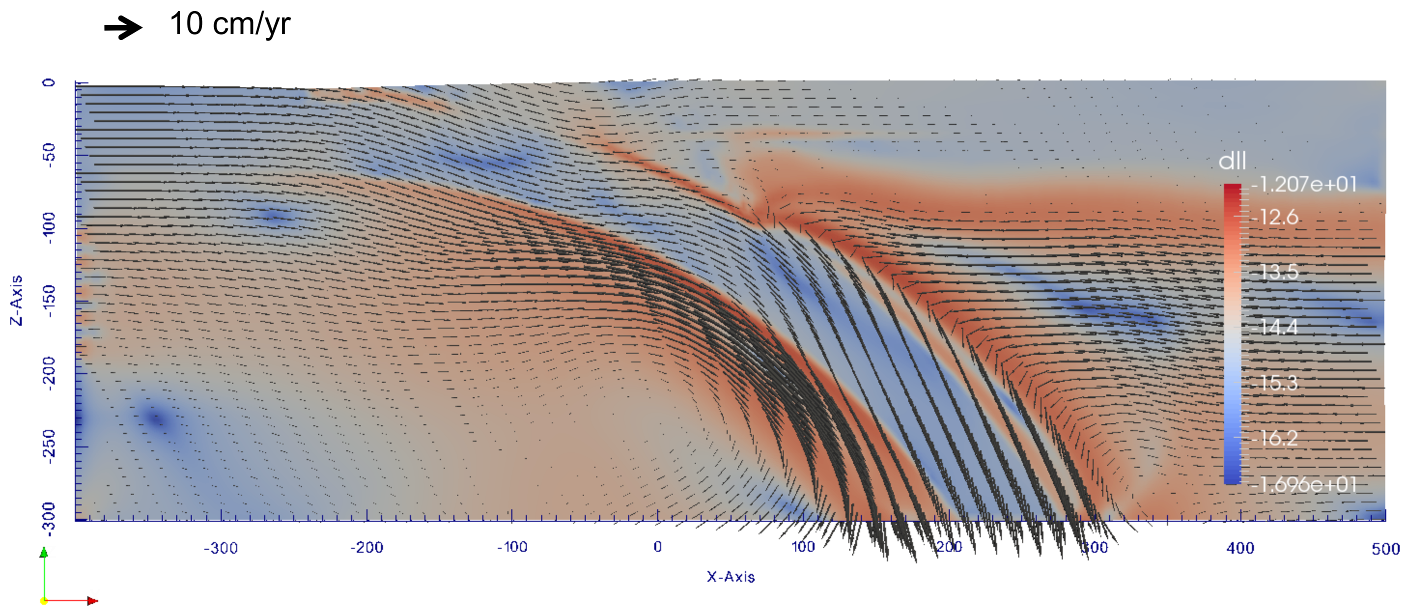


10 cm/yr
Z-Axis
0
-50
-100
-150
-200
-250
-300
-300
-200
-100
0
100
200
300
400
500
X-Axis
dll
-1.207e+01
-12.6
-13.3
-14
-14.7
-15.4
-1.607e+01

100 years

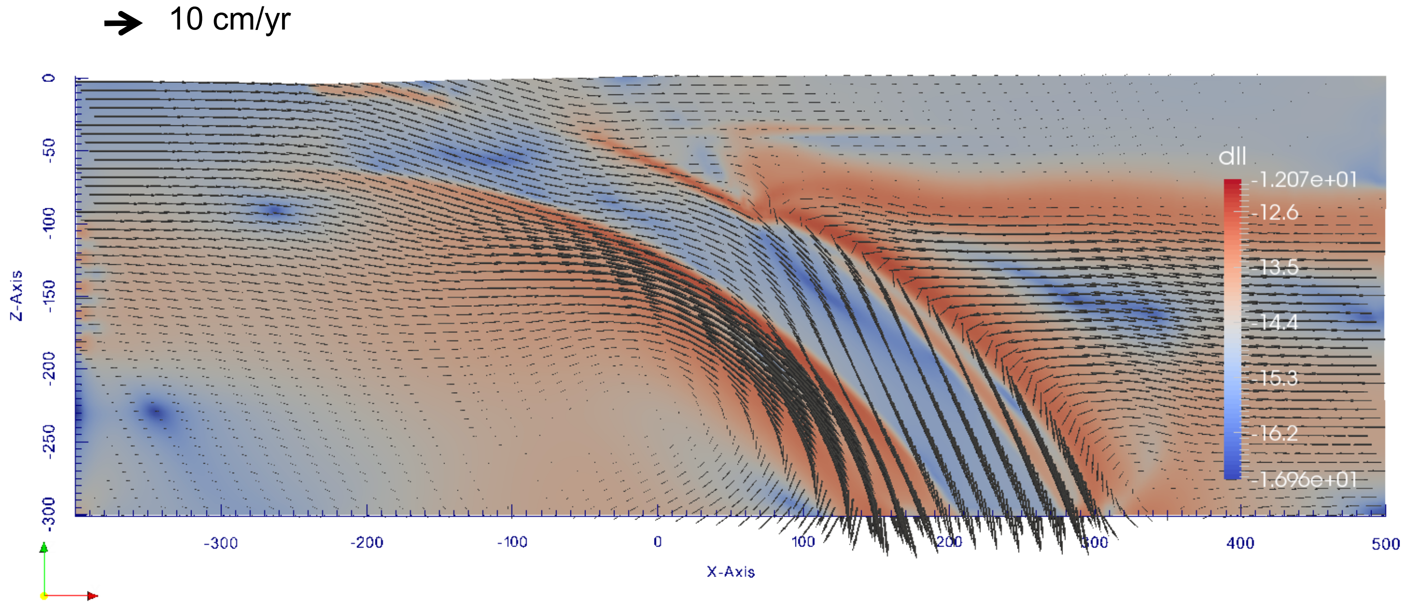

10 cm/yr
dll
-1.207e+01
-12.6
-13.5
-14.4
-15.3
-16.2
-1.696e+01
Z-Axis
0
-50
-100
-150
-200
-250
-300
X-Axis
-300
-200
-100
0
100
200
300
400
500

150 years

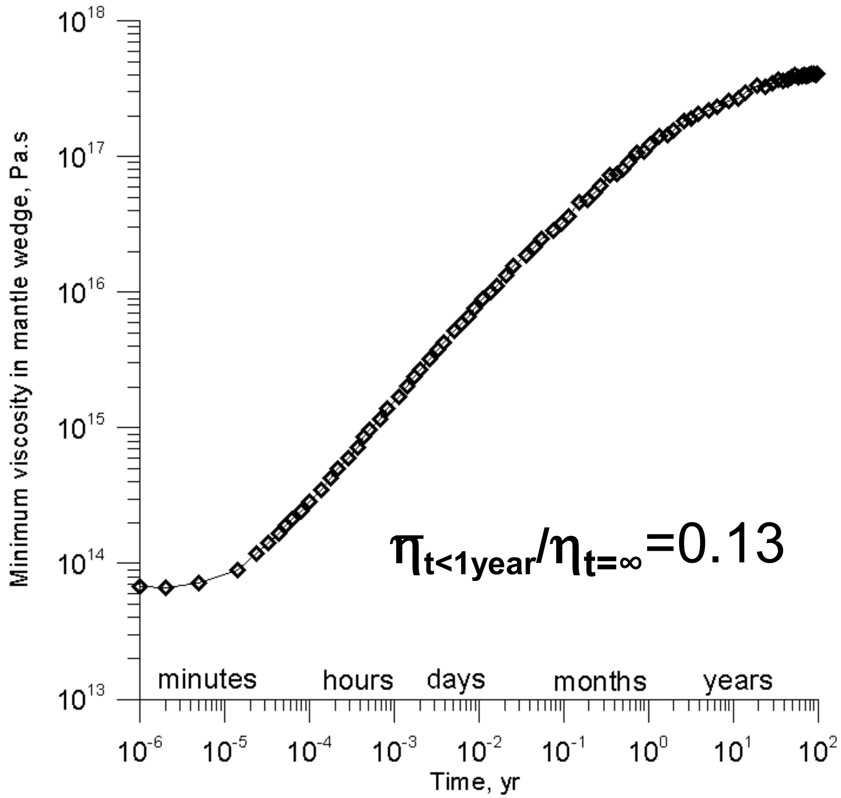


10 cm/yr
dII
-1.207e+01
-12.6
-13.5
-14.4
-15.3
-16.2
-1.696e+01
Z-Axis
0
-50
-100
-150
-200
-250
-300
X-Axis
-300
-200
-100
0
100
200
300
400
500

200 years


10 cm/yr
Z-Axis
0
-50
-100
-150
-200
-250
-300
X-Axis
-300
-200
-100
0
100
200
300
400
500
dII
-1.207e+01
-12.6
-13.5
-14.4
-15.3
-16.2
-1.696e+01

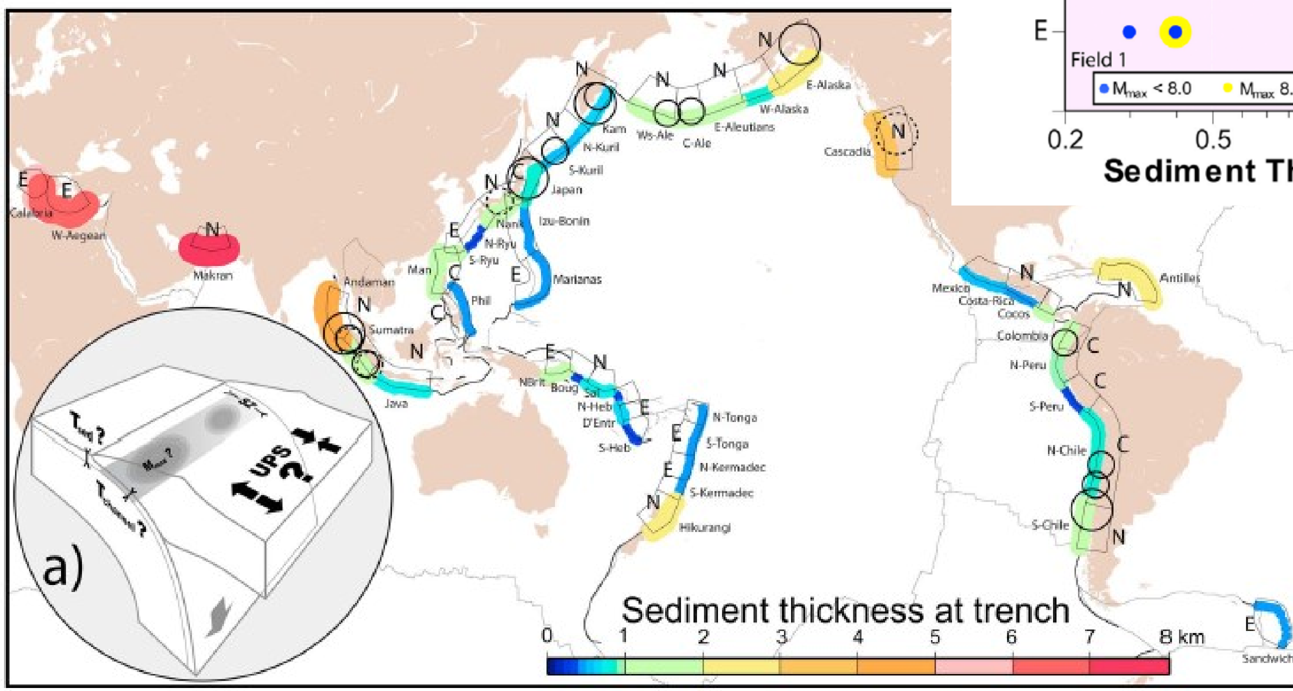
Evolution of viscosity in mantle wedge

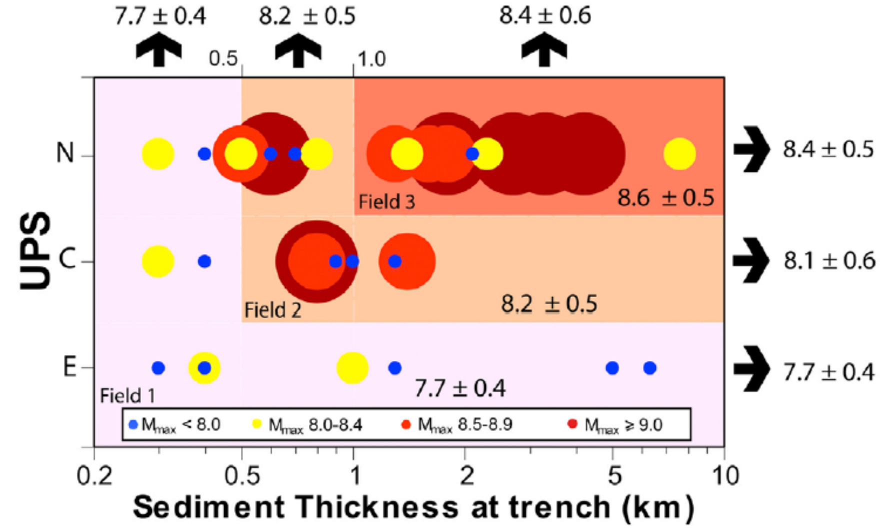


$\eta_{t<1year}/\eta_{t=\infty}=0.13$

almost 4 orders of magnitude!

Heuret et al, GRL 2012





Conclusions Cycle (2D)

- We have developed the model able to simulate seismic cycle and subduction process in time scale range from rupture (minute) to geological time (Mln years)

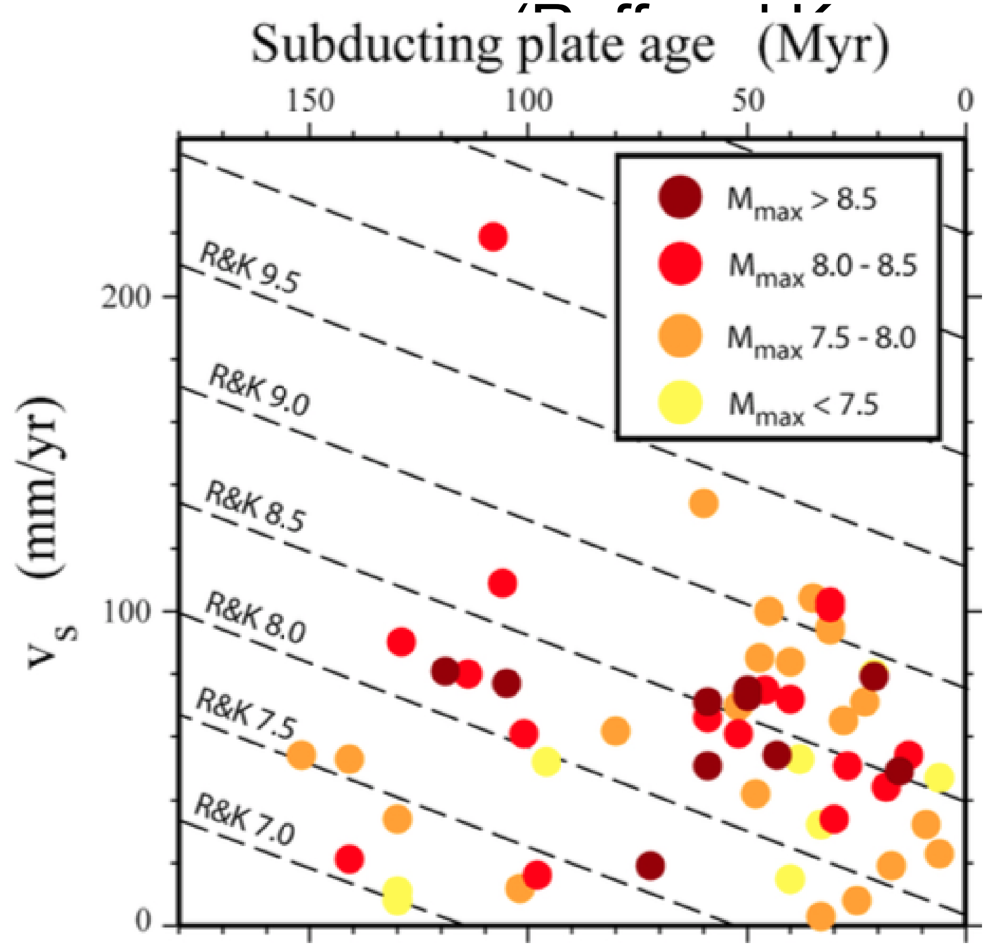
- The model suggests that after the great (M>9) earthquake viscosity in the mantle wedge can drop by up to 3-4 orders of magnitude. As a result, surface displacements are controlled by the relaxation in mantle wedge already <u>since 1 hour after the earthquake</u>.

- The model is consistent with the short-time scale GPS data for Tohoku 2011 earthquake

Maximum magnitudes

Mechanical coupling as a key factor

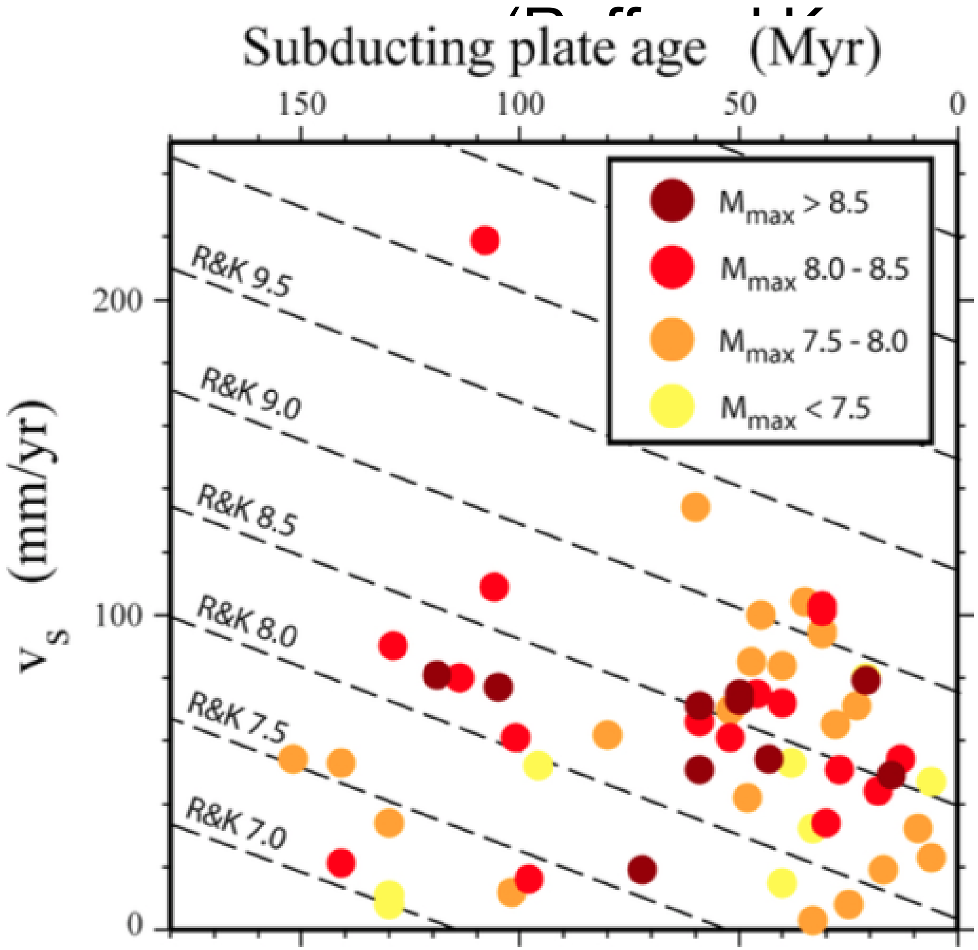
ri,1980)



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

Mechanical coupling as a key factor

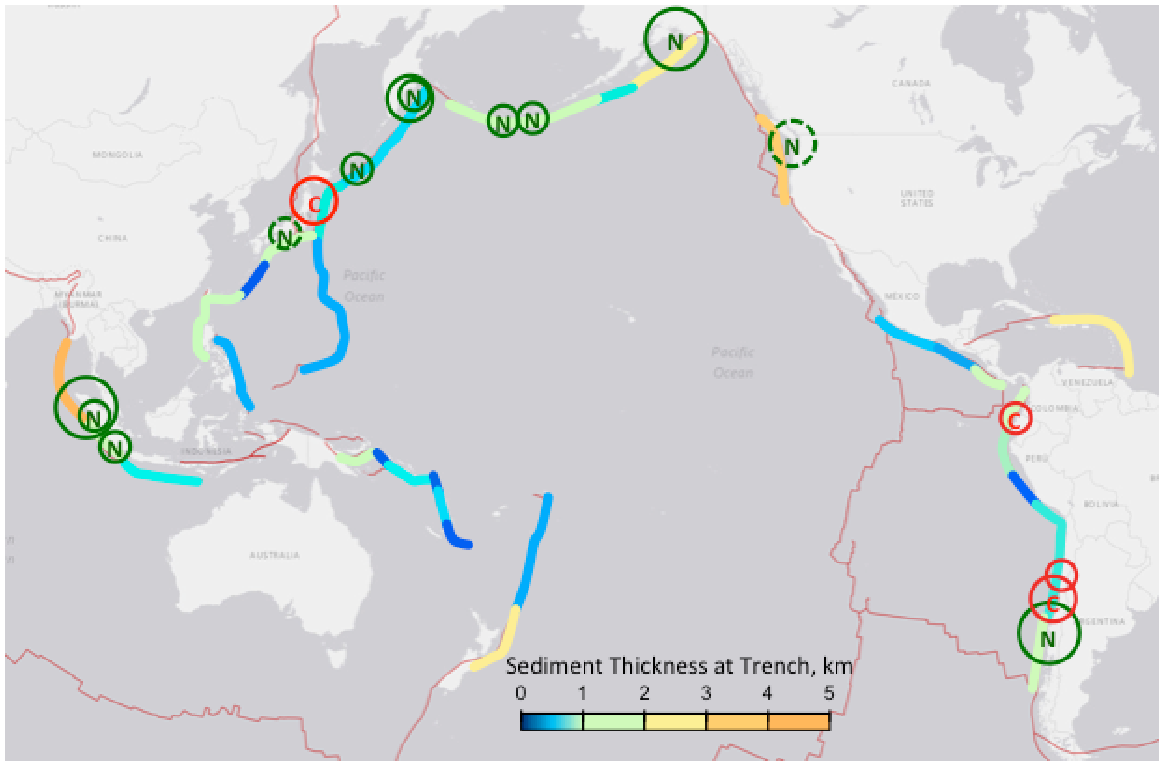
ri,1980)



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

Does not work!

Sediment Thickness in Trench

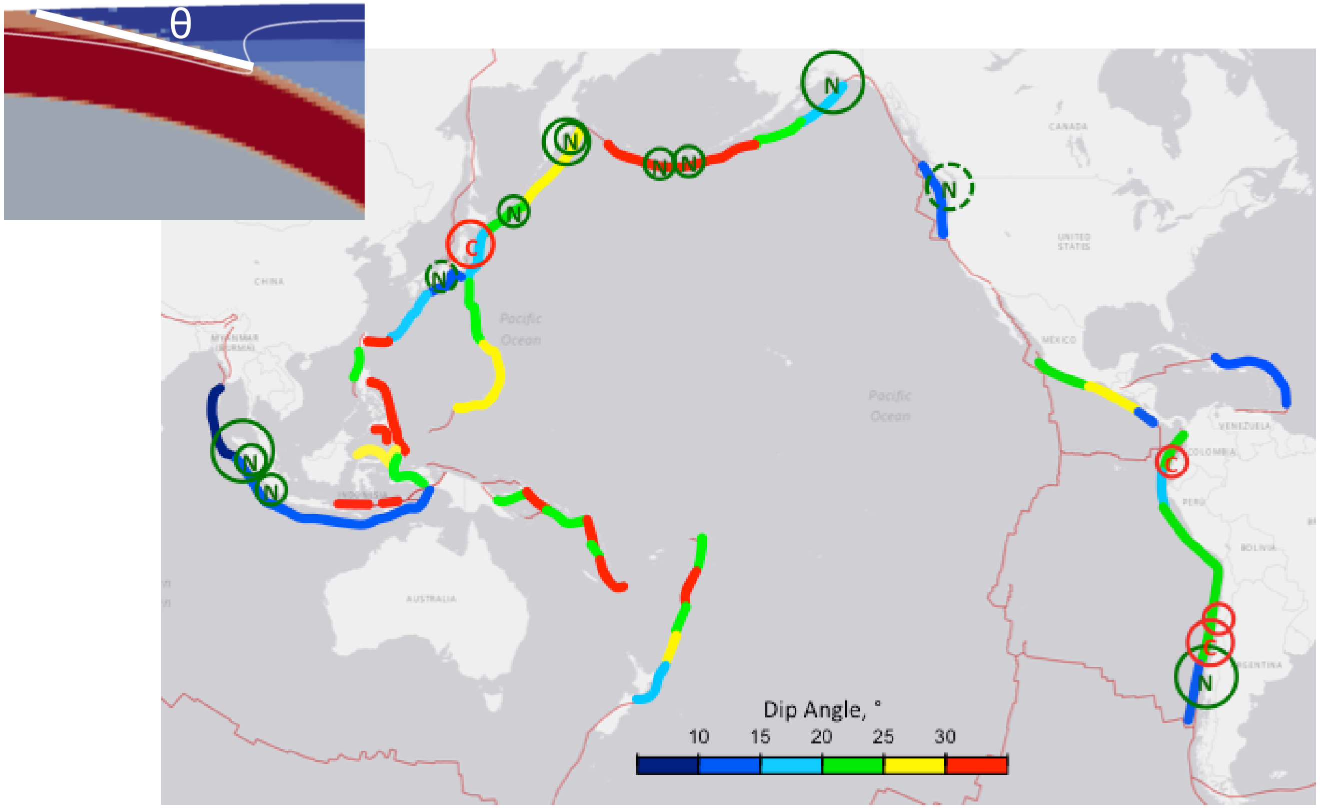


9.2 ≤ Mw 8.8 ≤ Mw < 9.2 8.4 ≤ Mw < 8.8

Compressive UPS Neutral UPS

(Modified from Heuret et al, 2011)

Dipping Angle

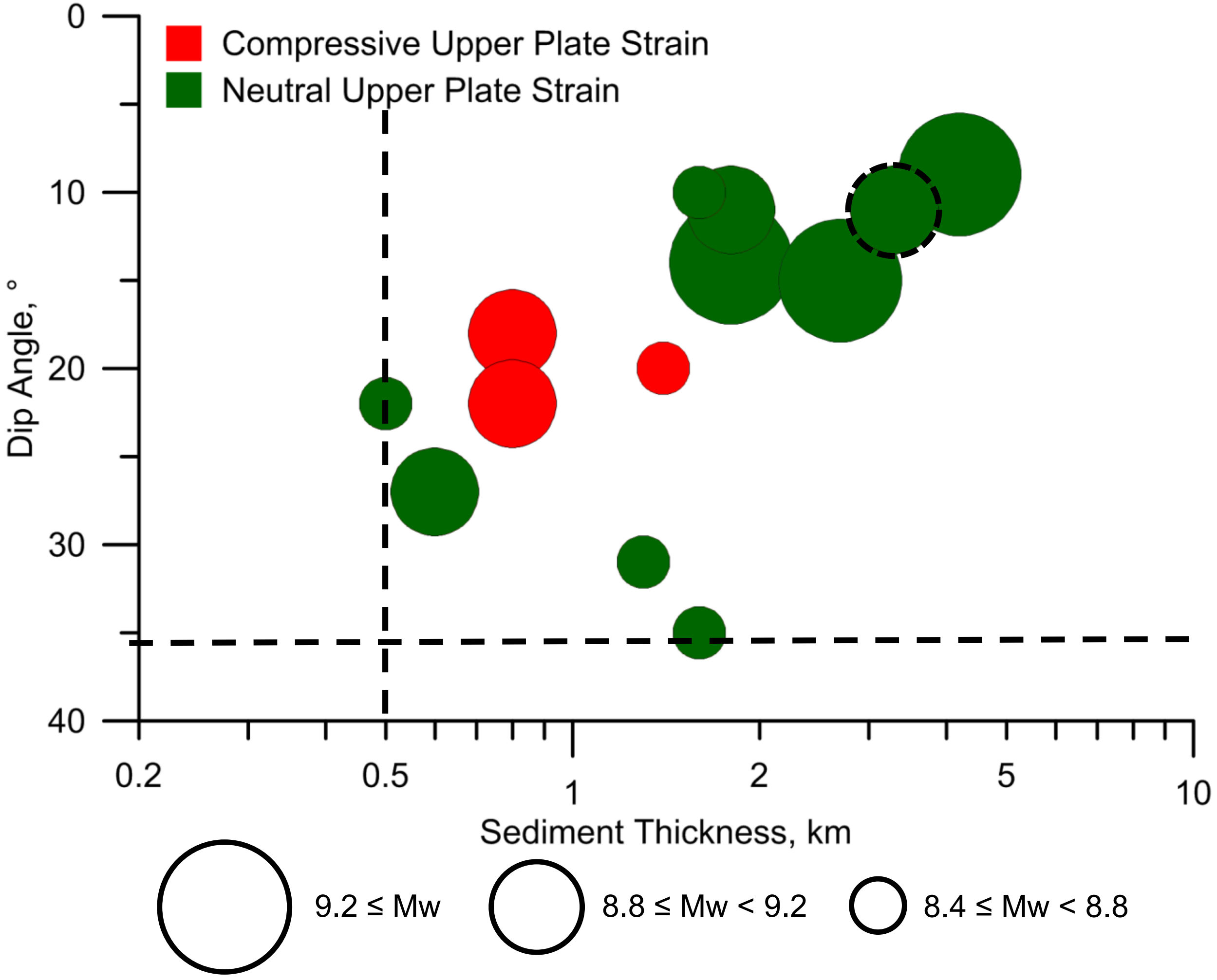


9.2 ≤ Mw 8.8 ≤ Mw < 9.2 8.4 ≤ Mw < 8.8

Compressive UPS Neutral UPS

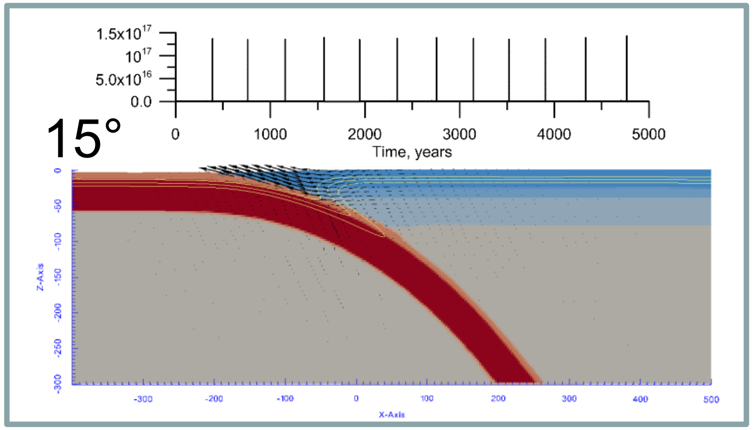
(Modified from Heuret et al, 2011)

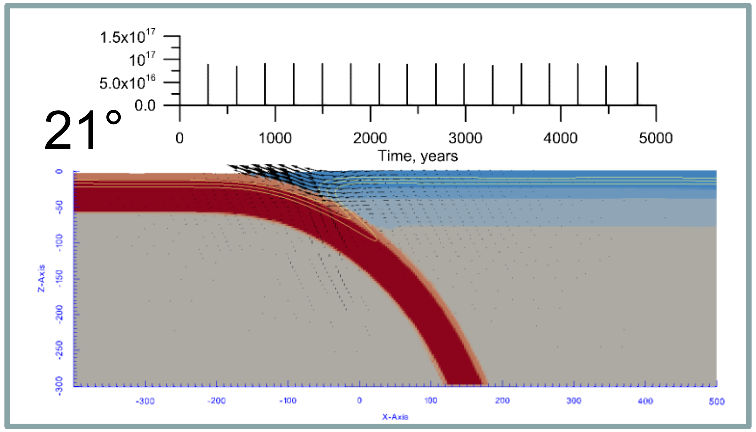
Key parameters

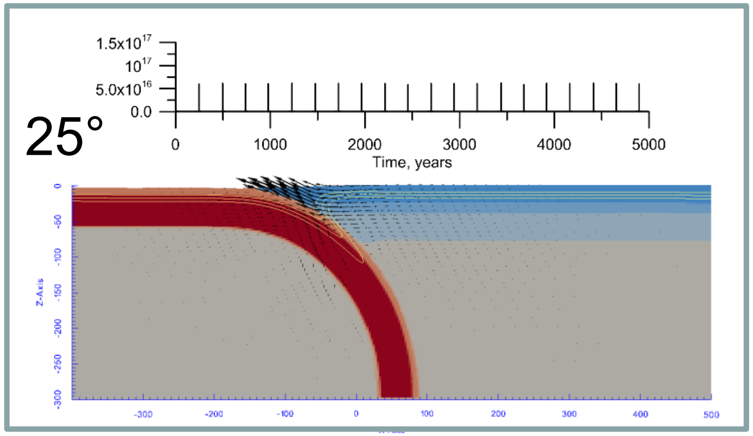


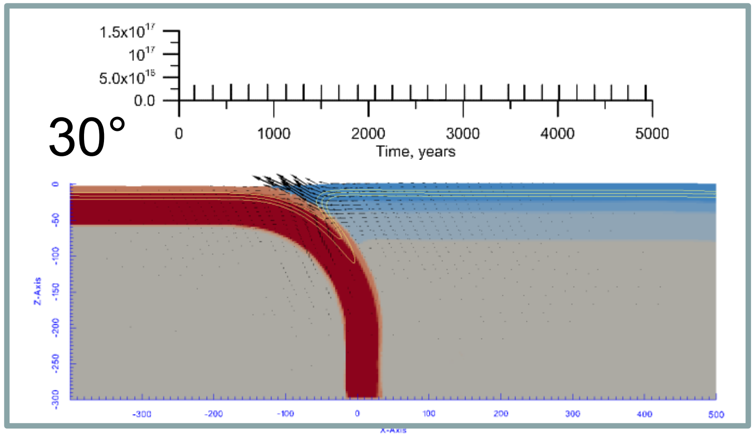
Parameter's Sensitivity

(dipping angle, static friction, subduction velocity)

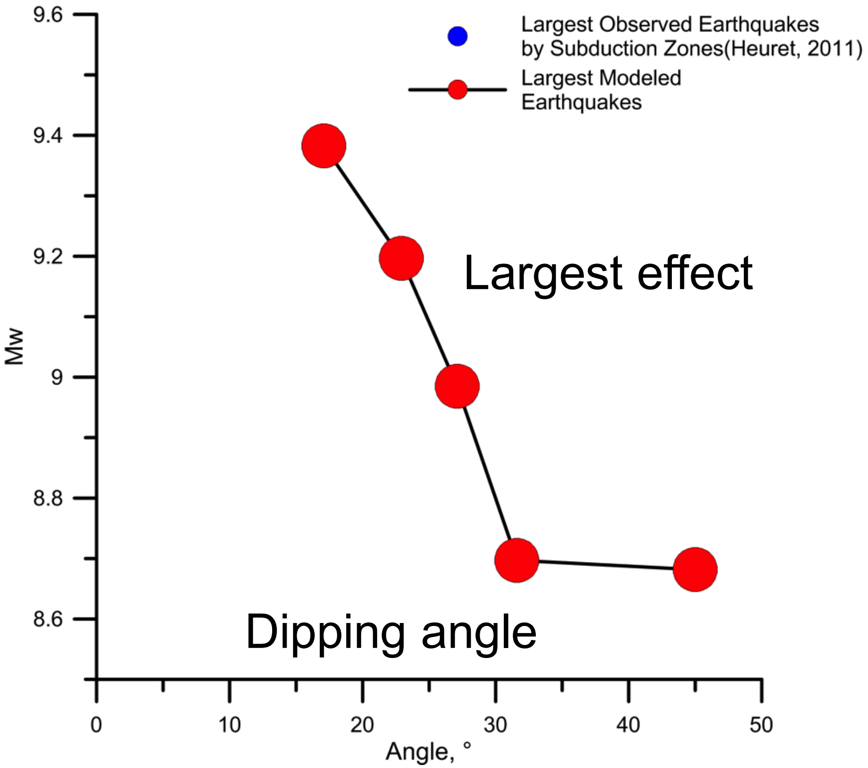


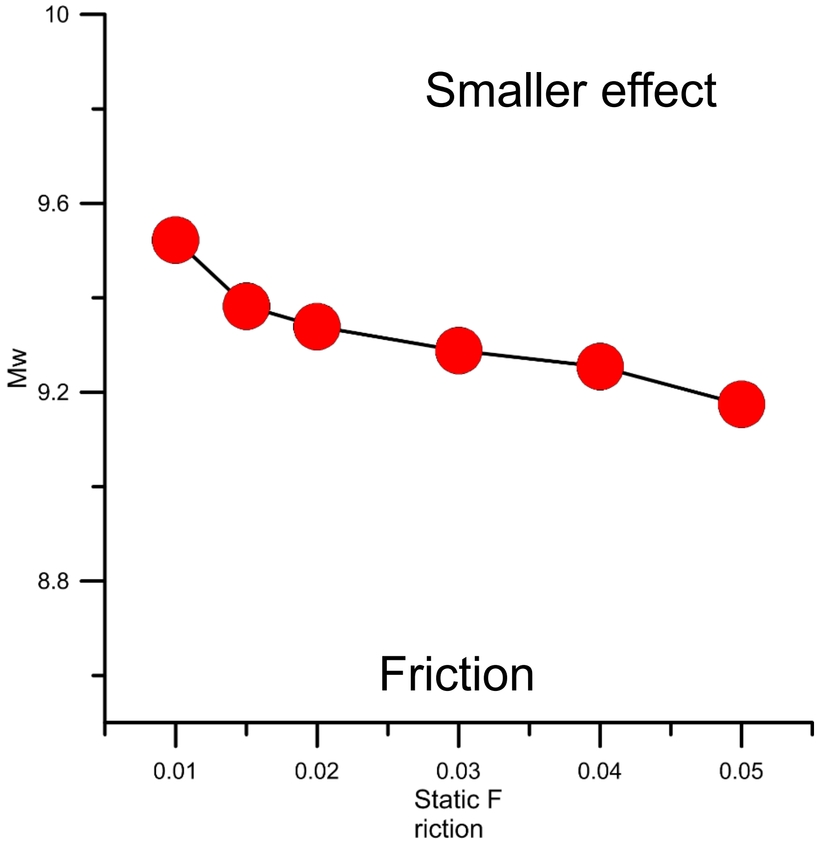






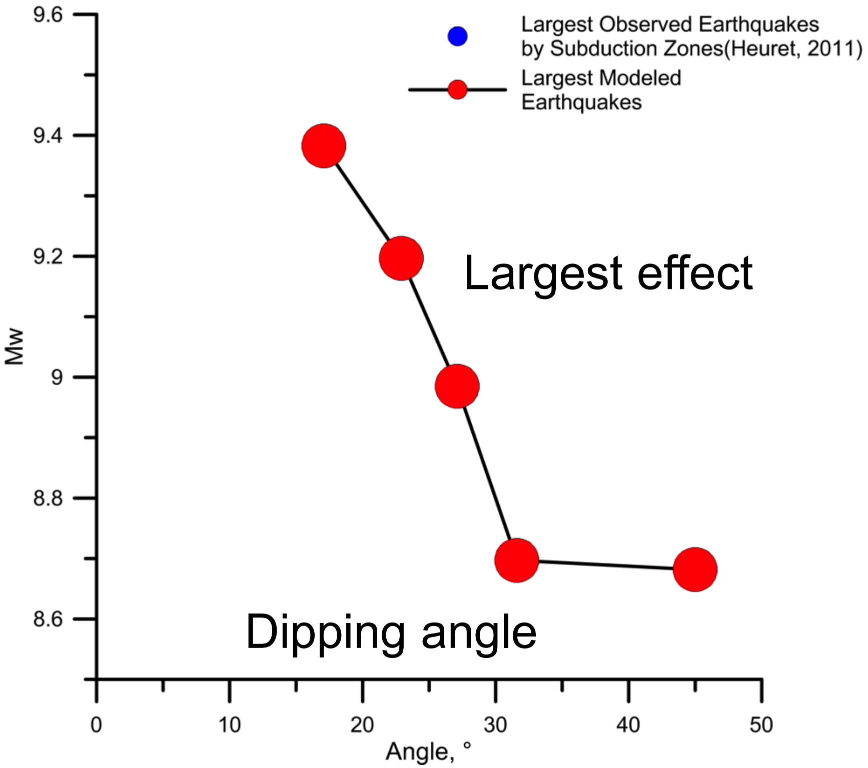
Effects of Parameters

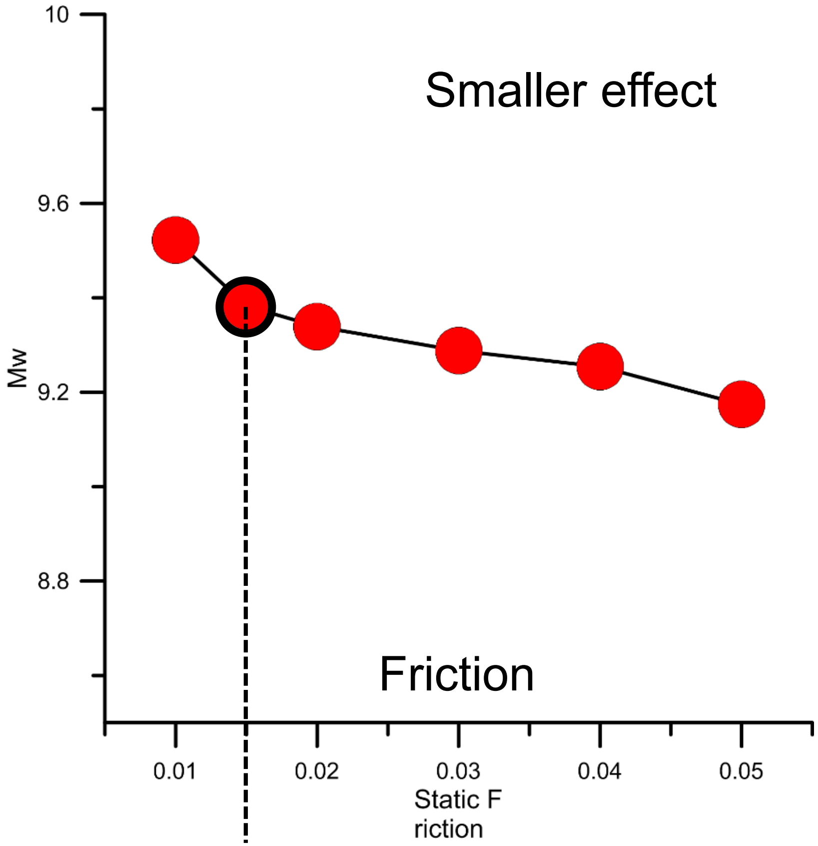




Scaling to 3D (rupture length) by Strasser et al. (2010)

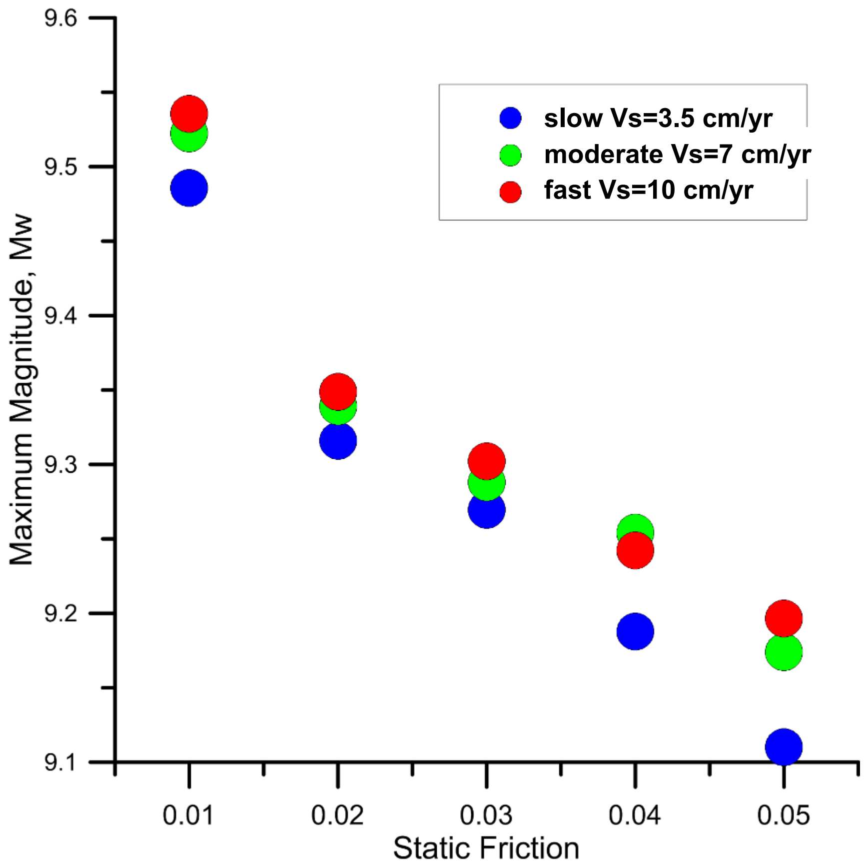
Effects of Parameters



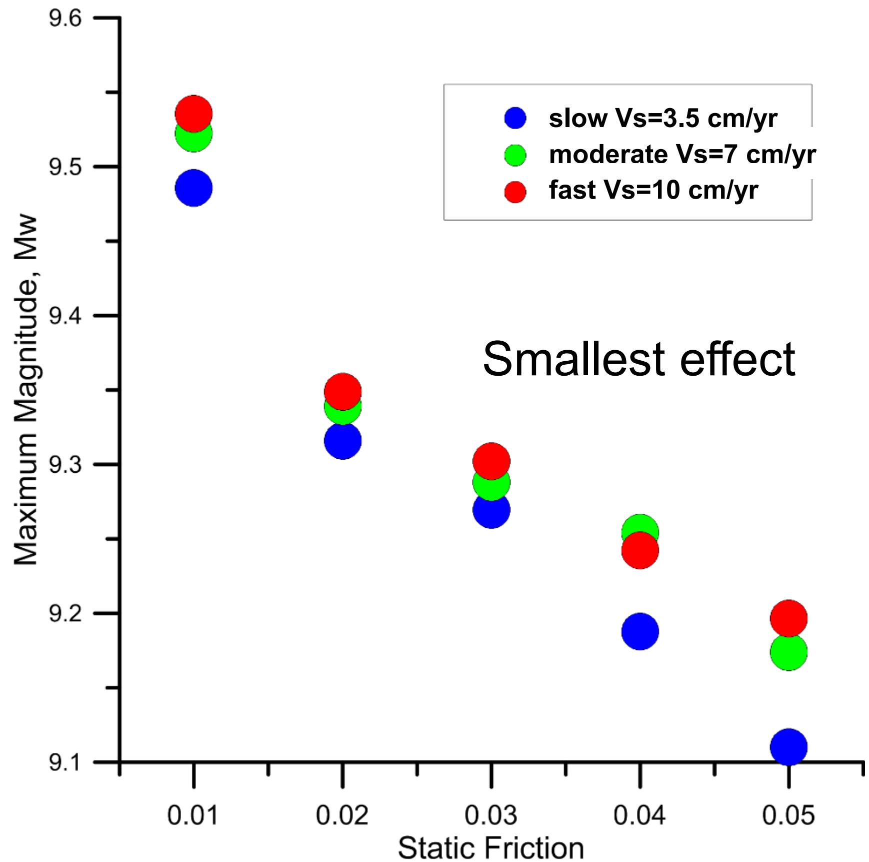


Lowest friction for S. Andes (Sobolev et al.,2006)

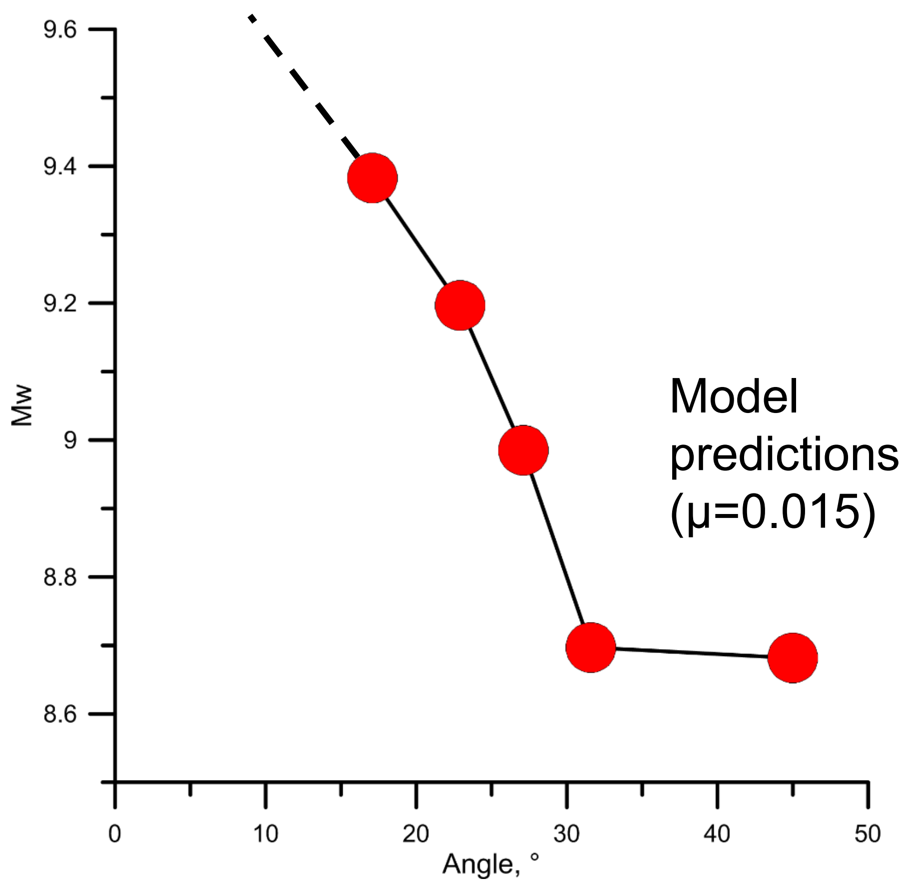
Effect of Subduction Velocity



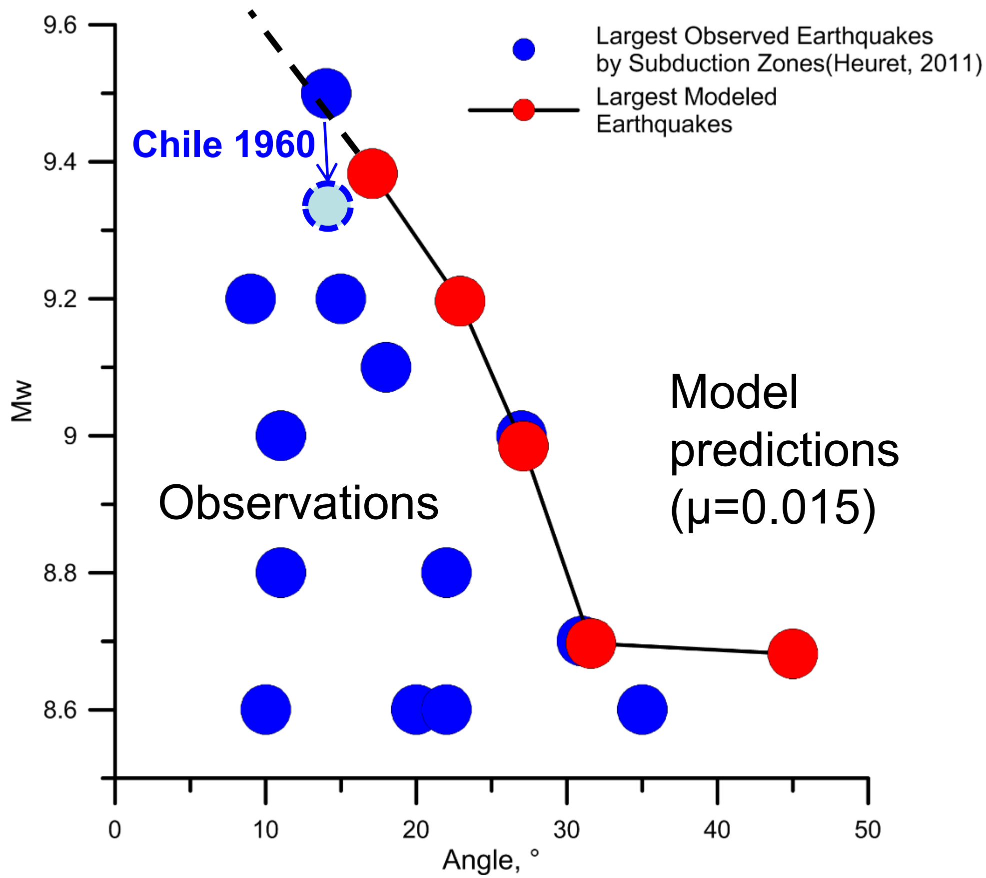
Effect of Subduction Velocity



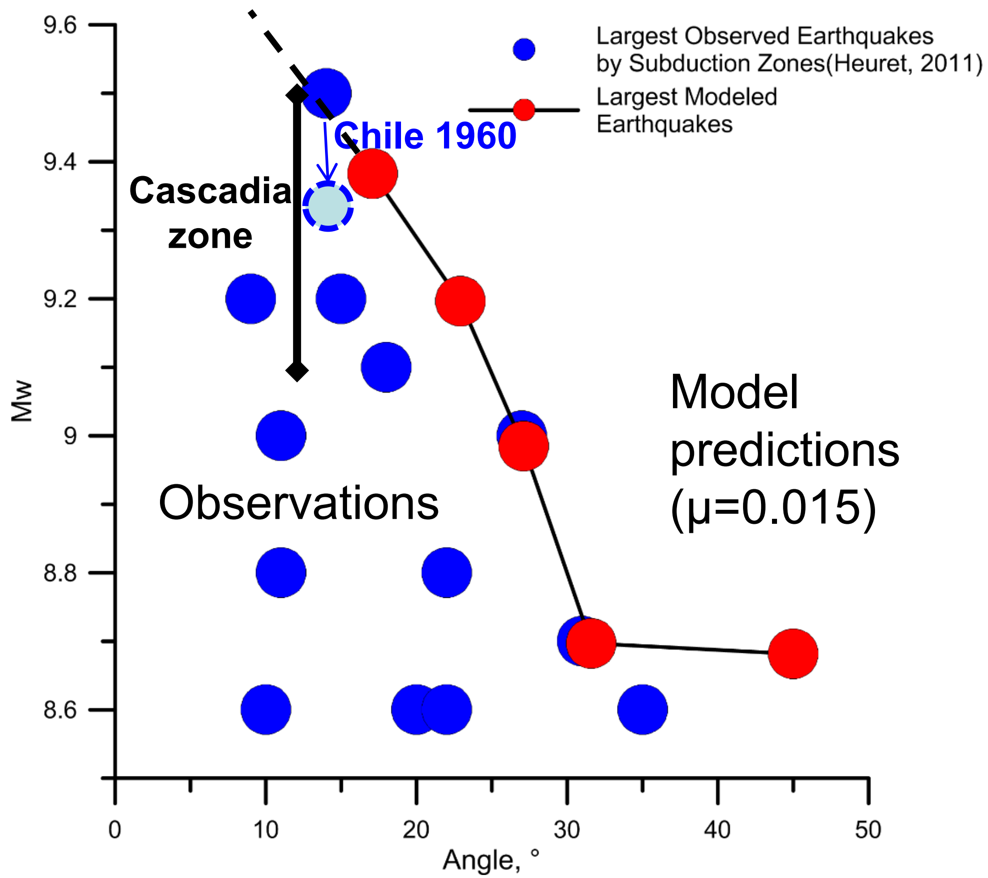
Largest Observed Earthquakes vs Model Predictions



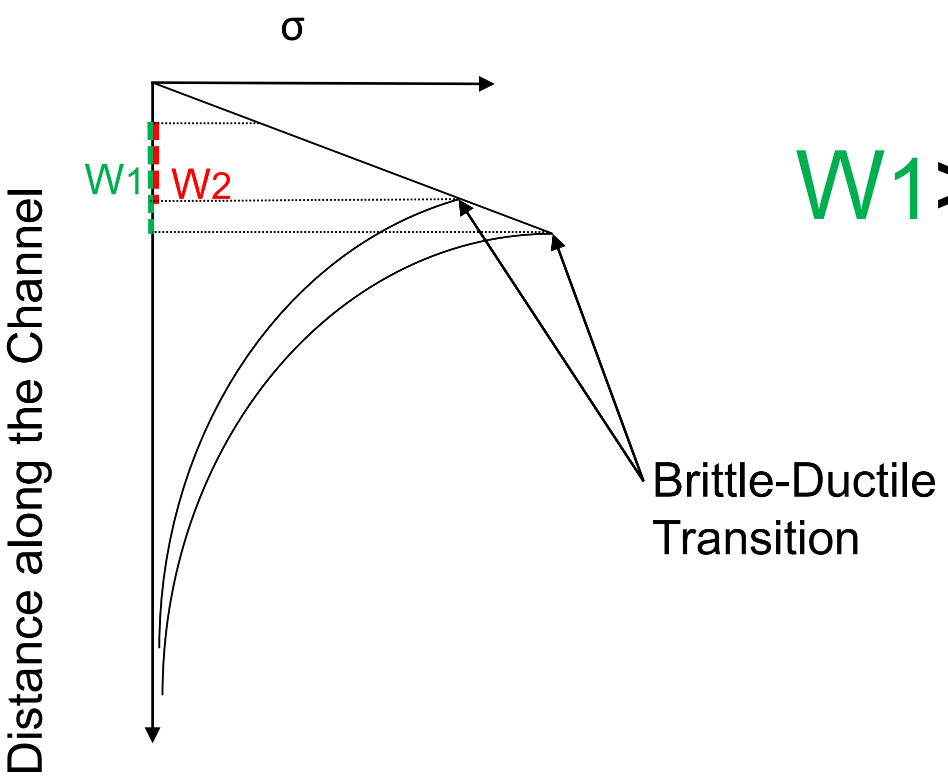
Largest Observed Earthquakes vs Model Predictions



Largest Observed Earthquakes vs Model Predictions

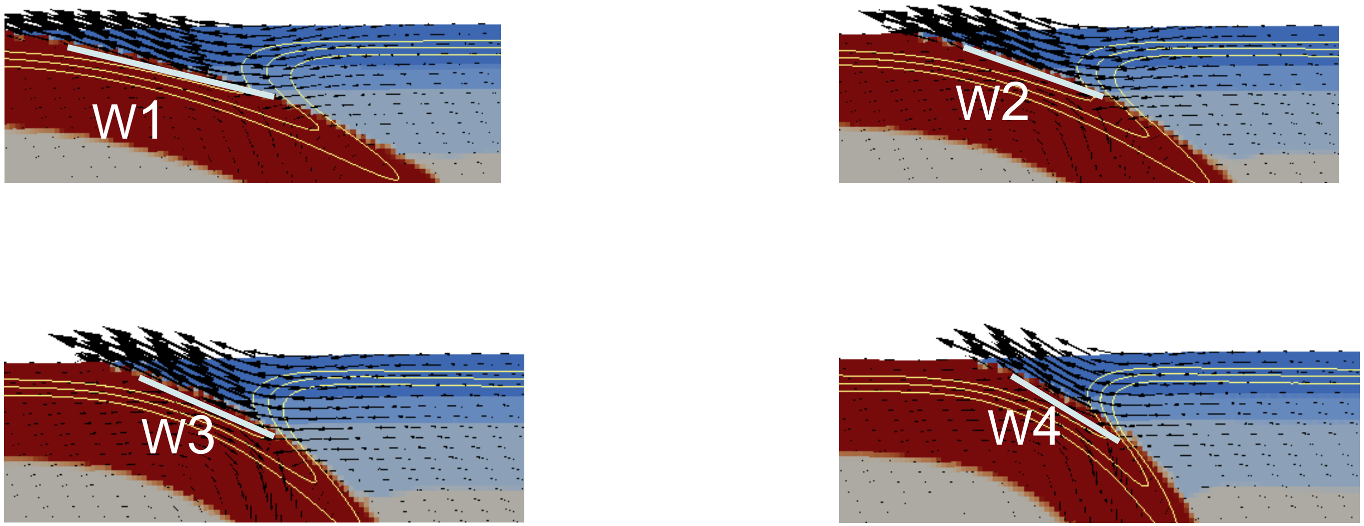


Effect of Subduction Velocity



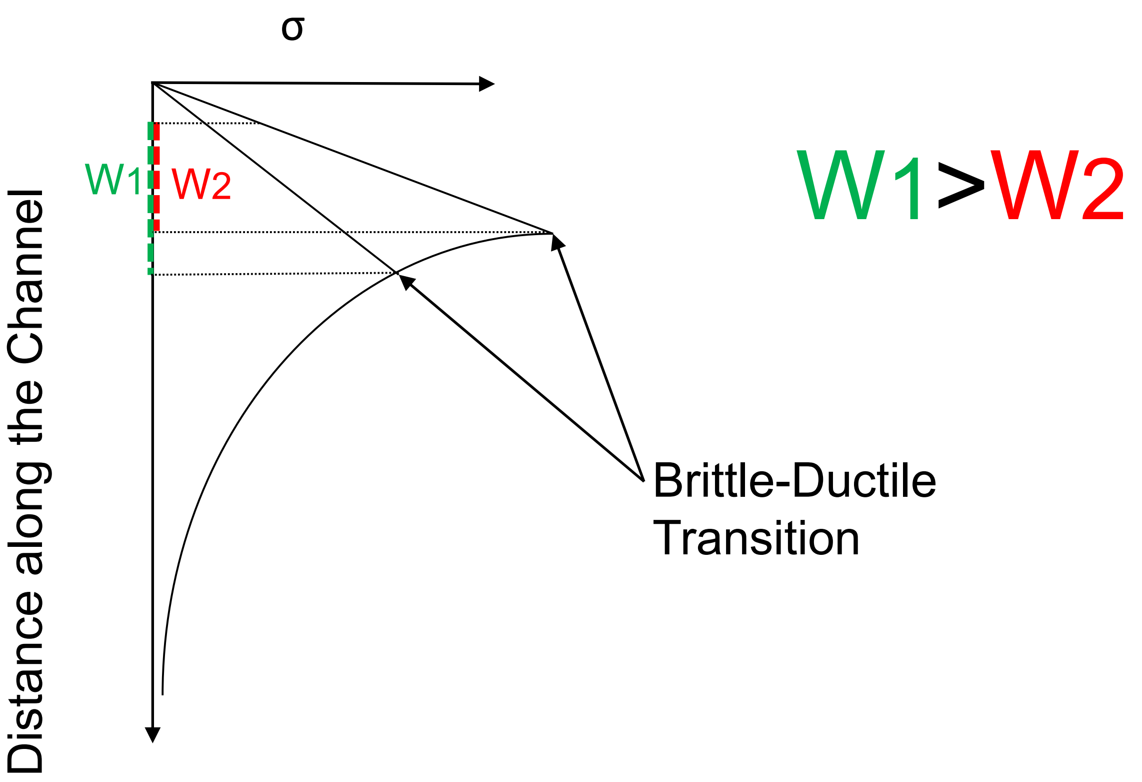
W1>W2

Effect of Dipping Angle on Seismogenic Zone Width

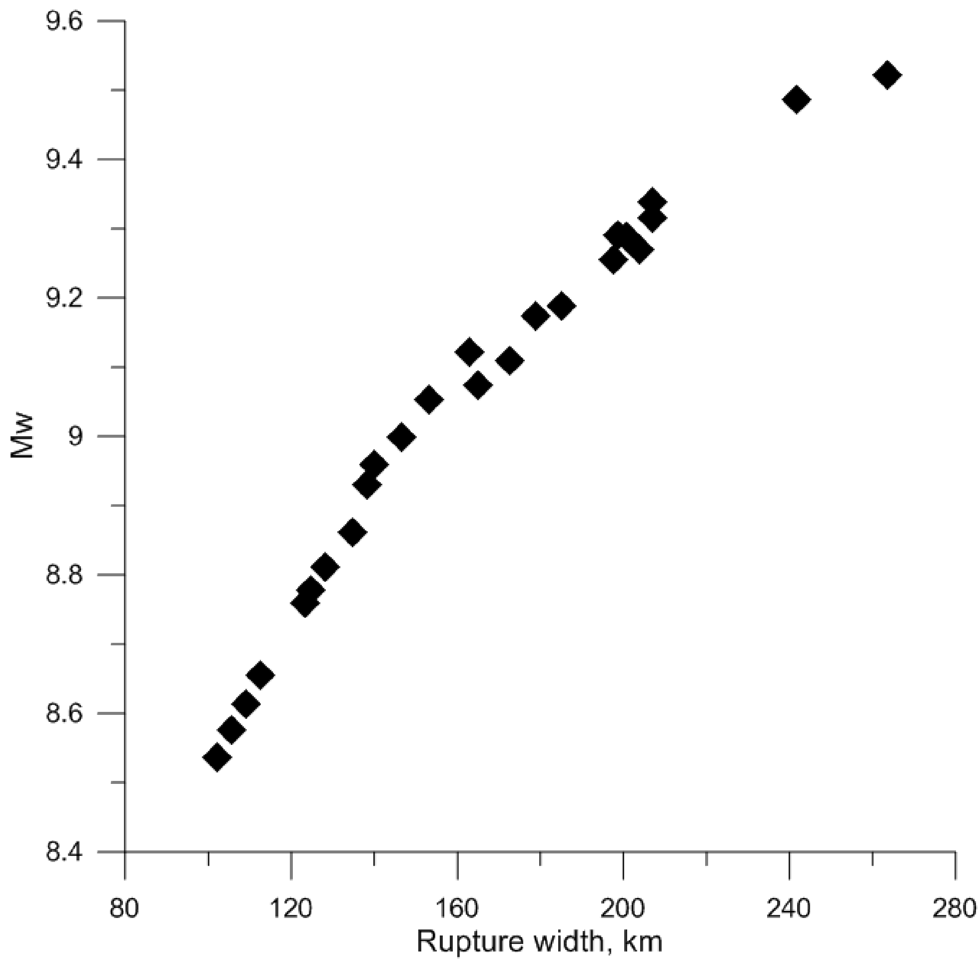


W1 > W2 > W3 > W4

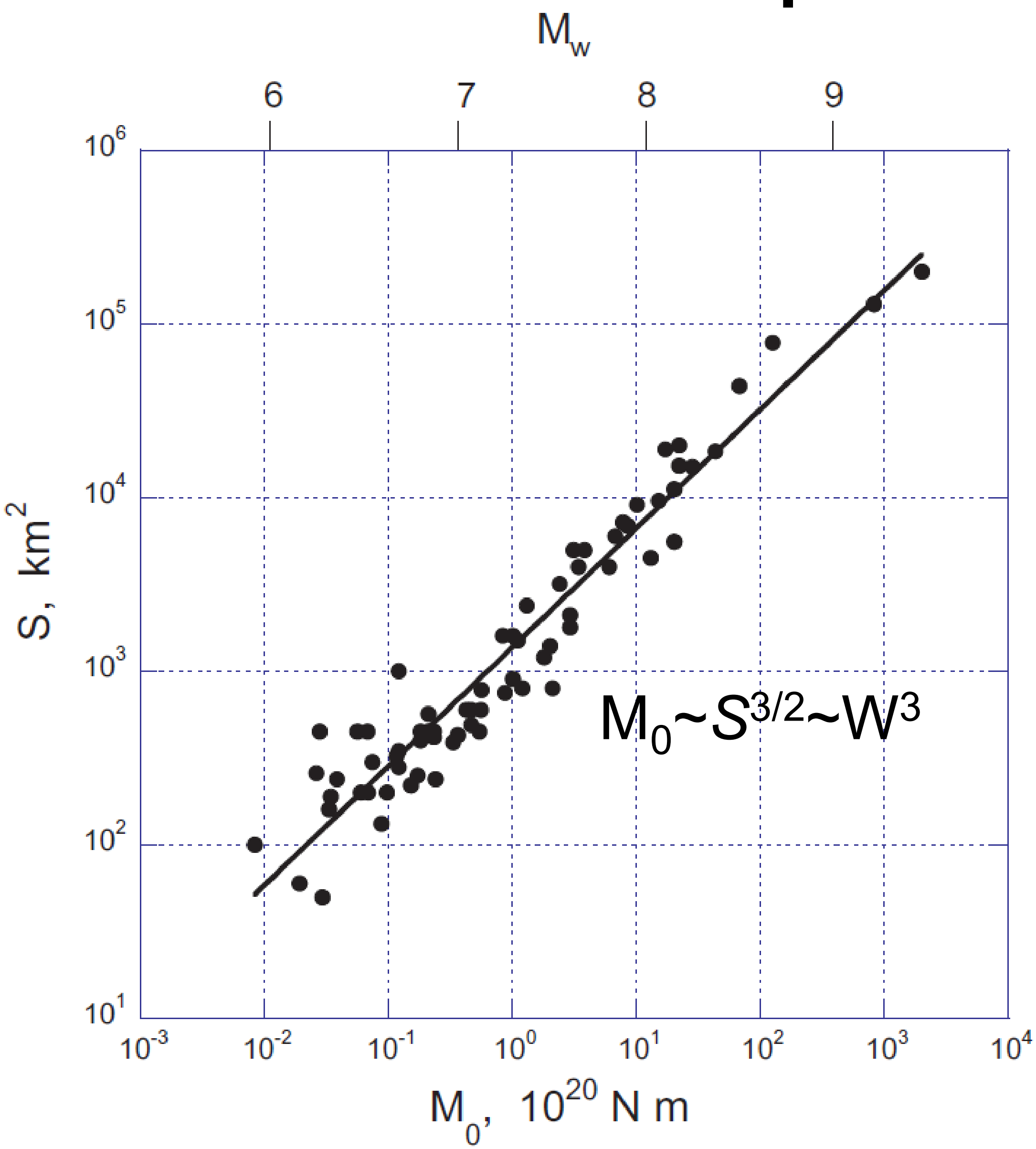
Effect of Static Friction on Seismogenic Zone Width



Effect of Rupture Width



Effect of Rupture Width



That means

$\overline{\Delta\sigma_S} \approx const$

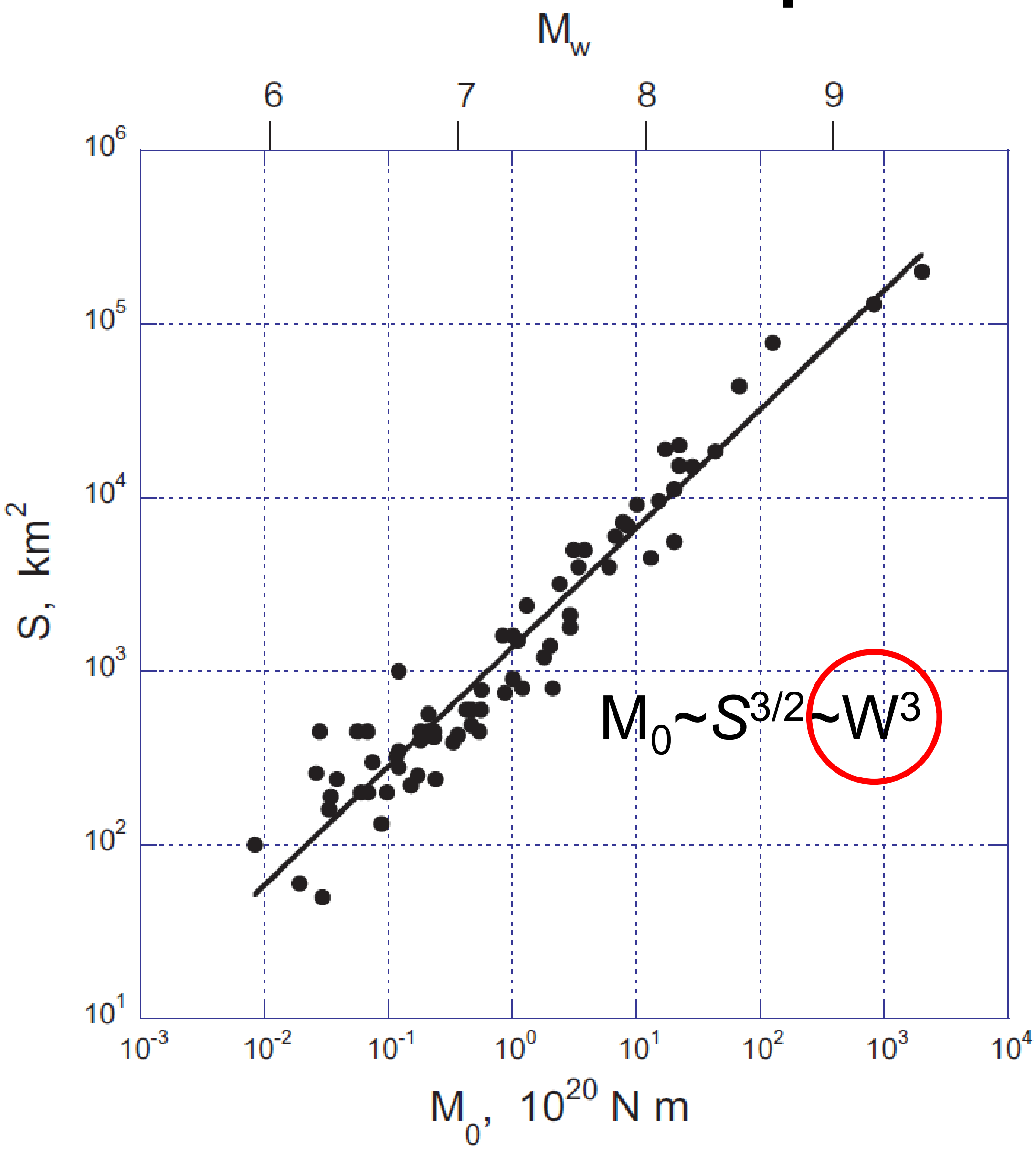
Mean value of $\overline{\Delta\sigma_S}$ is about 3 MPa

$M_0 \approx \overline{\Delta\sigma_S} \cdot S^{3/2}$;

$D \approx S^{1/2}\, \overline{\Delta\sigma_S} / G$

Kanamori and Brodsky, 2004

Effect of Rupture Width



That means

$\overline{\Delta\sigma_s} \approx const$

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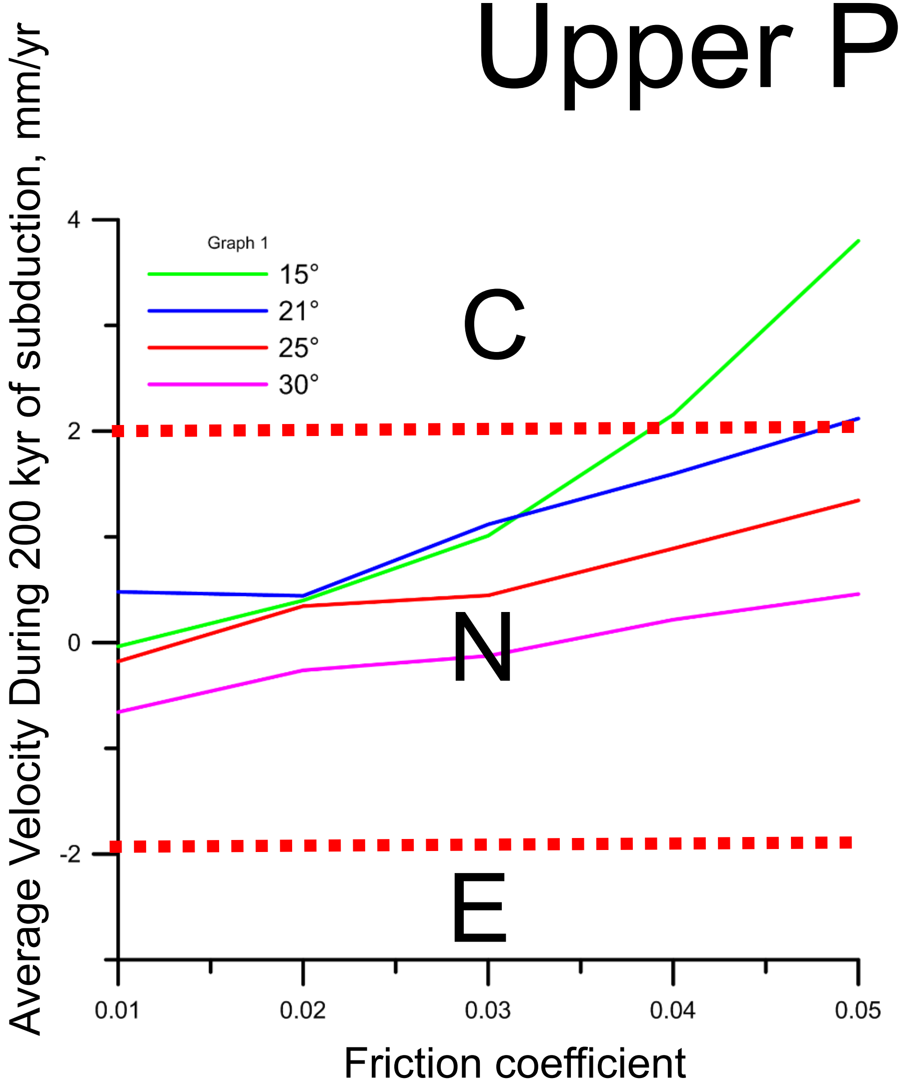
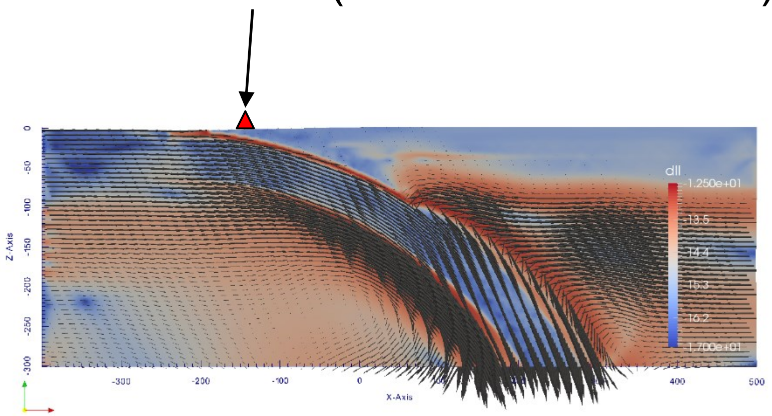
Kanamori and Brodsky, 2004

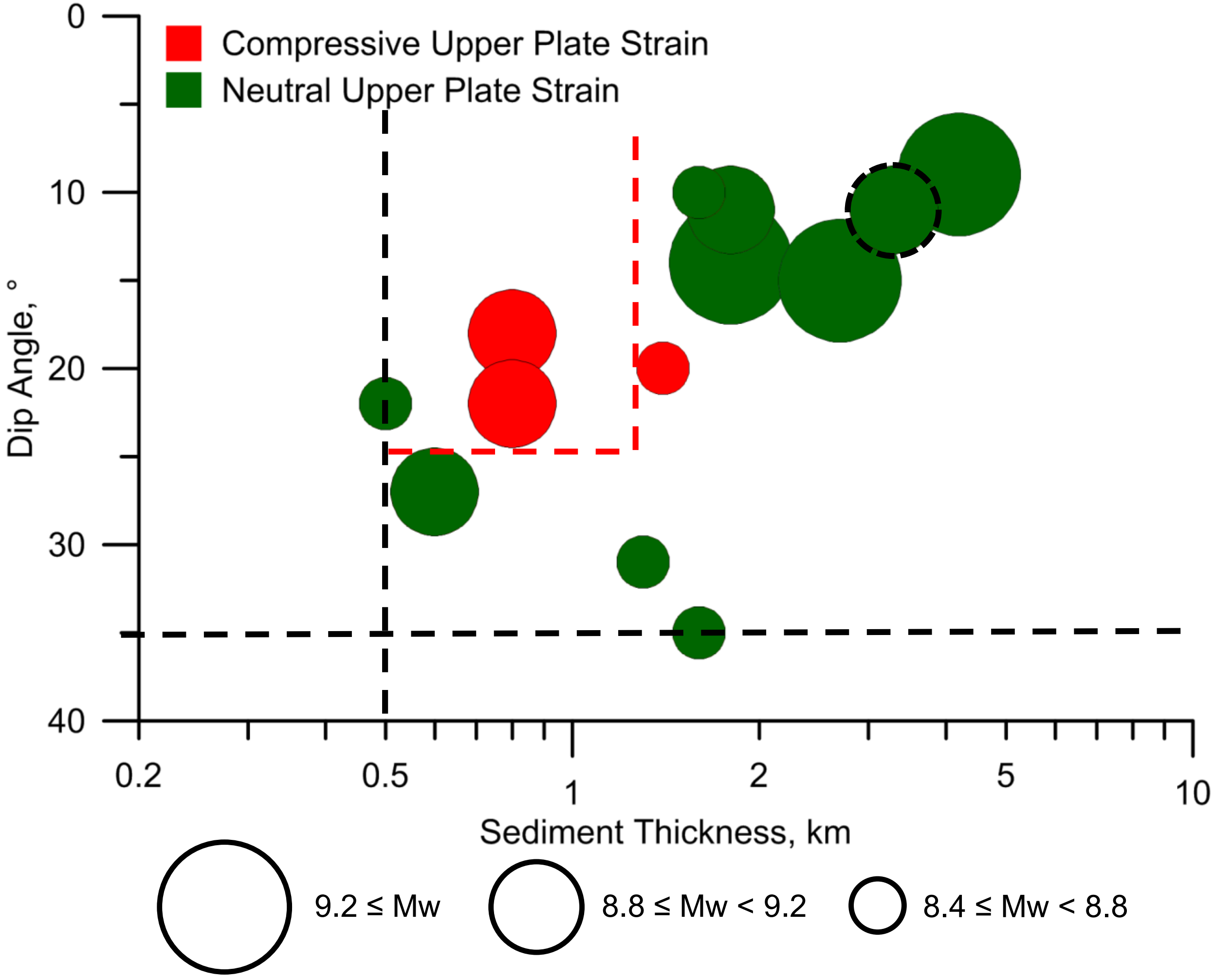
Upper Plate Strain



Observation Point (~50 km from trench)



Key parameters



Coupling paradox

Is the idea about low mechanical coupling at subduction zones consistent with the occurrence there great earthquakes?

Great earthquakes may well happen within the very weak fault zones (subduction channels) with static friction about 0.01-0.05 due to the friction drop of about 0.005-0.01.

What makes earthquake great is not large stress drop, but rupturing at large area (homogeneous channel structure, no barriers).

Conclusions

- Modeling confirms that **low-angle subduction** (large effect) and **thick sediments** (smaller effect) in subduction channel are **fundamental necessary conditions for giant earthquakes.**

  HIGH MECHANICAL COUPLING IS NOT REQUIRED

- Modeling suggests that **thick sediments** in subduction channel (=low friction) result in **neutral or slightly 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.