New views of subduction faults

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- Susan Bilek, New Mexico Tech, U.S.A.
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- John He, Pacific Geoscience Centre, Geol Survey of Canada
- Ikuko Wada, University of Minnesota, U.S.A.

Outline

1. Strength of subduction faults (the “megathrusts”)
2. Earthquake rupture and stress drop
3. Weak fault’s effect on upper plate stress
4. Smooth faults and rough faults
5. Frictional heating of seismogenic and creeping faults

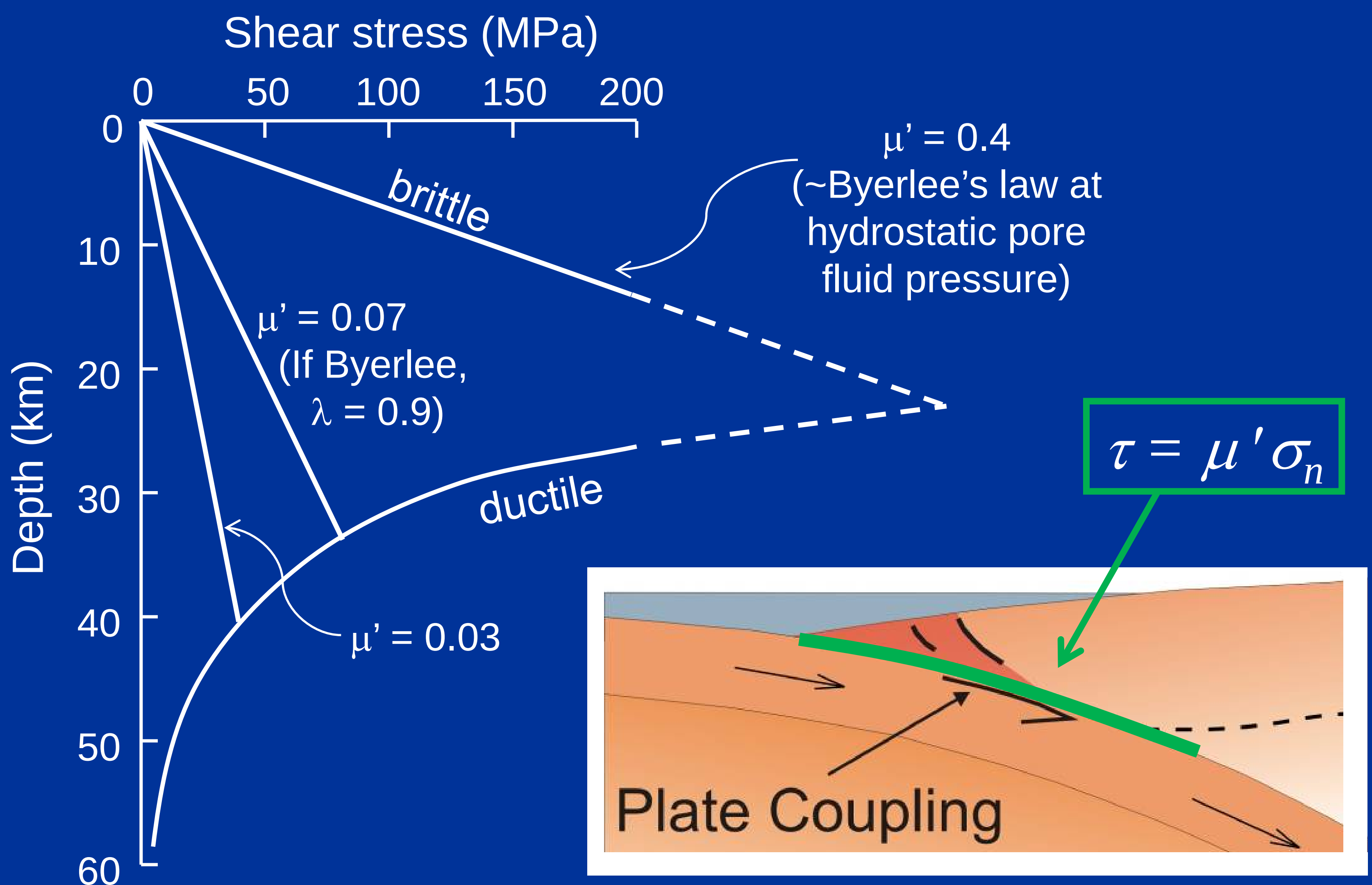
1. **Strength of subduction faults**

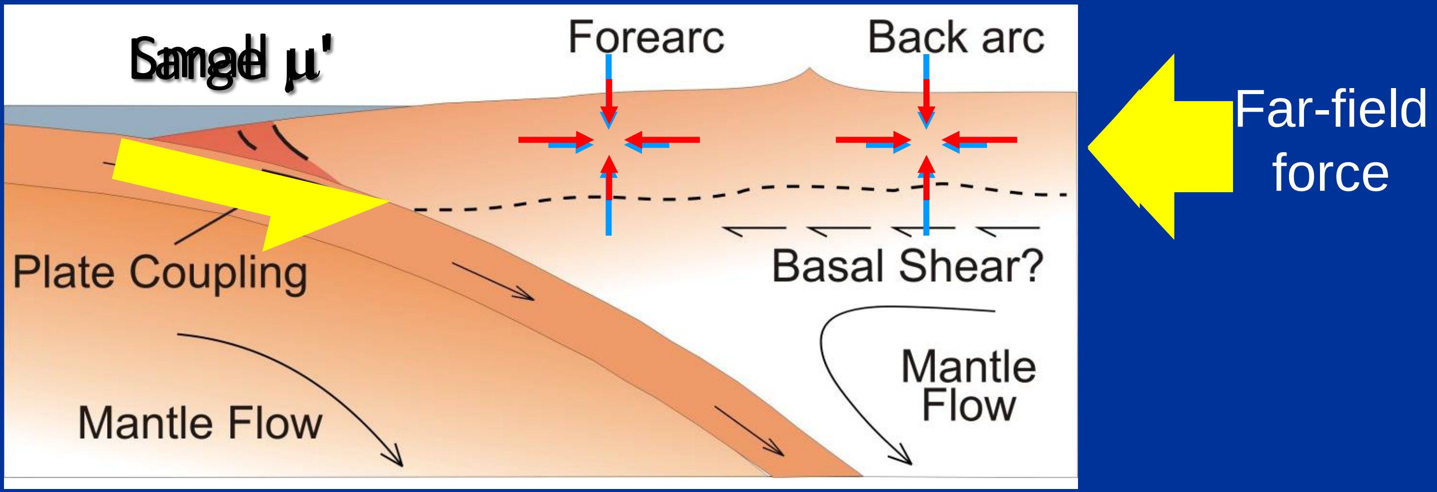
– Very weak, never “strongly coupled”

$$\tau = \mu' \sigma_n$$

μ' is apparent coefficient of friction

σ_n is normal stress (~ weight of rock column for megathrusts)

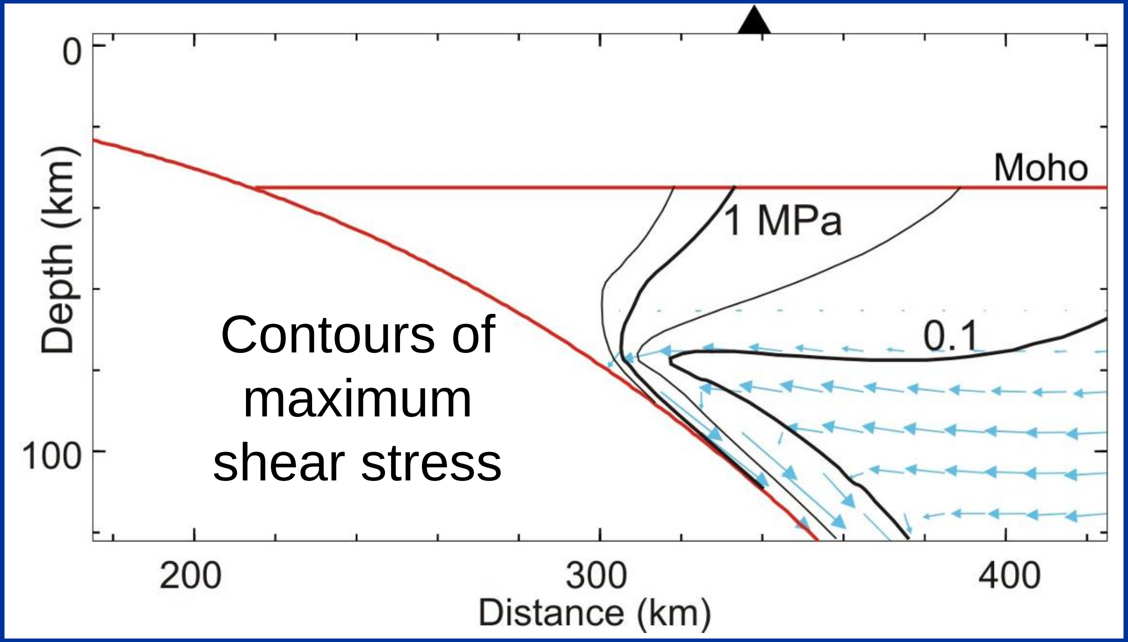

Shear stress (MPa)
0
50
100
150
200
0
10
20
30
40
50
60
Depth (km)
brittle
μ' = 0.4
(~Byerlee's law at
hydrostatic pore
fluid pressure)
μ' = 0.07
(If Byerlee,
λ = 0.9)
ductile
μ' = 0.03
$\tau = \mu' \sigma_n$
Plate Coupling



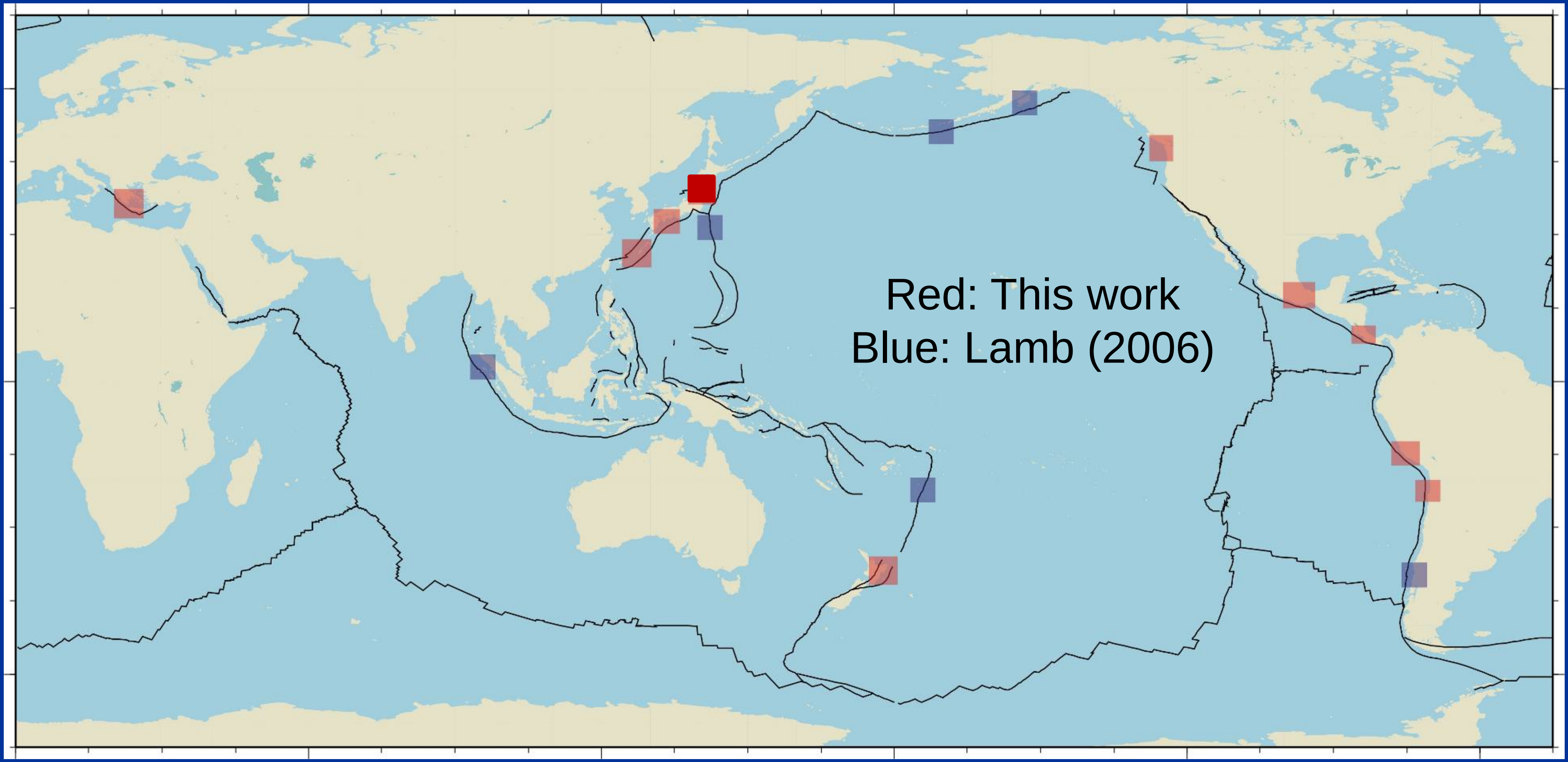
Mantle wedge rheology:
Dislocation creep

Effective viscosity:

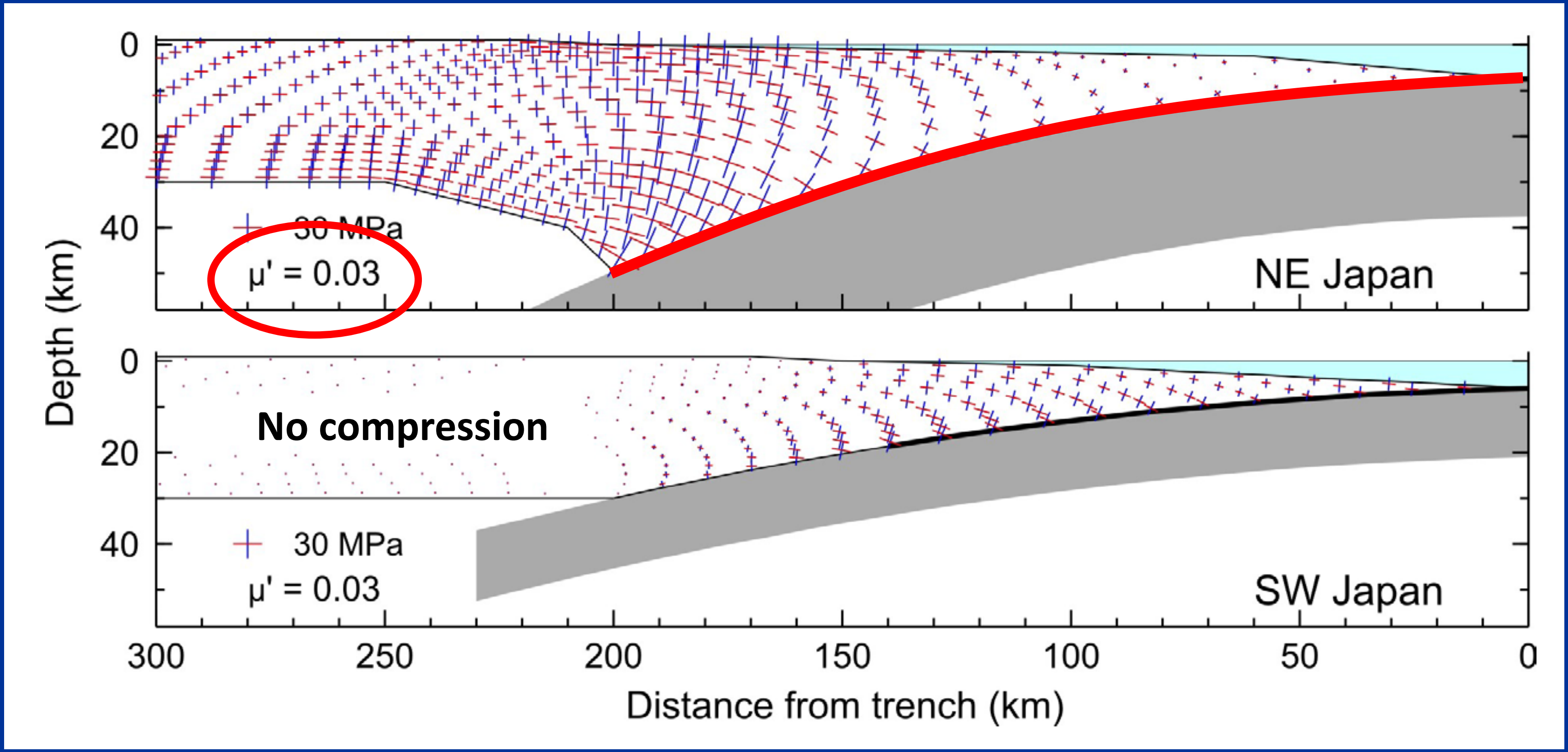
$$\eta = \frac{\mu^n}{2A}\sigma^{1-n}\exp\left(\frac{E+PV}{RT}\right)$$



$\mu' = 0.03 - 0.06$ for most subduction zones studied



Deviatoric stress (red is compressive)



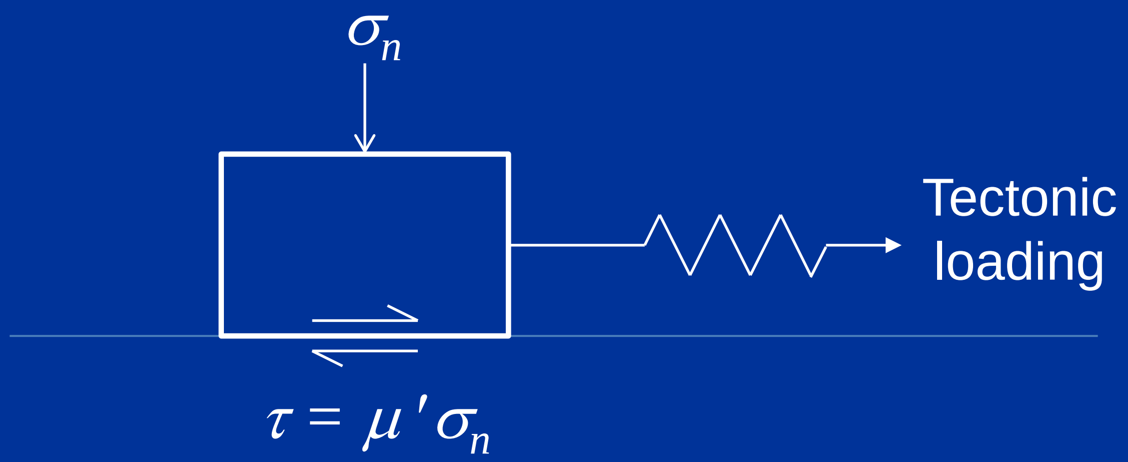
Wang and Suyehiro, 1999 GRL

2. **Earthquake rupture and stress drop**

– Faults weaken in earthquakes, but not by much

$$\tau = \mu' \sigma_n$$

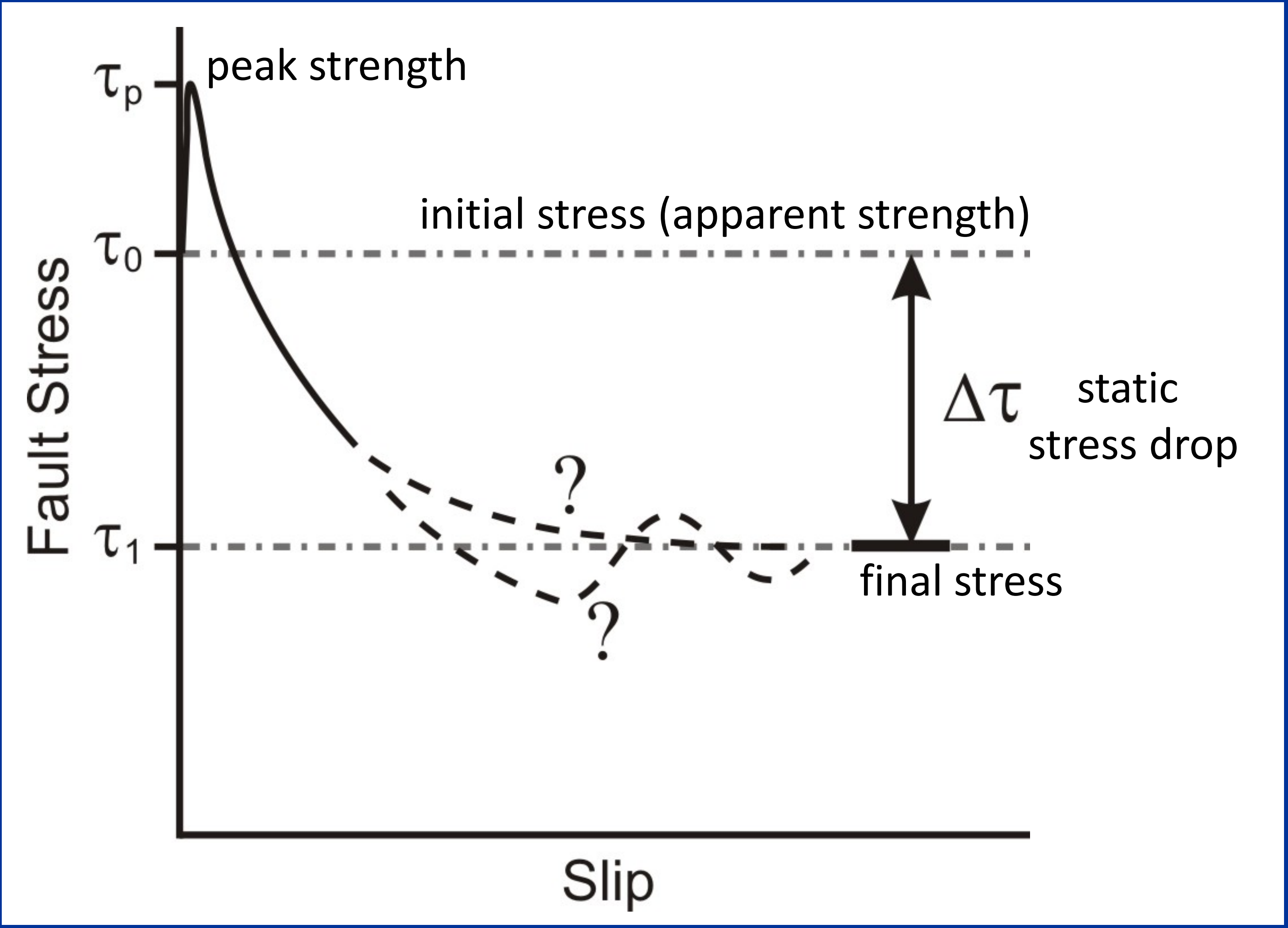
$$\Delta\tau = \Delta\mu' \sigma_n$$



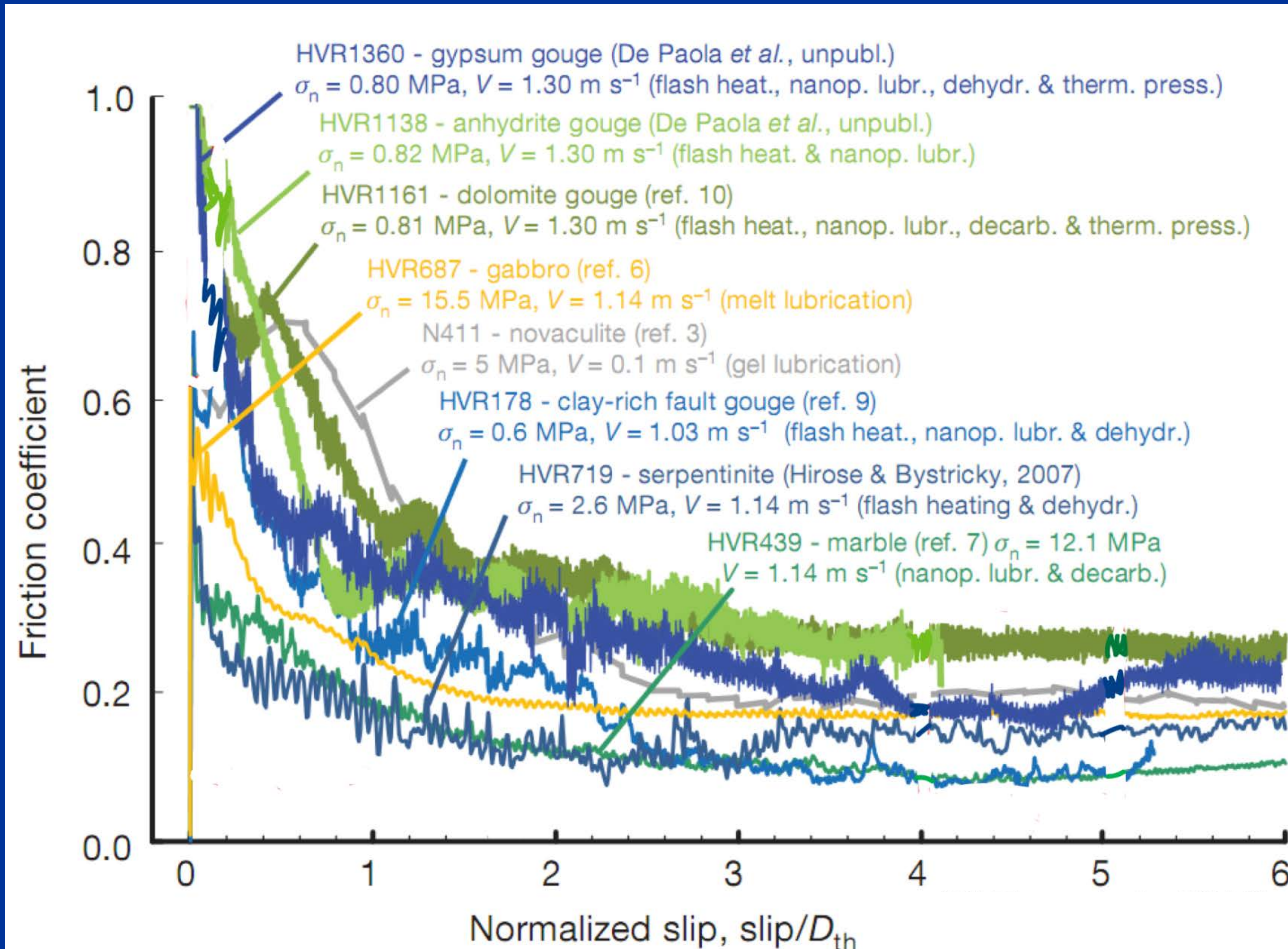
Rupture initiation: low slip rate; velocity-weakening

Rupture development: high slip rate; dynamic weakening

Fault stress evolution during seismic slip

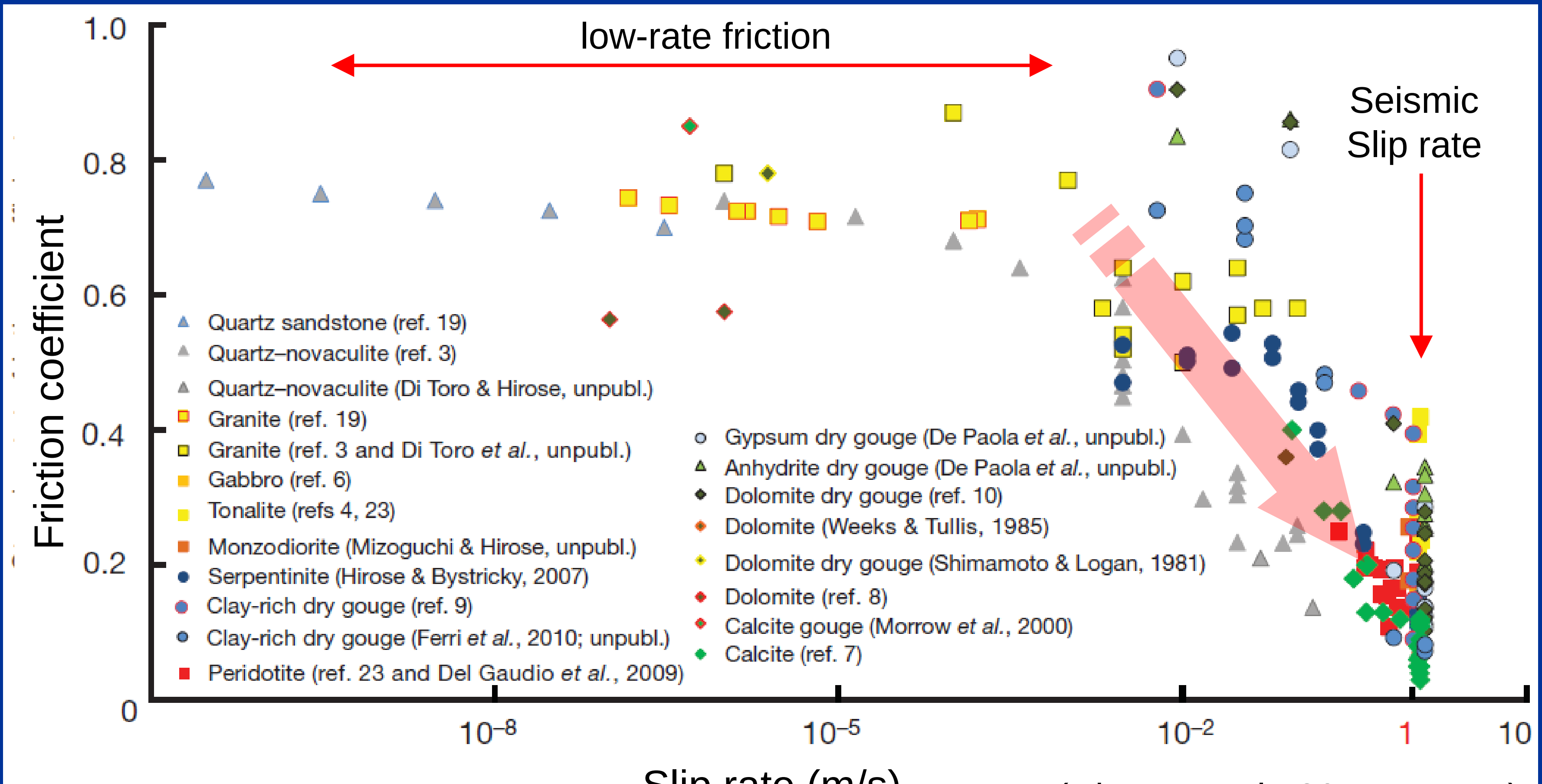


Experimental results on dynamic weakening



(Di Toro et al., 2011, Nature)

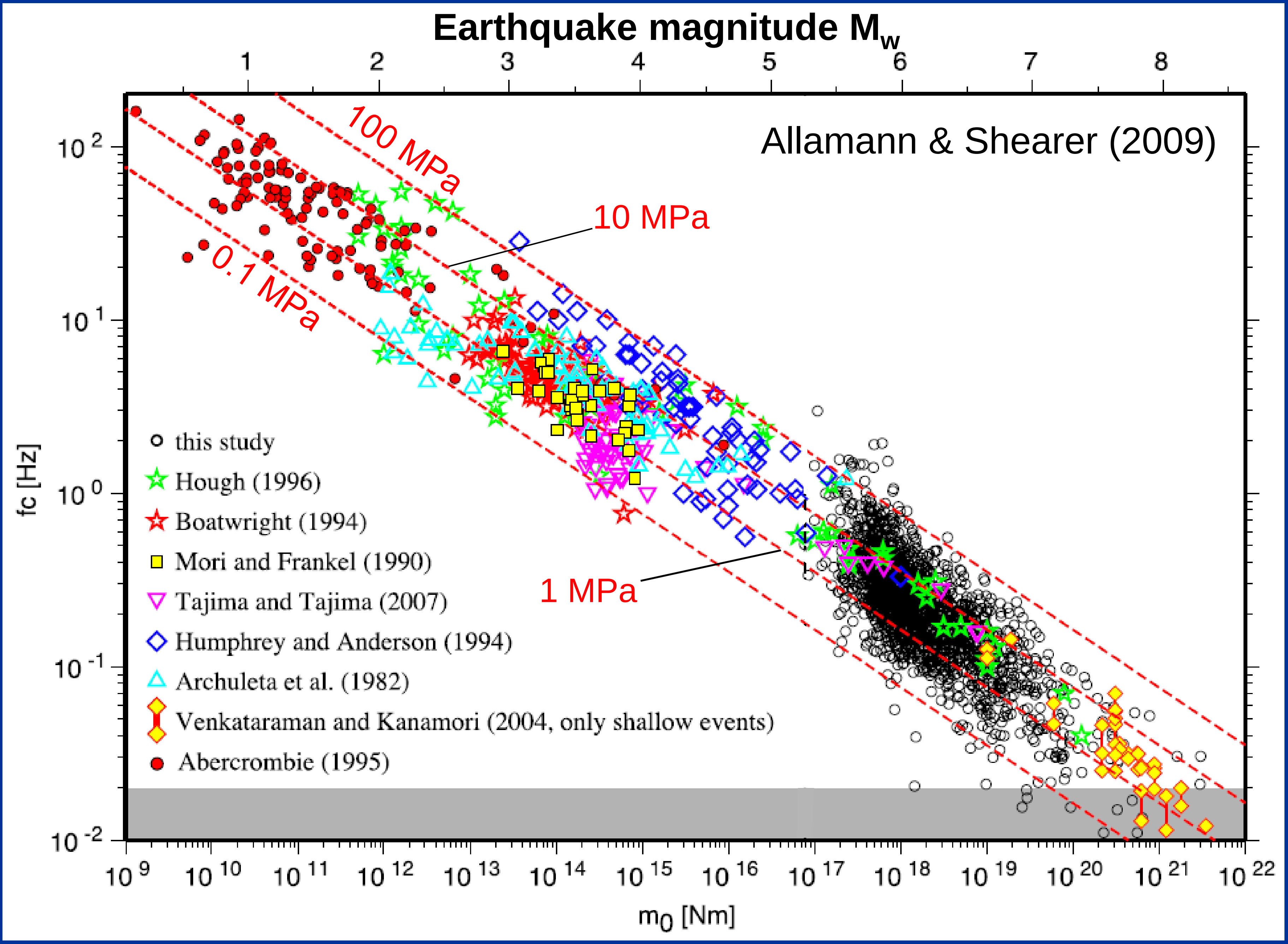
Experimental results on dynamic weakening



(Di Toro et al., 2011, Nature)

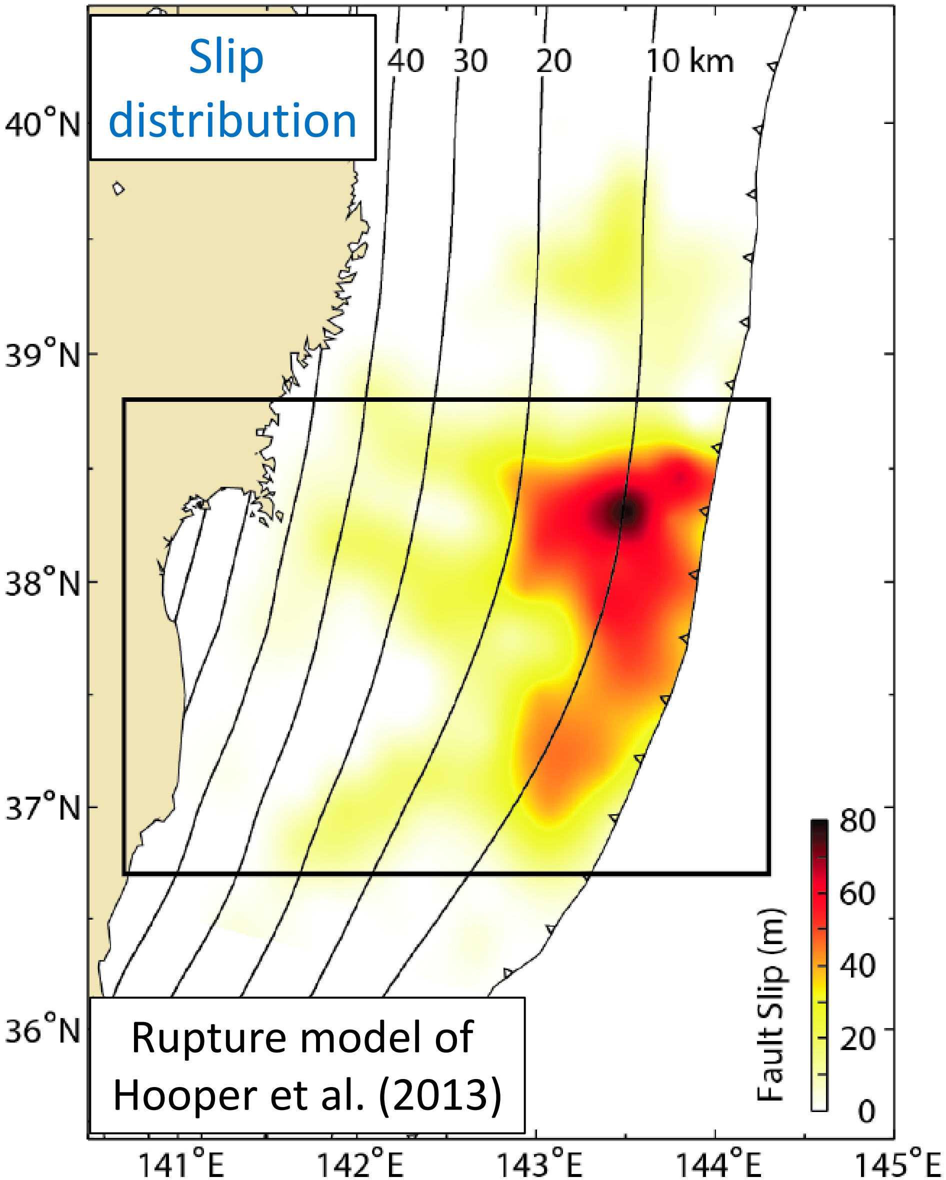
~ a factor of 3~5 decrease in fault strength

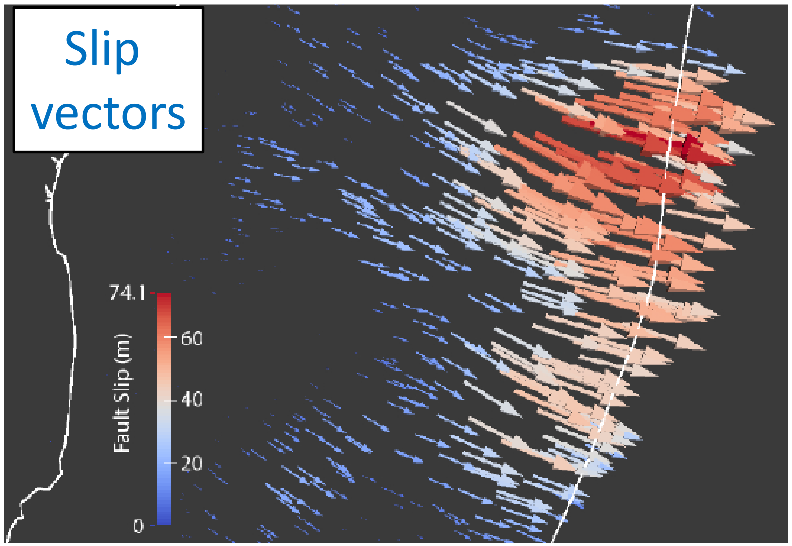
But it cannot massively happen over the rupture area !

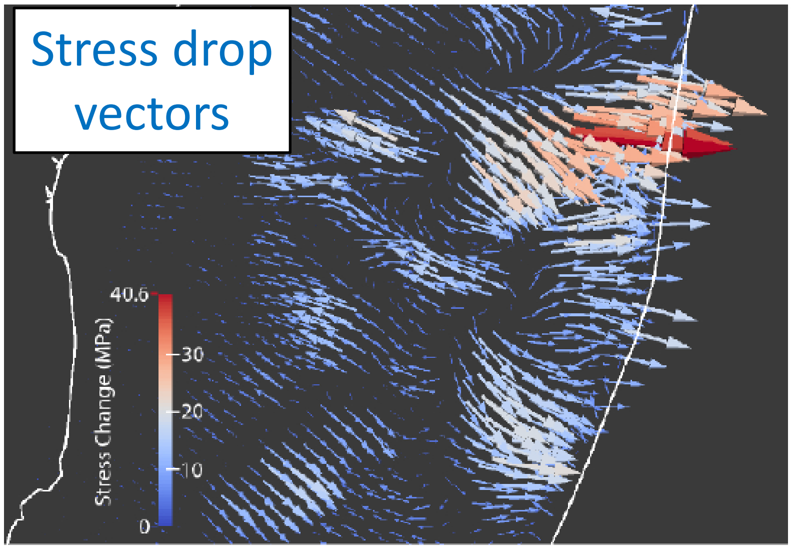


Earthquake magnitude M_w
1
2
3
4
5
6
7
8
Allamann & Shearer (2009)
100 MPa
10 MPa
1 MPa
0.1 MPa
fc [Hz]
10^2
10^1
10^0
10^{-1}
10^{-2}
this study
Hough (1996)
Boatwright (1994)
Mori and Frankel (1990)
Tajima and Tajima (2007)
Humphrey and Anderson (1994)
Archuleta et al. (1982)
Venkataraman and Kanamori (2004, only shallow events)
Abercrombie (1995)
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
10^{22}
m_0 [Nm]

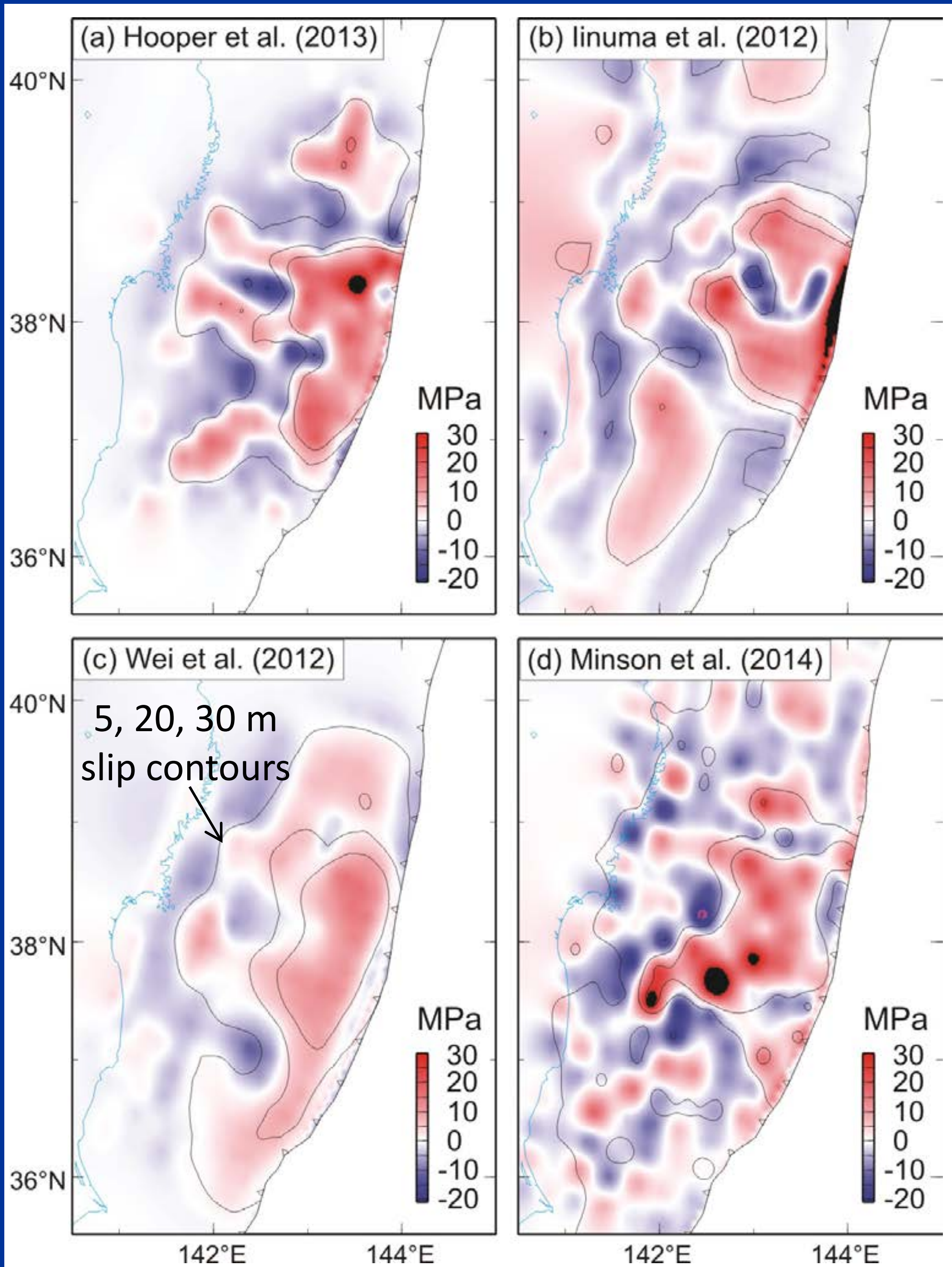
2011 M=9.0 Tohoku-oki earthquake

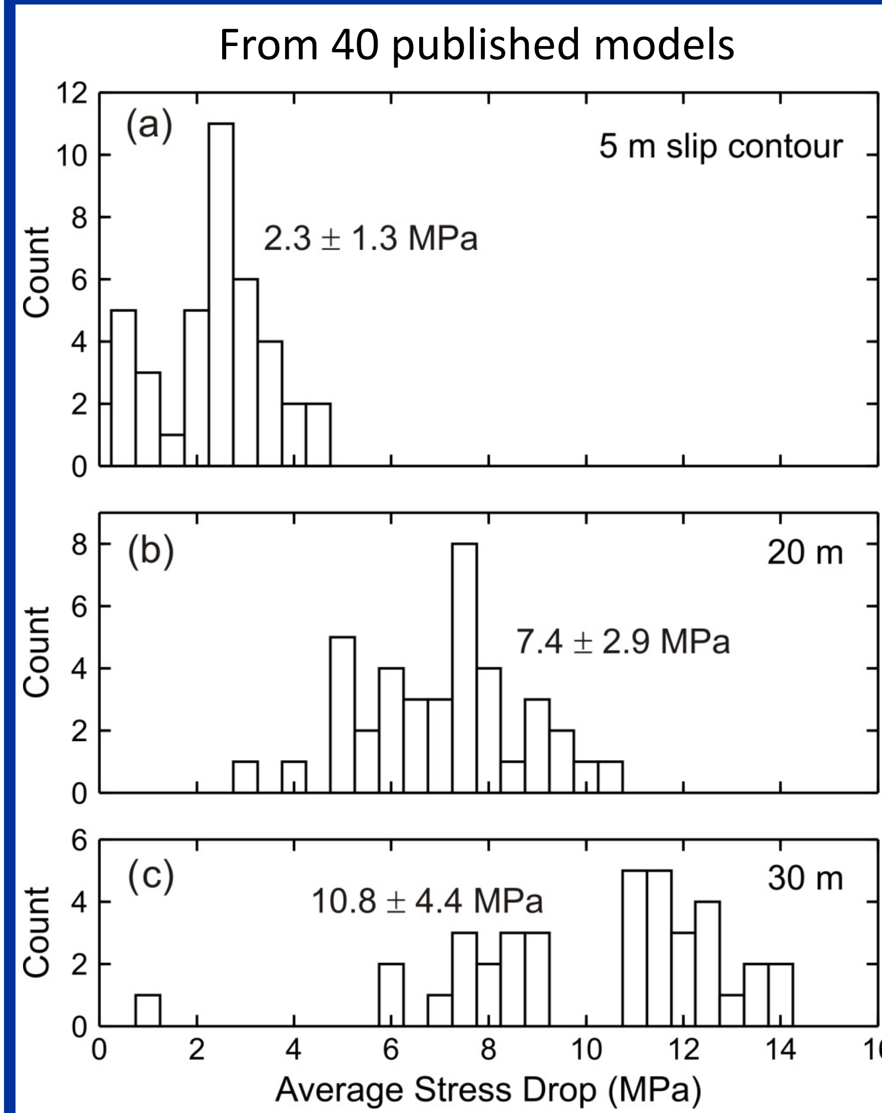






Brown et al., submitted





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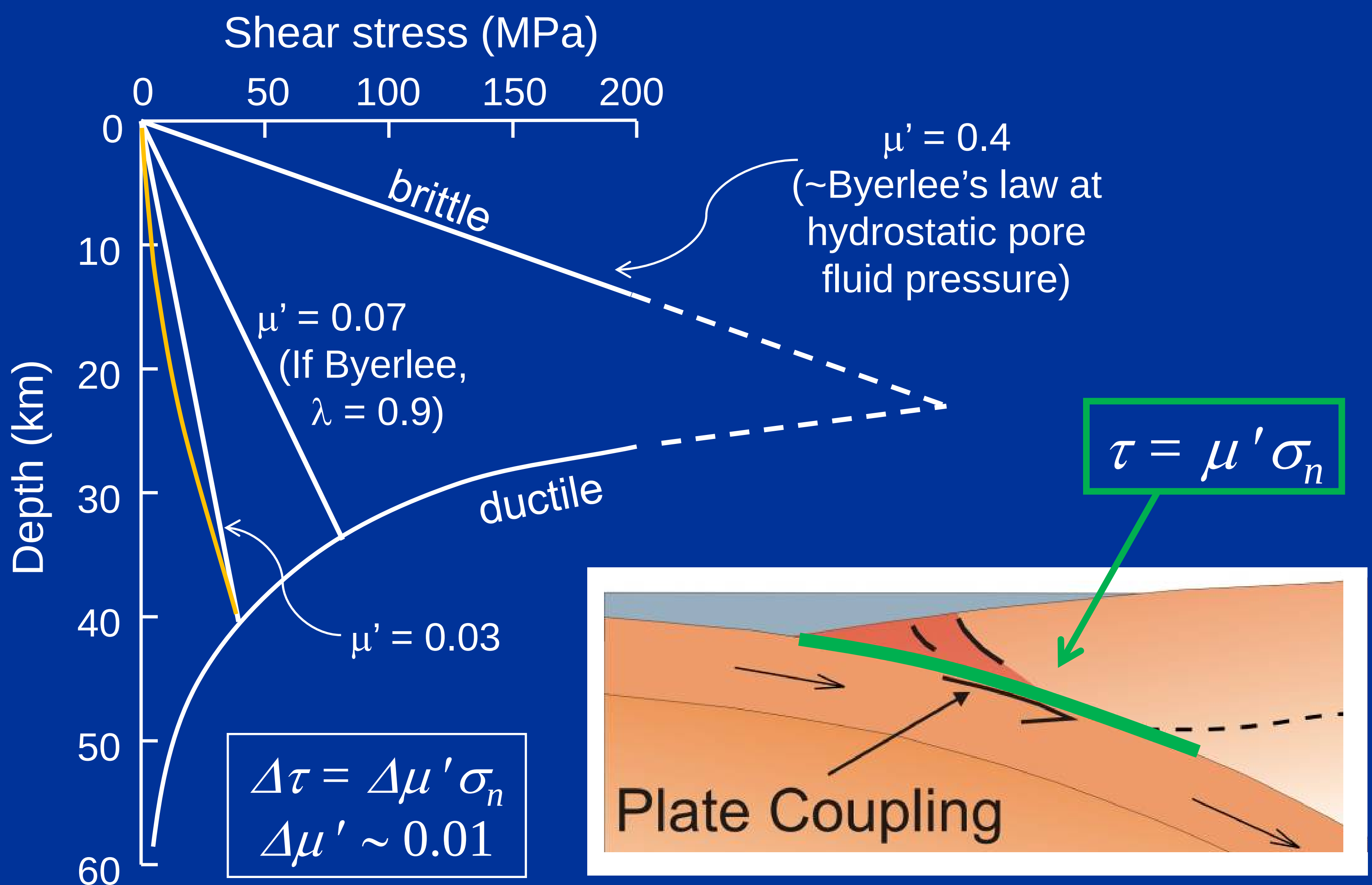
Shear stress (MPa)
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150
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Depth (km)
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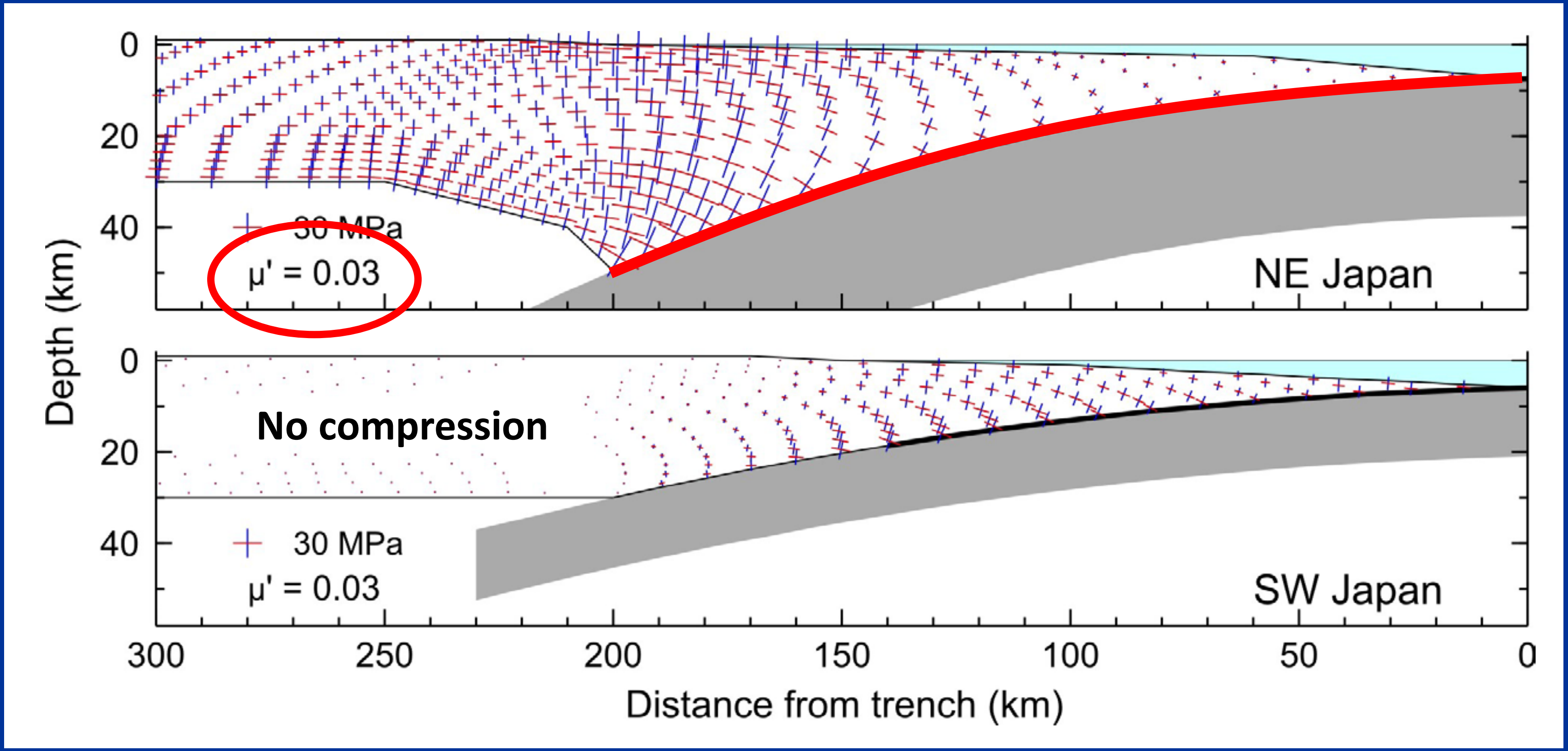
ductile
μ' = 0.4
(~Byerlee's law at
hydrostatic pore
fluid pressure)
μ' = 0.07
(If Byerlee,
λ = 0.9)
μ' = 0.03
$\Delta\tau = \Delta\mu'\sigma_n$
$\Delta\mu' \sim 0.01$
$\tau = \mu'\sigma_n$
Plate Coupling

3. Effect on upper plate stress

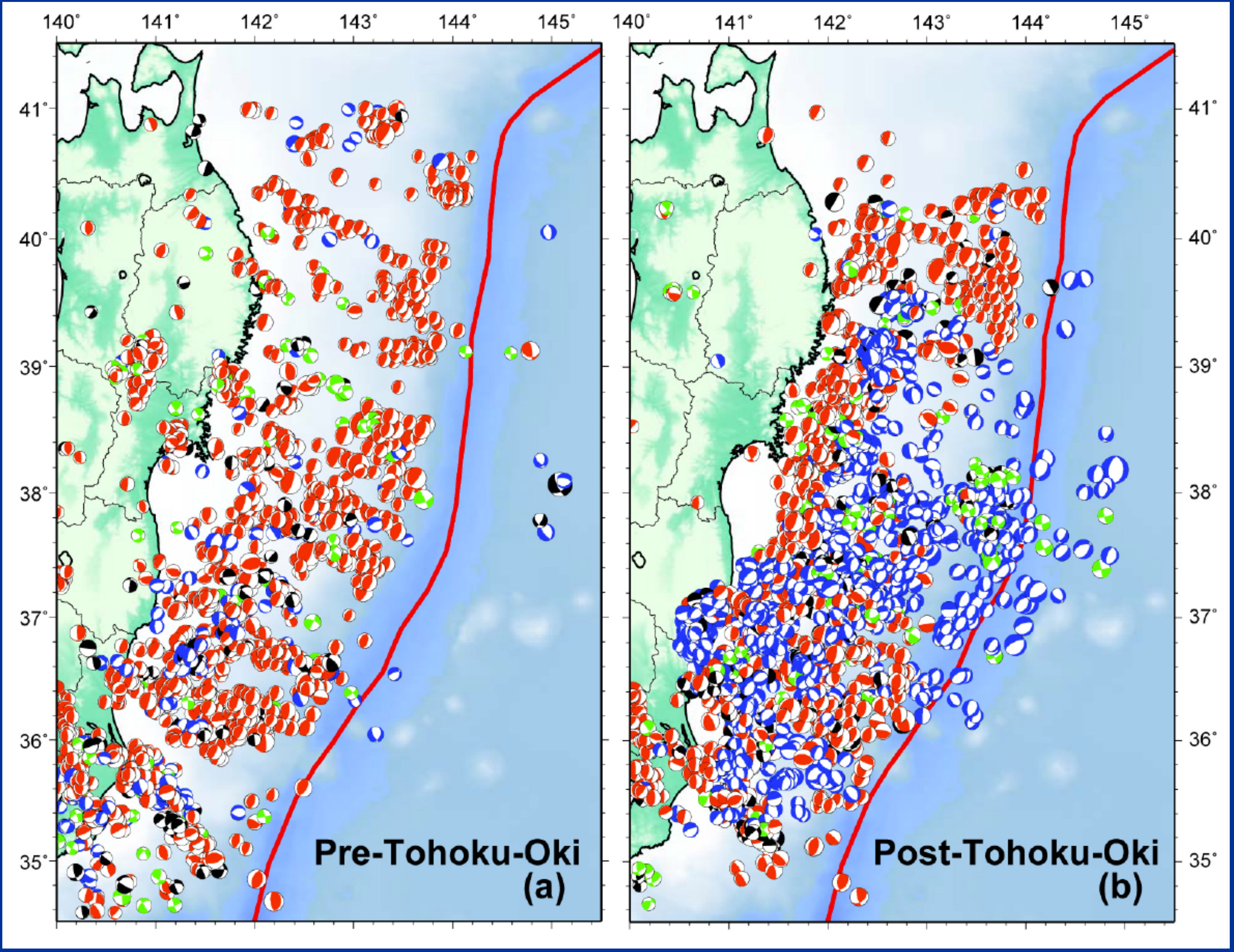
– Results in a very fragile state of stress in the forearc

Deviatoric stress (red is compressive)



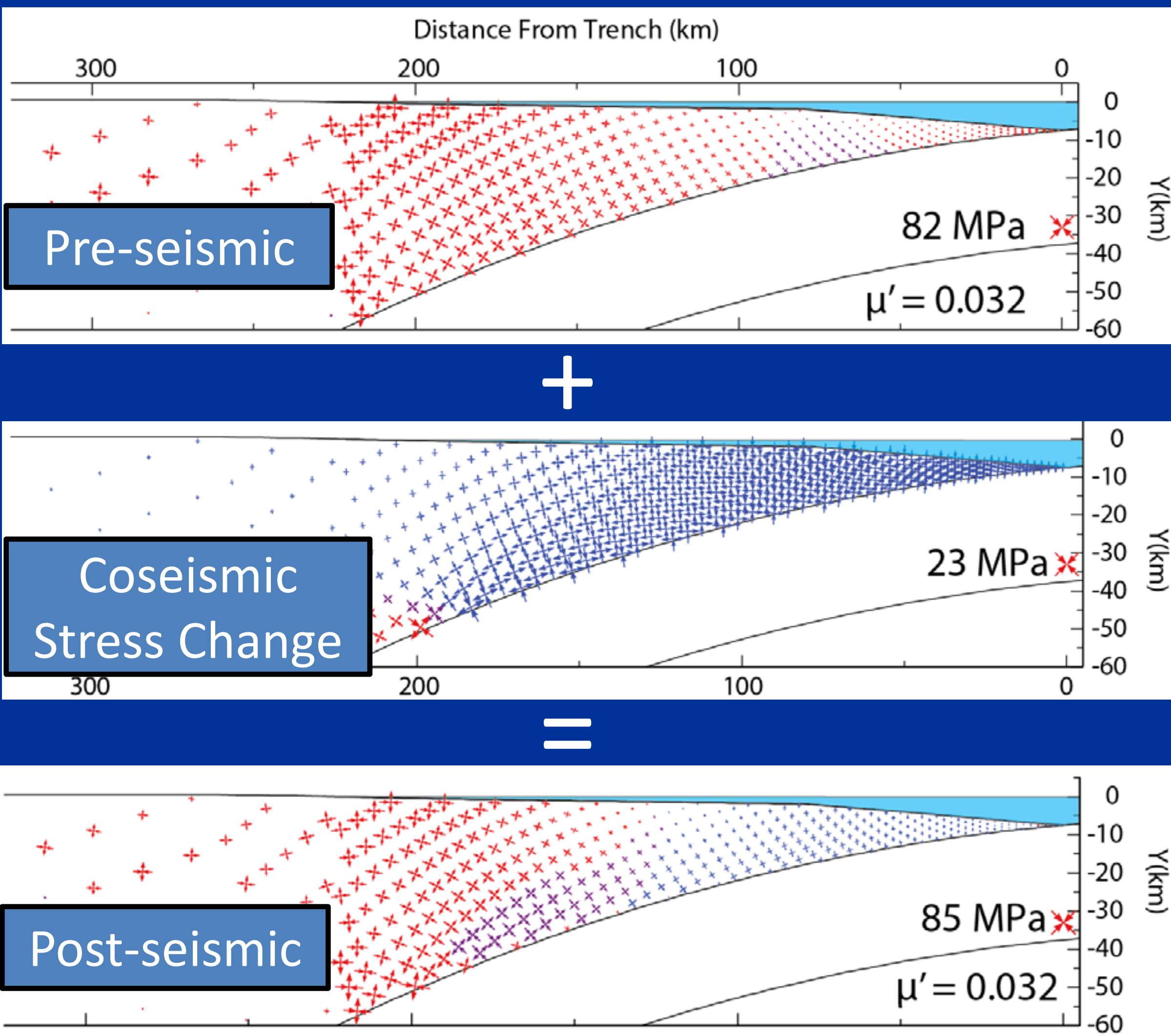
Wang and Suyehiro, 1999 GRL

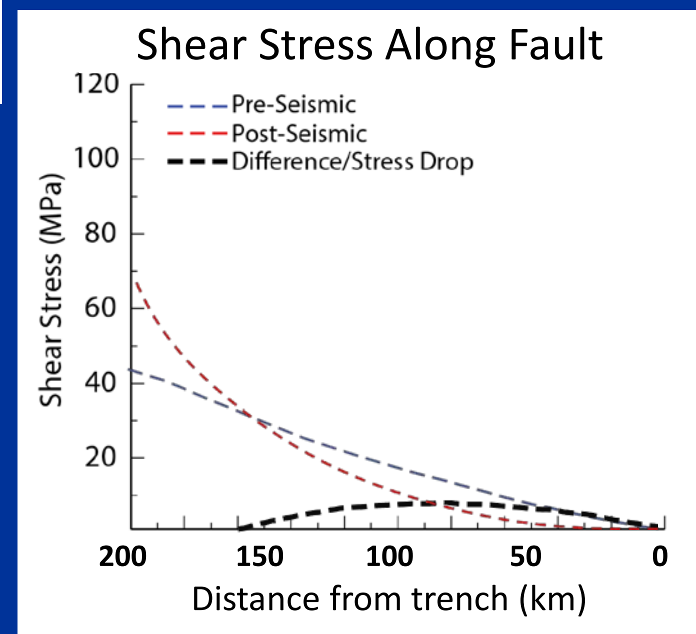
Hasegawa et al, 2012



Red = Thrust Blue = Normal

Deviatoric stresses in the Forearc
(red – compression; blue – tension)

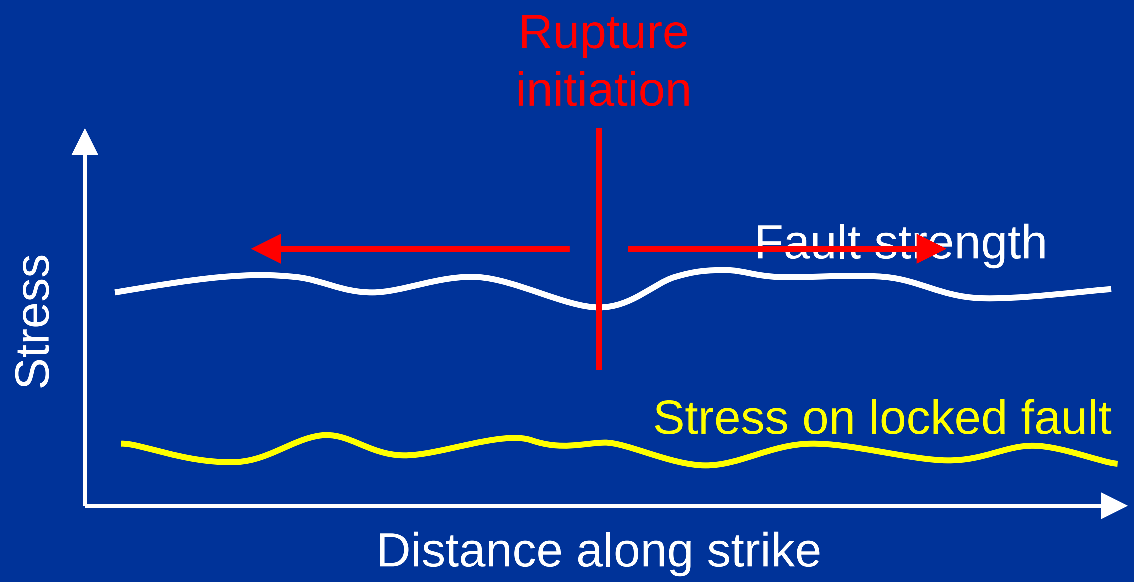




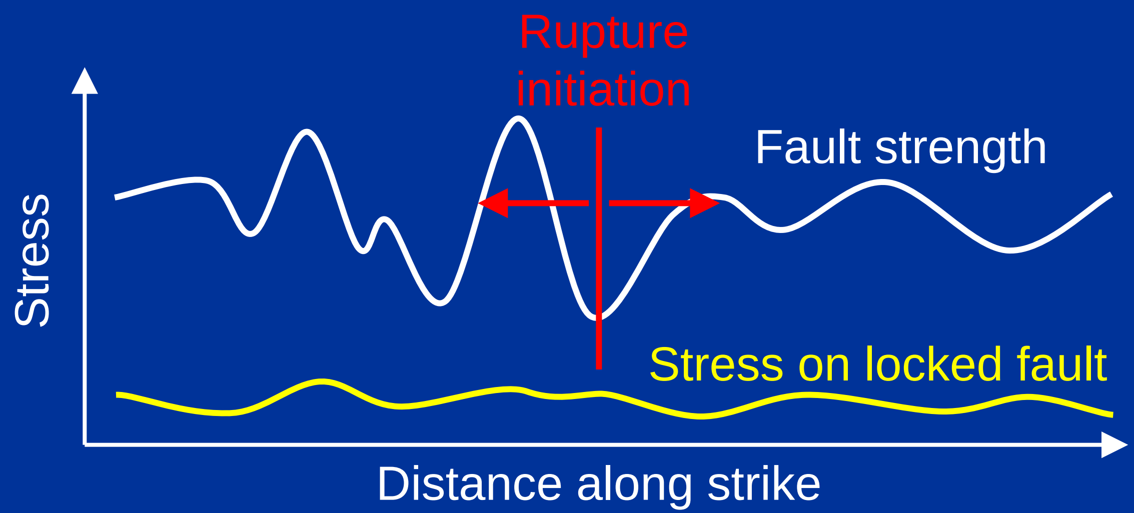
4. **Smooth faults and rough faults**

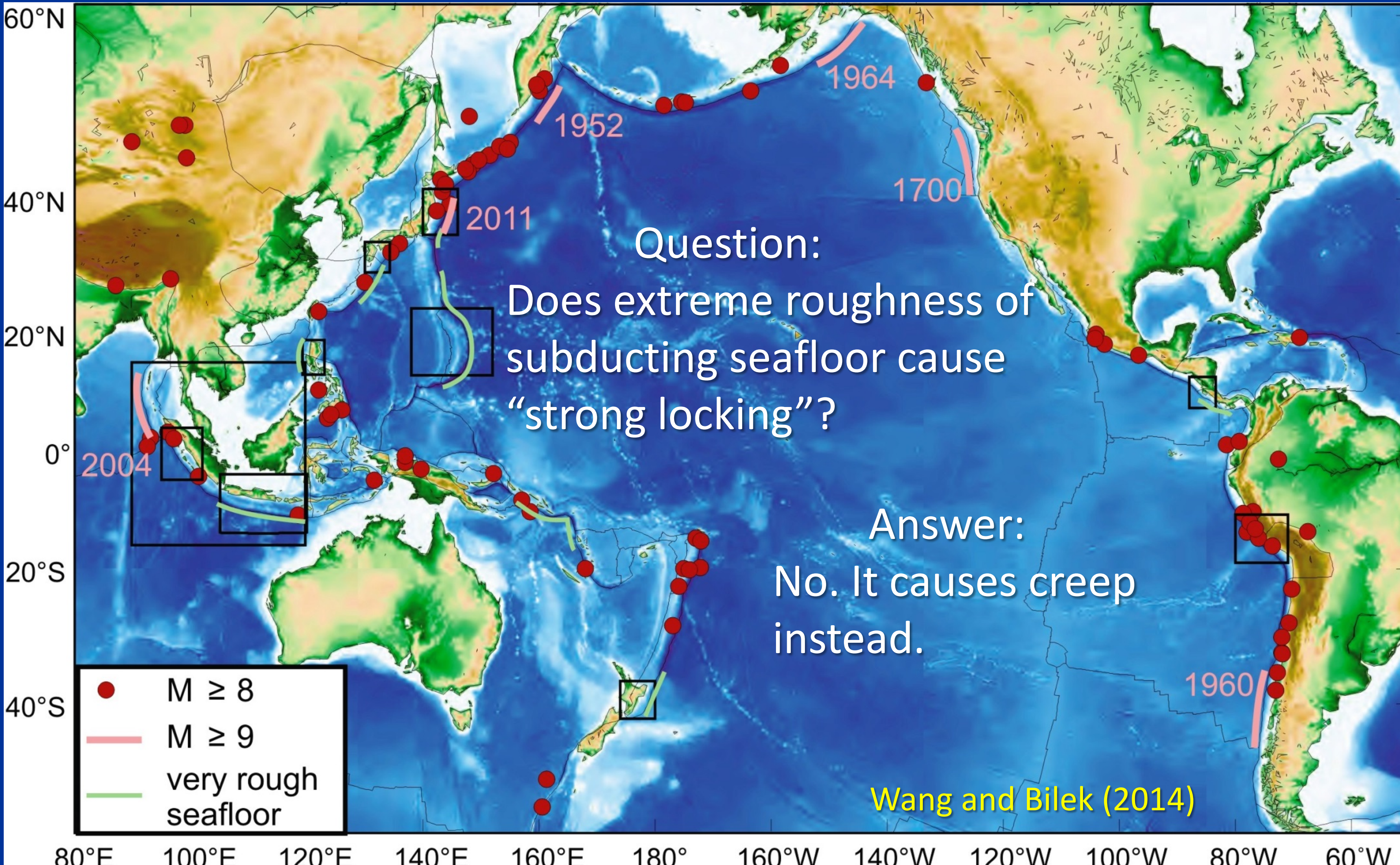
– Smoother and weaker faults cause great earthquakes

Smooth contact

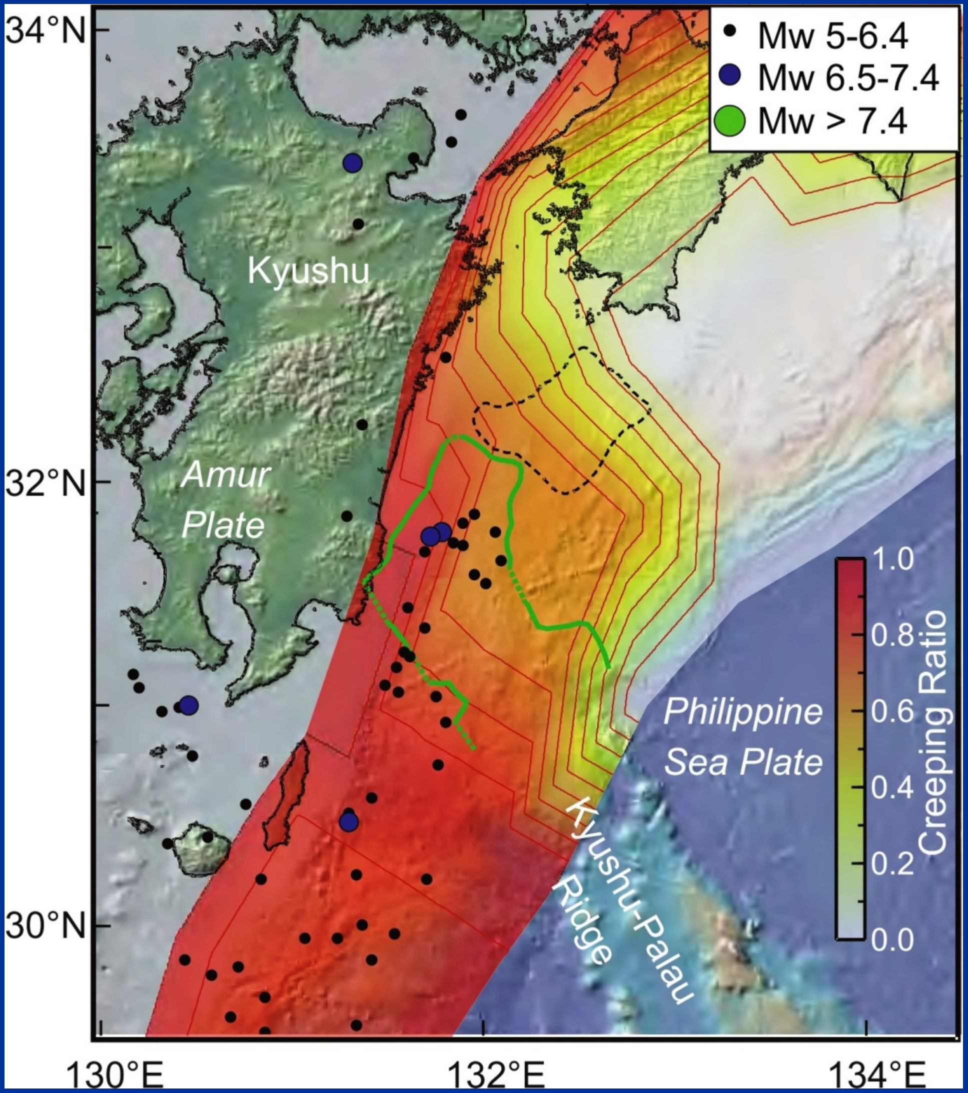


Rough contact





Correlation of giant quakes with smooth incoming plate

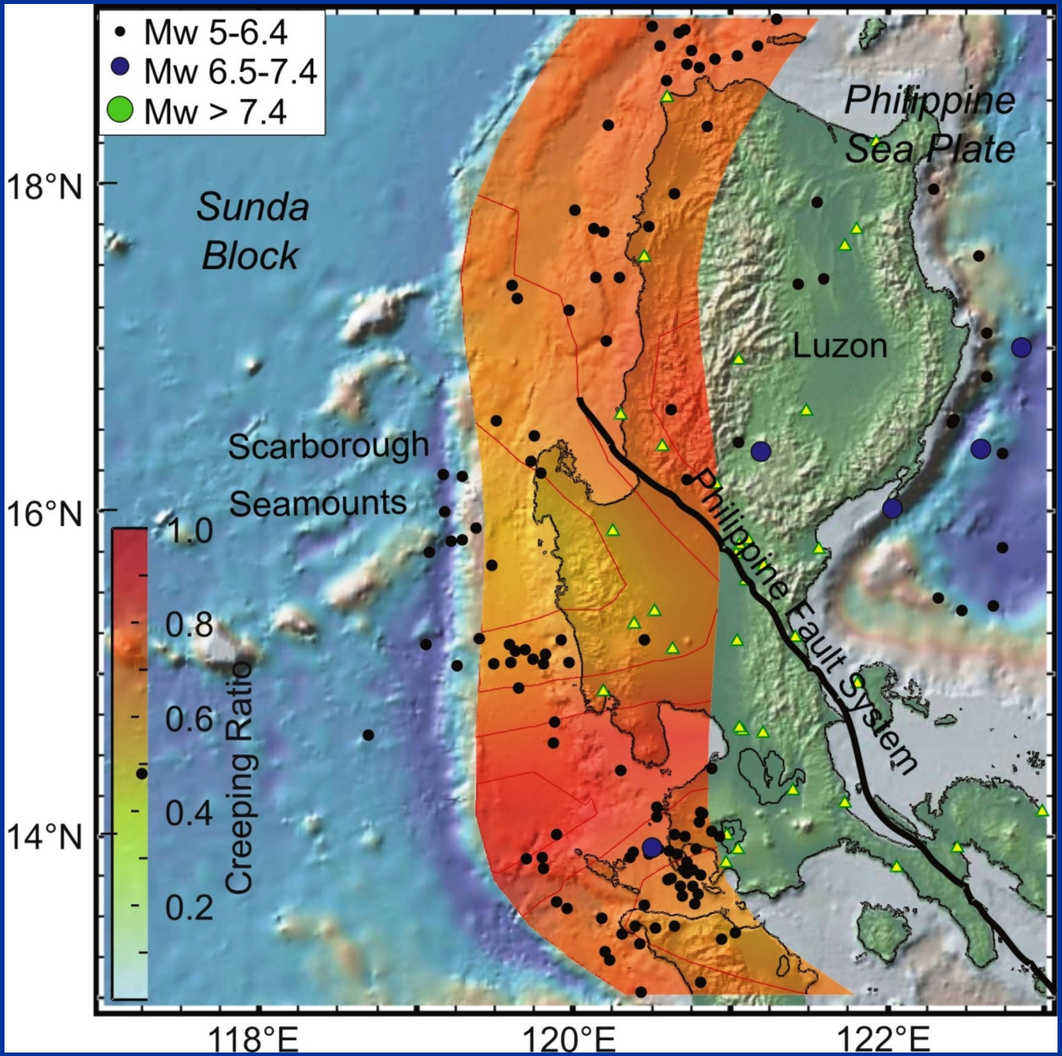


Nankai: Smooth, great earthquakes

Kyushu: Rough, Creeping

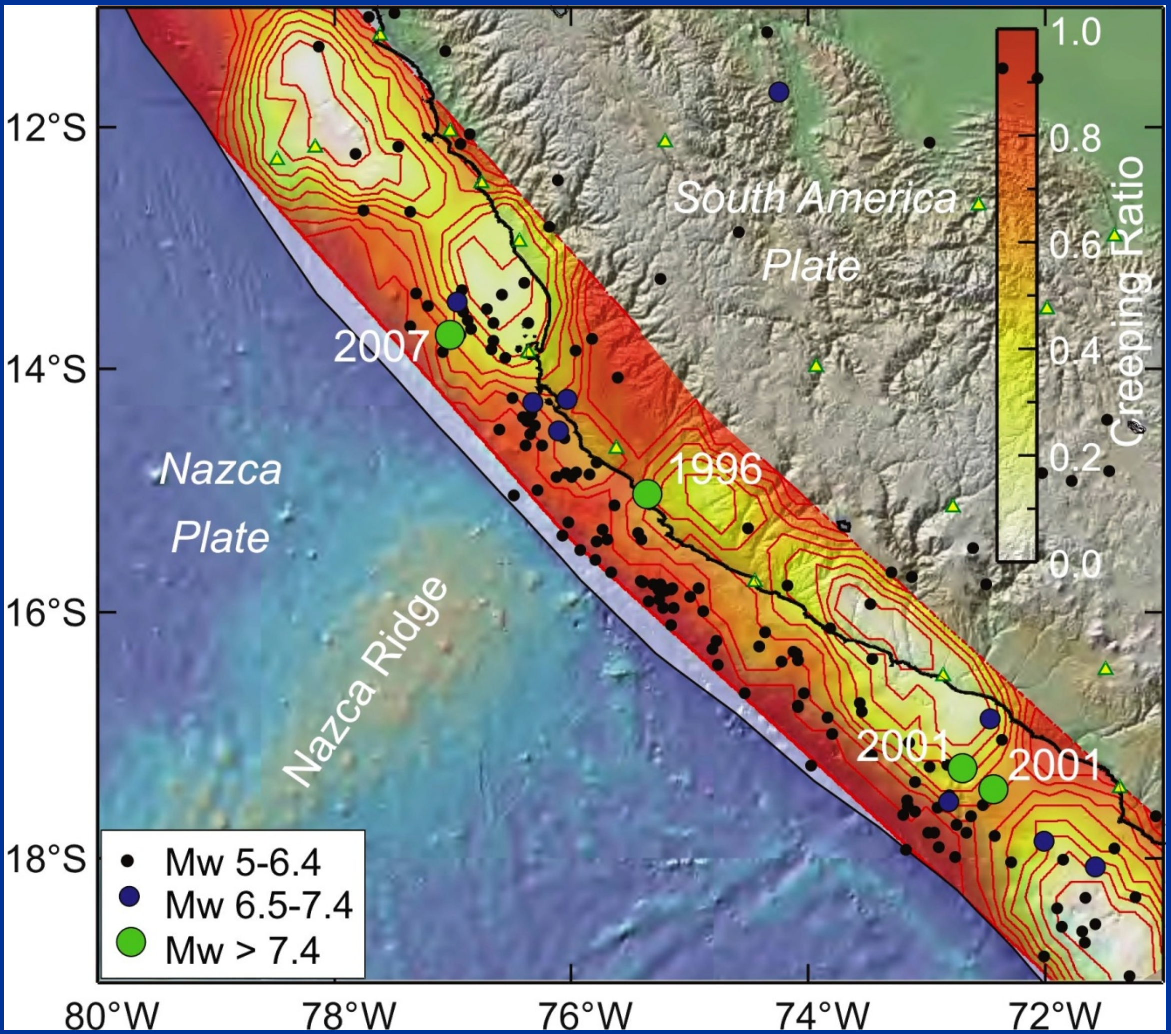
Creeping ratio from Wallace et al. (2009)

Manila Trench

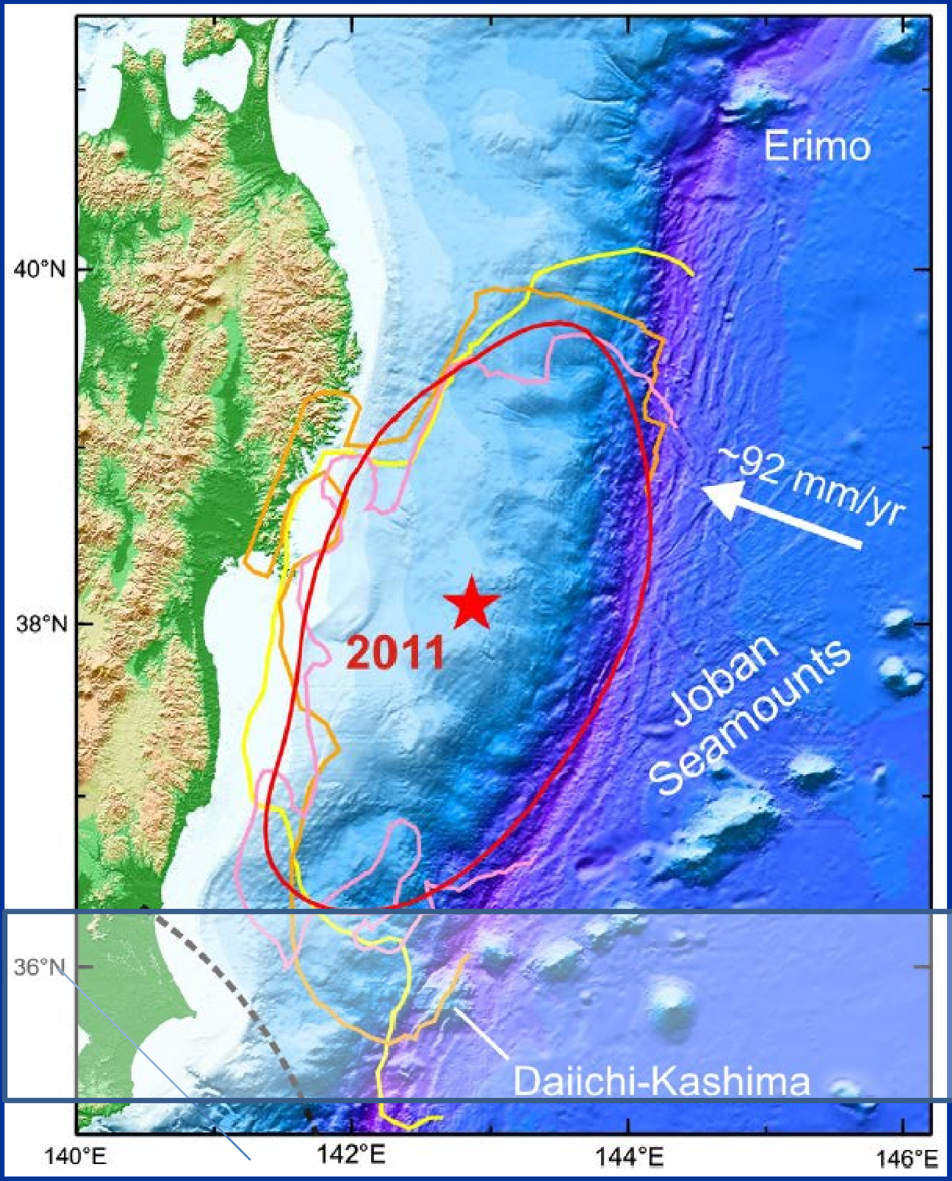


Creeping ratio from Hsu et al. (2012)

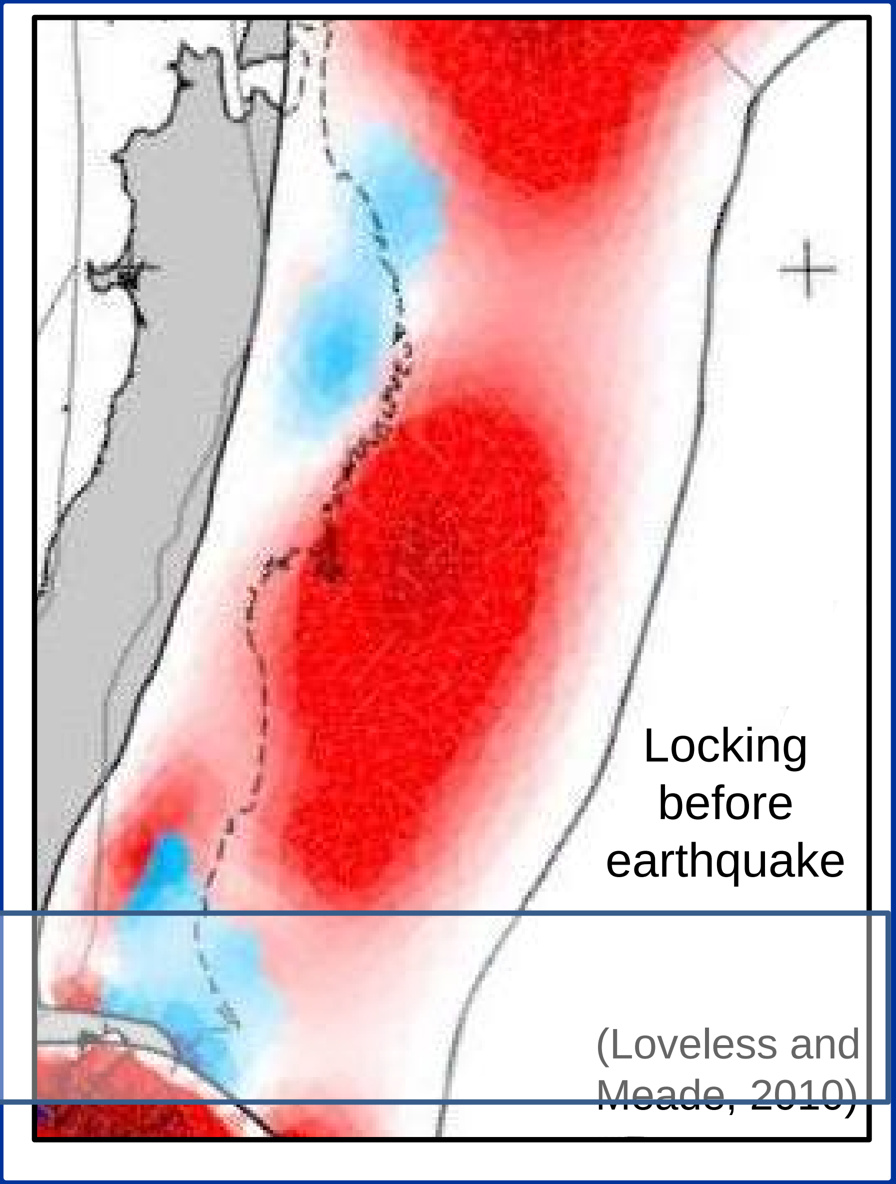
Peru: Creeping Nazca Ridge



Creeping ratio from Chlieh et al. (2011)



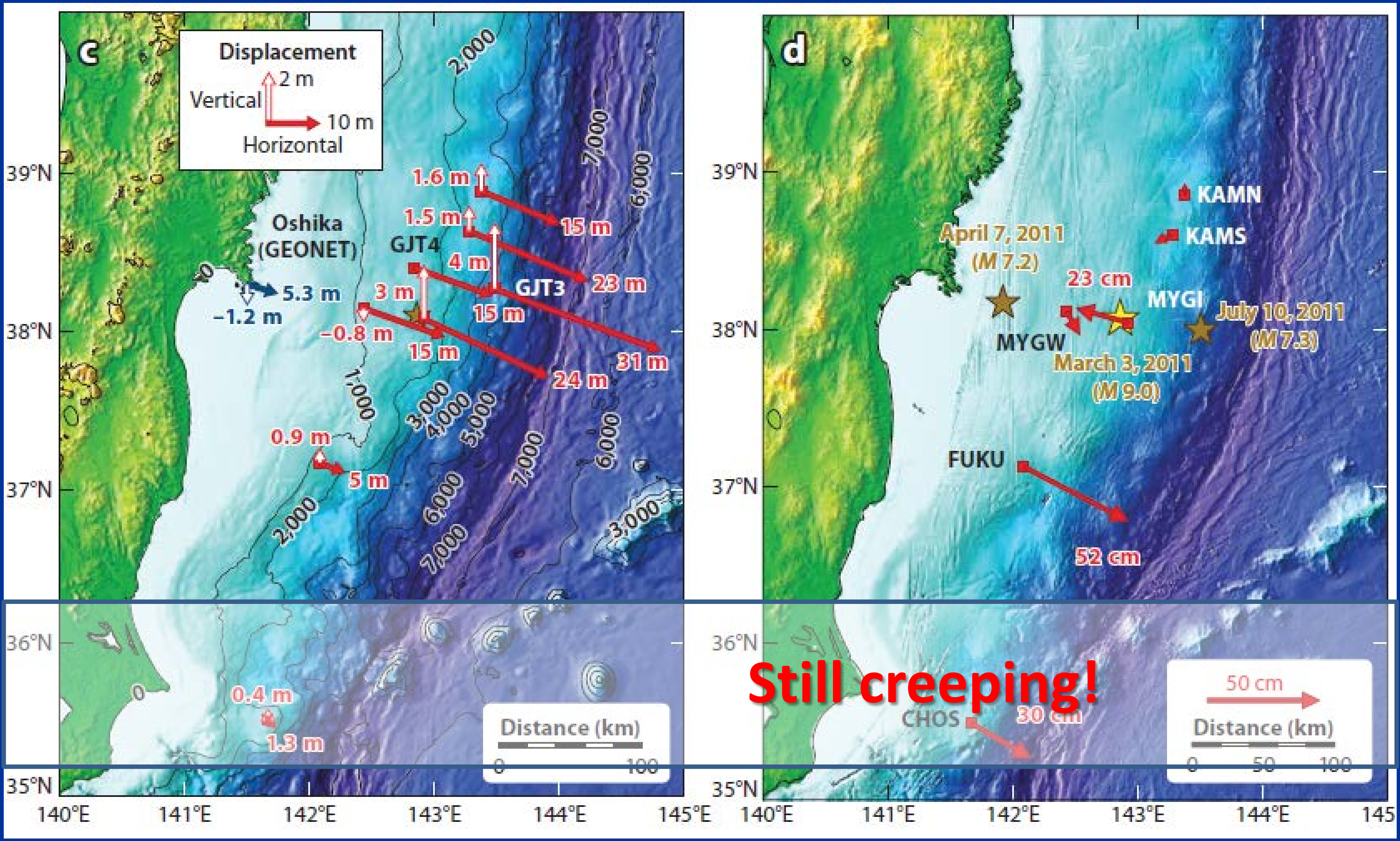
Erimo
40°N
~92 mm/yr
38°N
2011
Joban Seamounts
36°N
Daiichi-Kashima
140°E
142°E
144°E
146°E



Locking before earthquake
(Loveless and Meade, 2010)

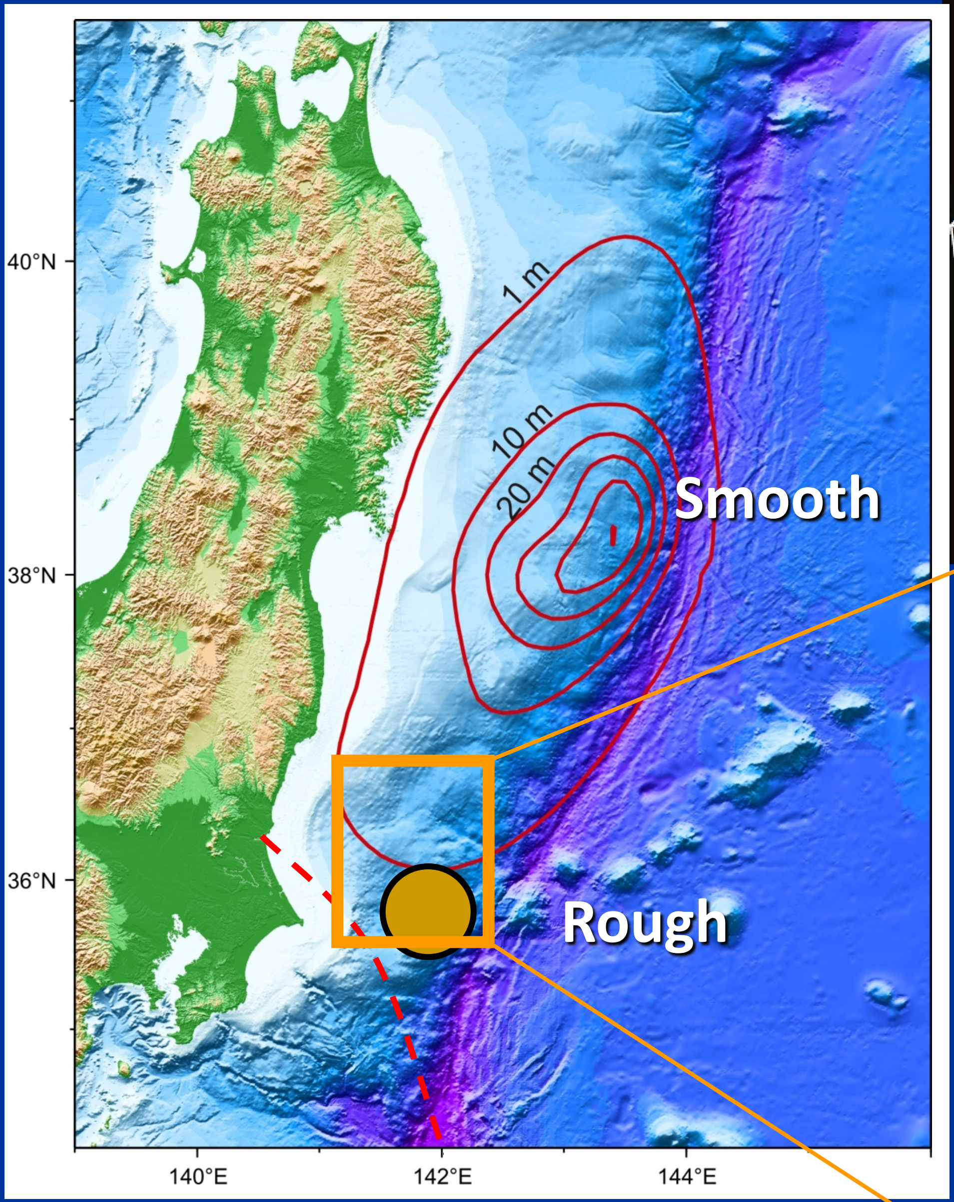
Coseismic

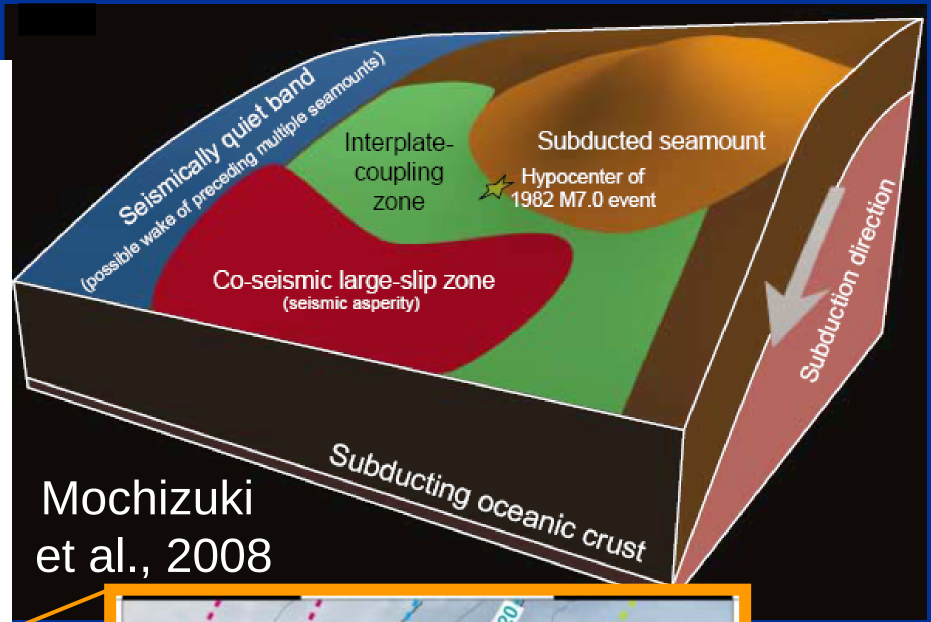
Postseismic (10 months)



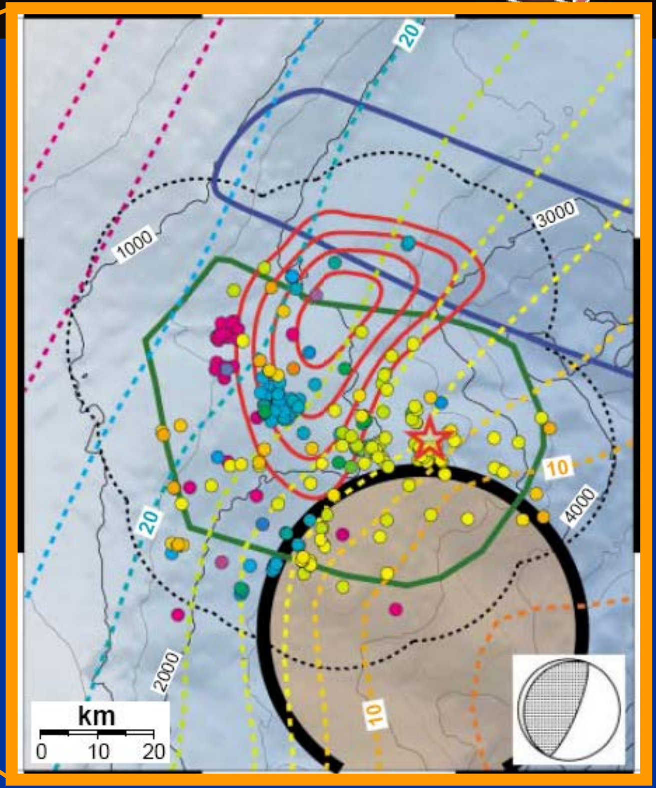
Data from Sato et al. (2011) and Kido et al. (2011)

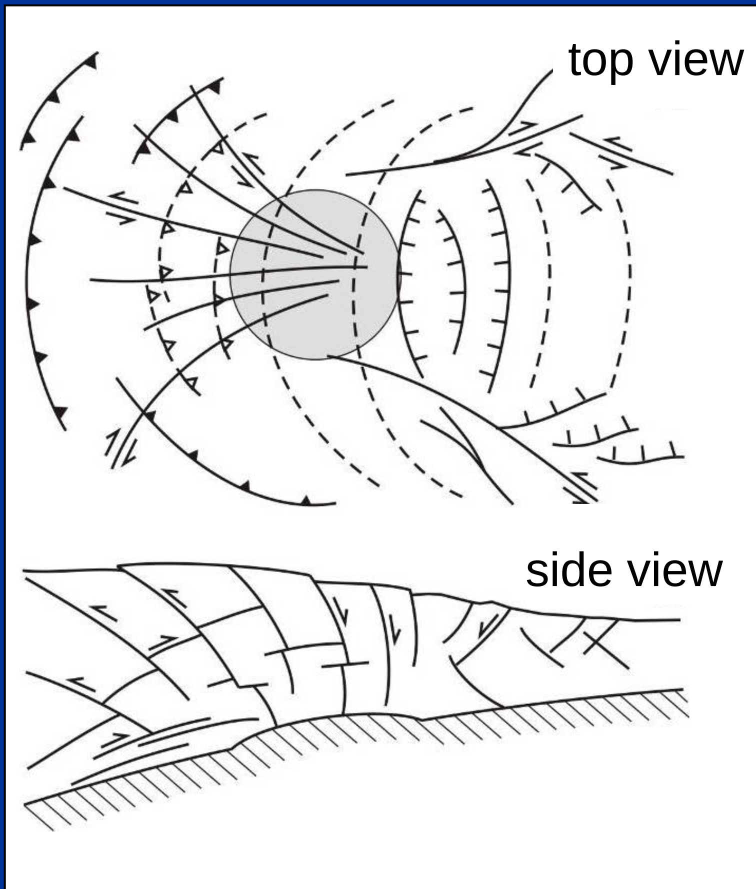
Data from Japan Coast Guard
Figure by Burgmann and Chadwell

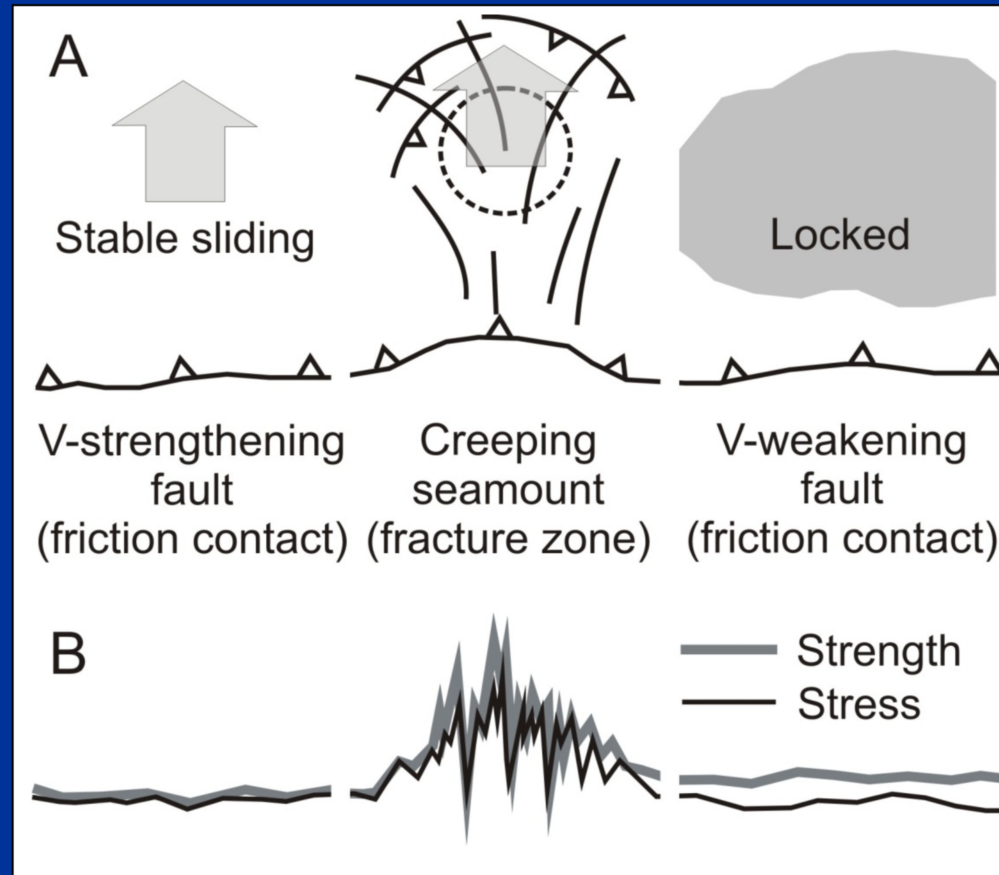




Mochizuki et al., 2008





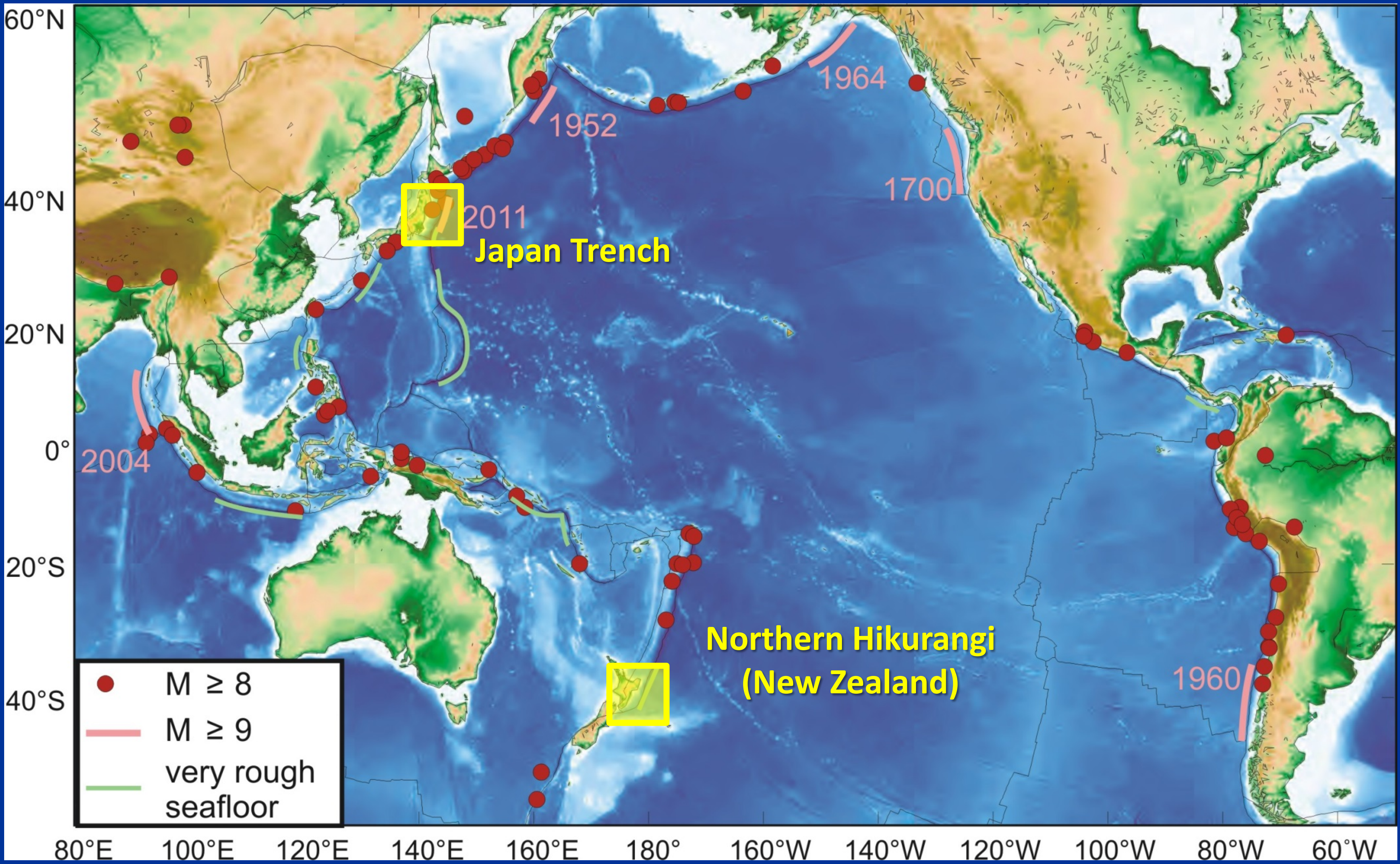


Wang and Bilek (2011, Geology):

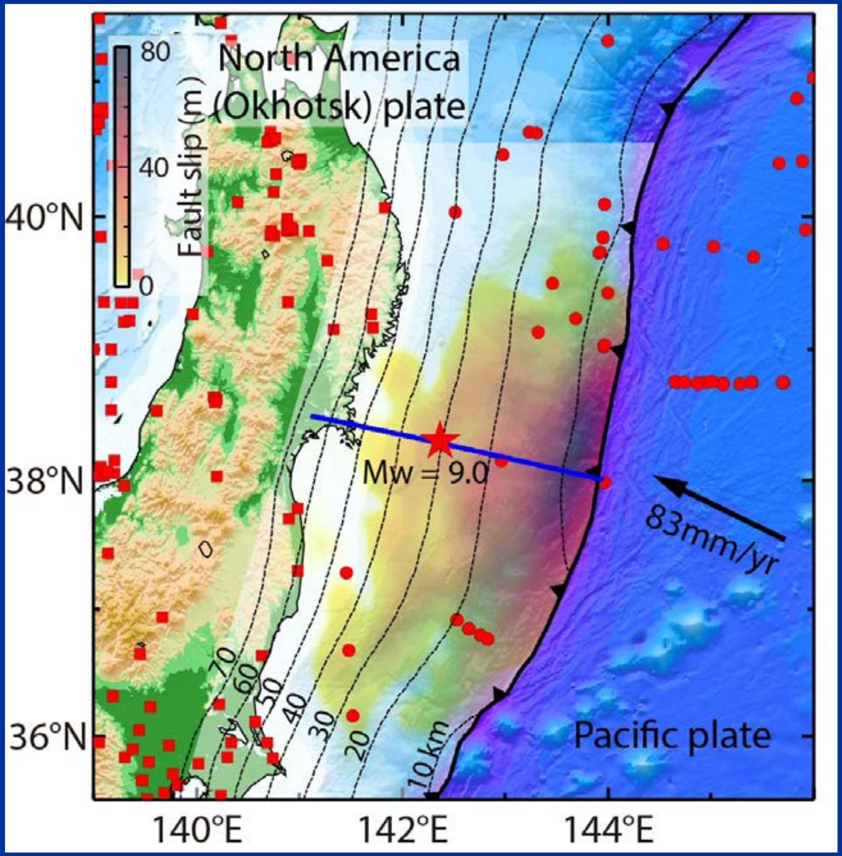
It is difficult to lock a seamount because of stress and structural complexity

5. **Frictional heating of seismogenic and creeping megathrust faults**

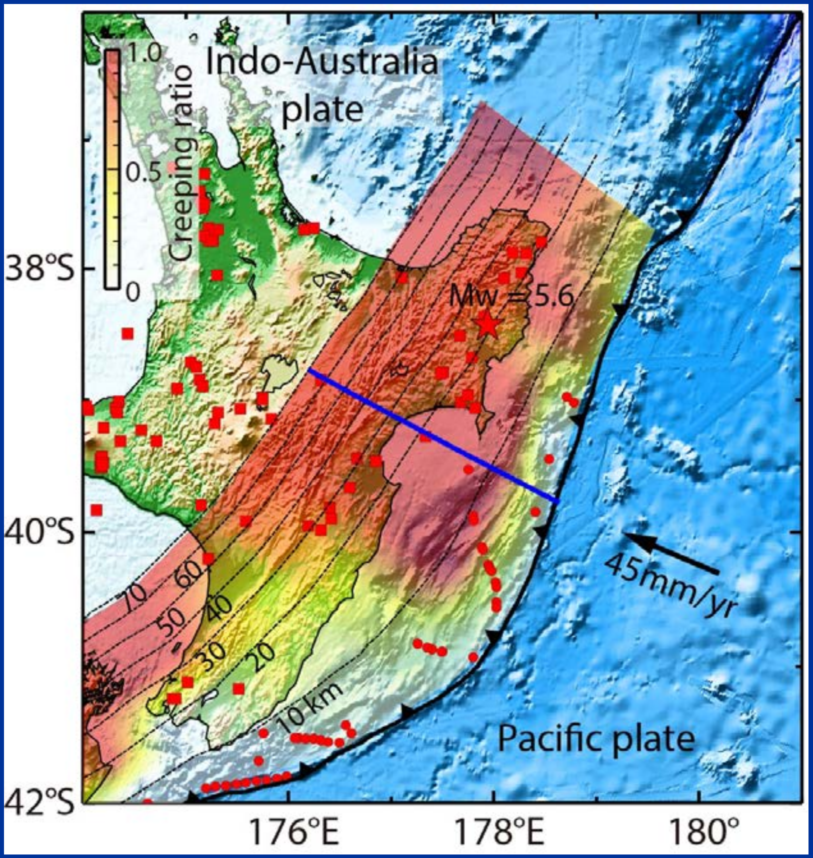
– Creeping megathrusts dissipate more heat (stronger)



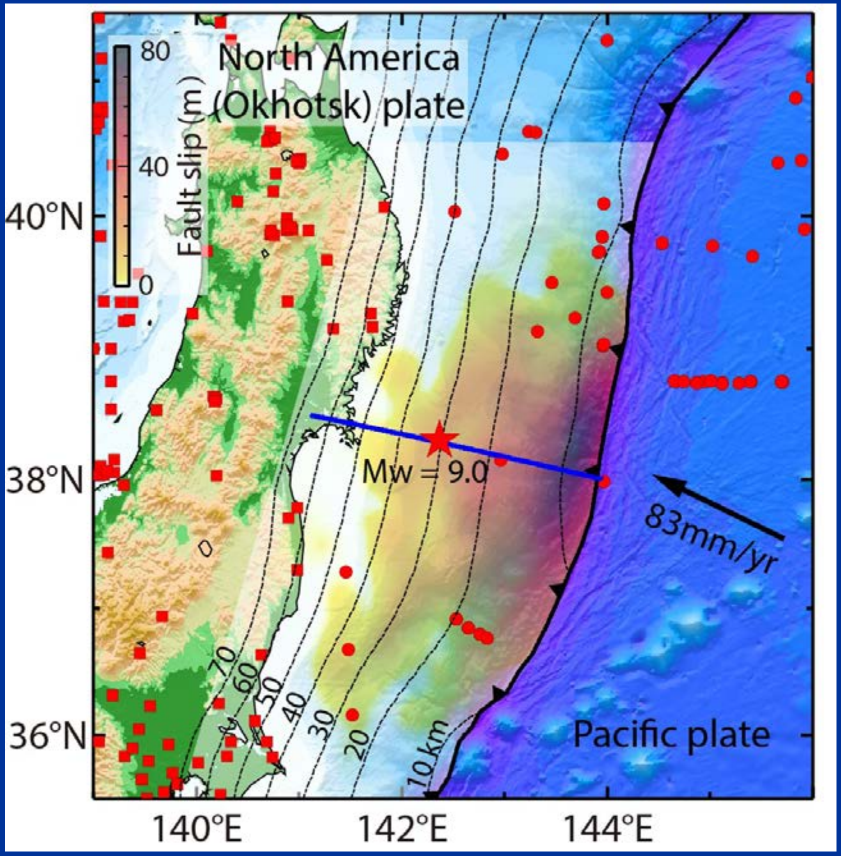
60°N
40°N
20°N
0°
20°S
40°S
80°E
100°E
120°E
140°E
160°E
180°
160°W
140°W
120°W
100°W
80°W
60°W
1952
1964
1700
2011
2004
1960
Japan Trench
Northern Hikurangi
(New Zealand)
M ≥ 8
M ≥ 9
very rough
seafloor



Japan Trench
Smooth subducting seafloor
Strongly seismogenic fault
(2011 coseismic slip: Shao et al., 2012)



Northern Hikurangi
Rough subducting seafloor
Creeping fault
(creeping ratio: Wallace et al., 2009)



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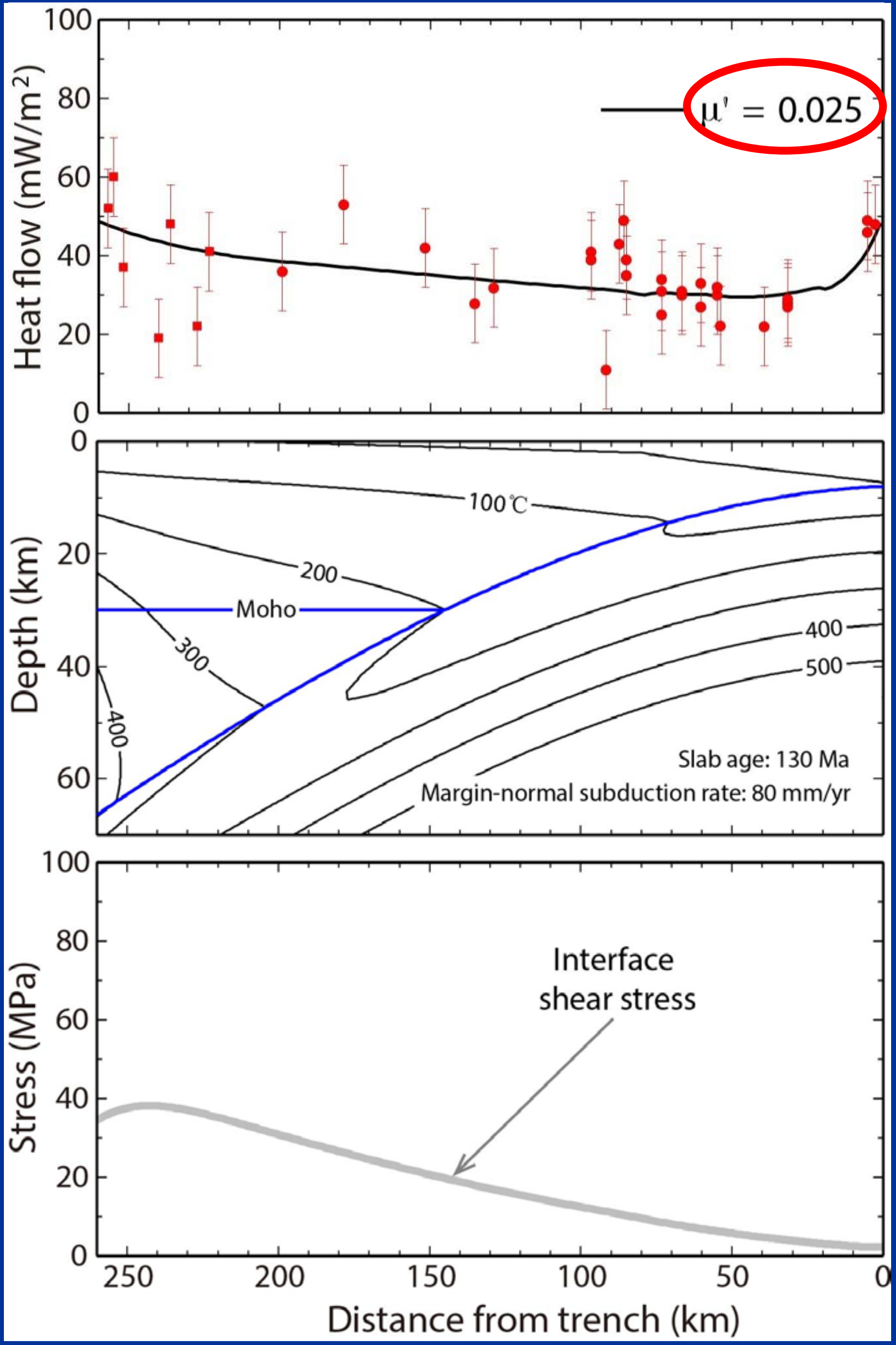
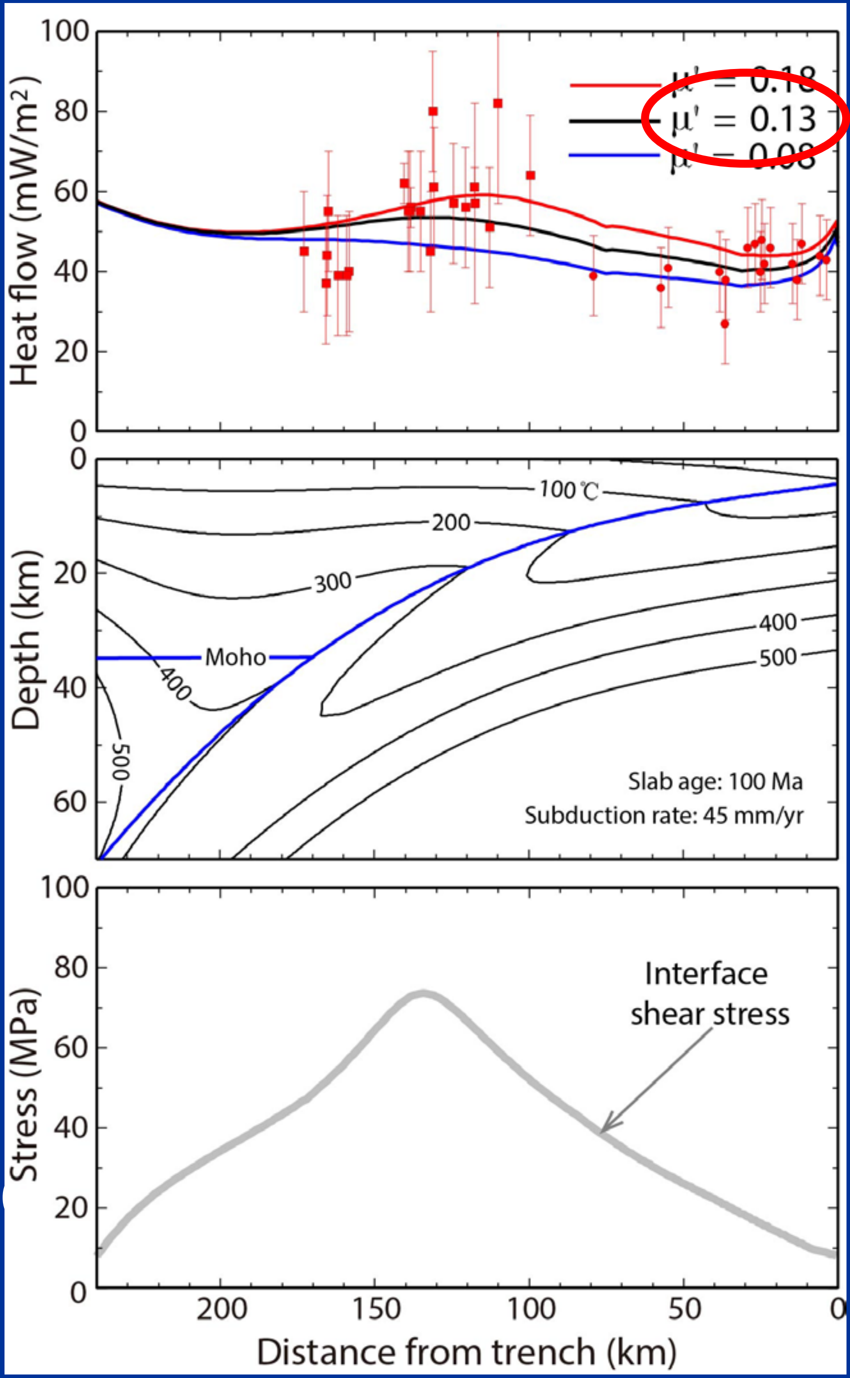
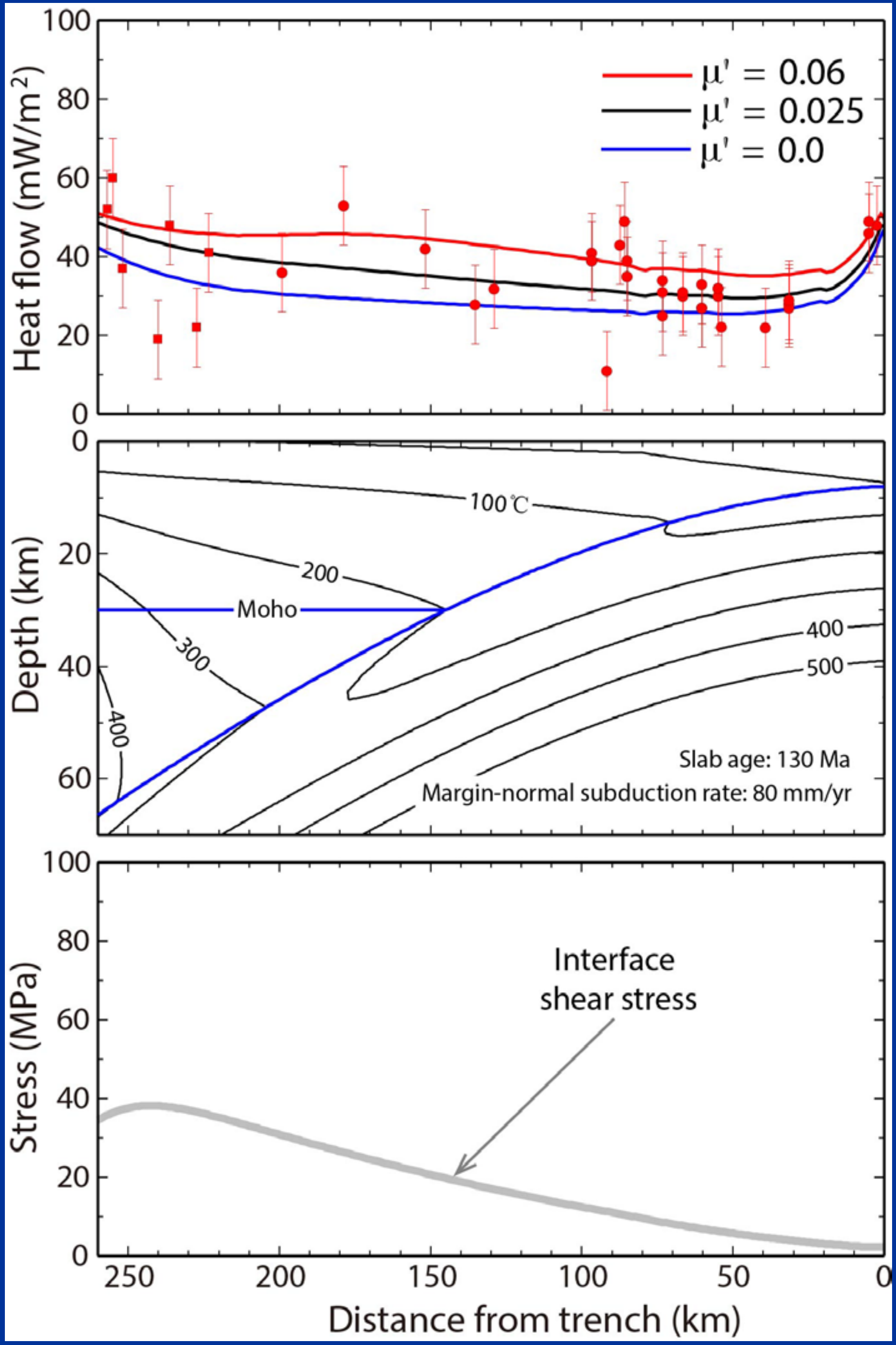
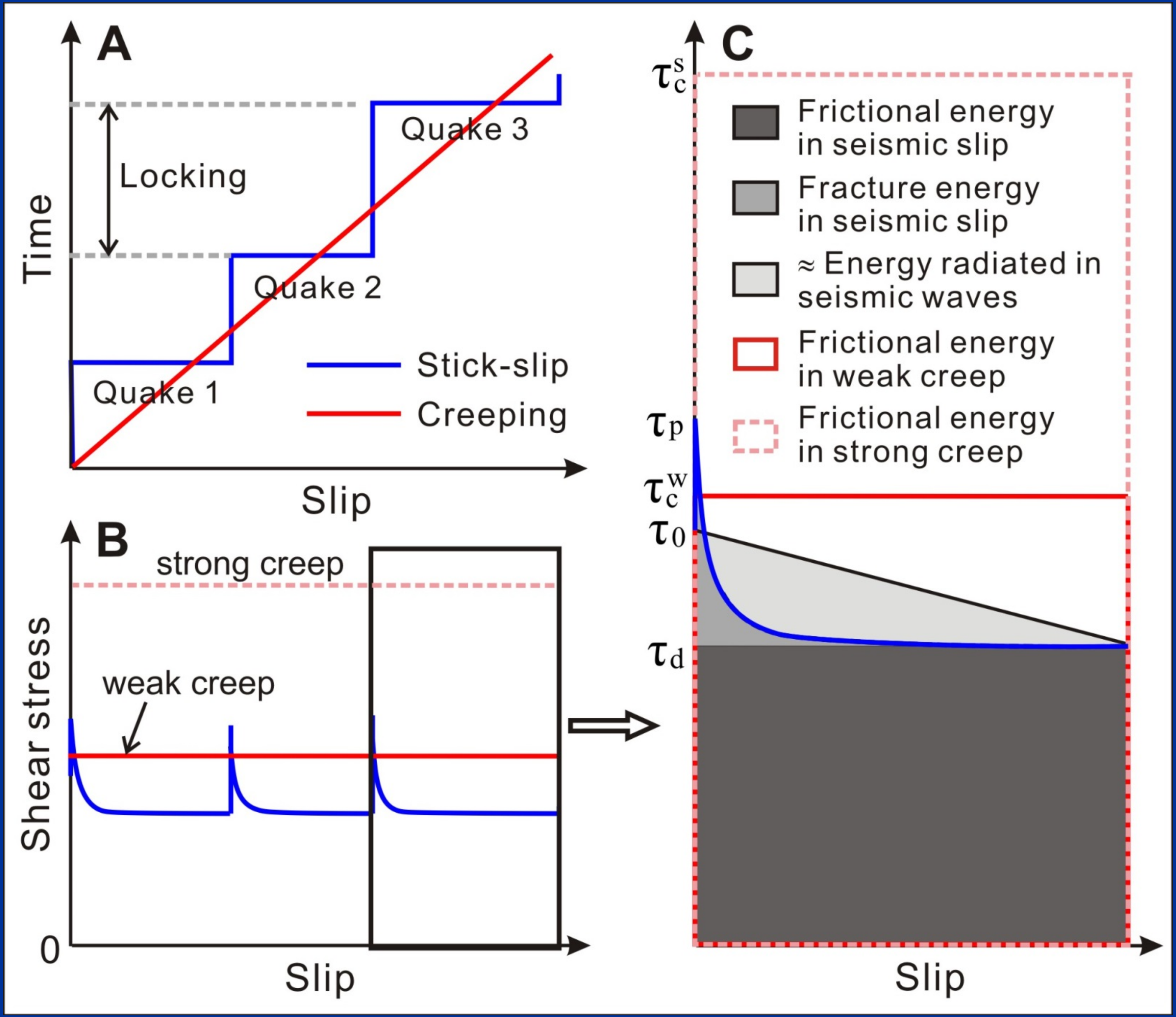




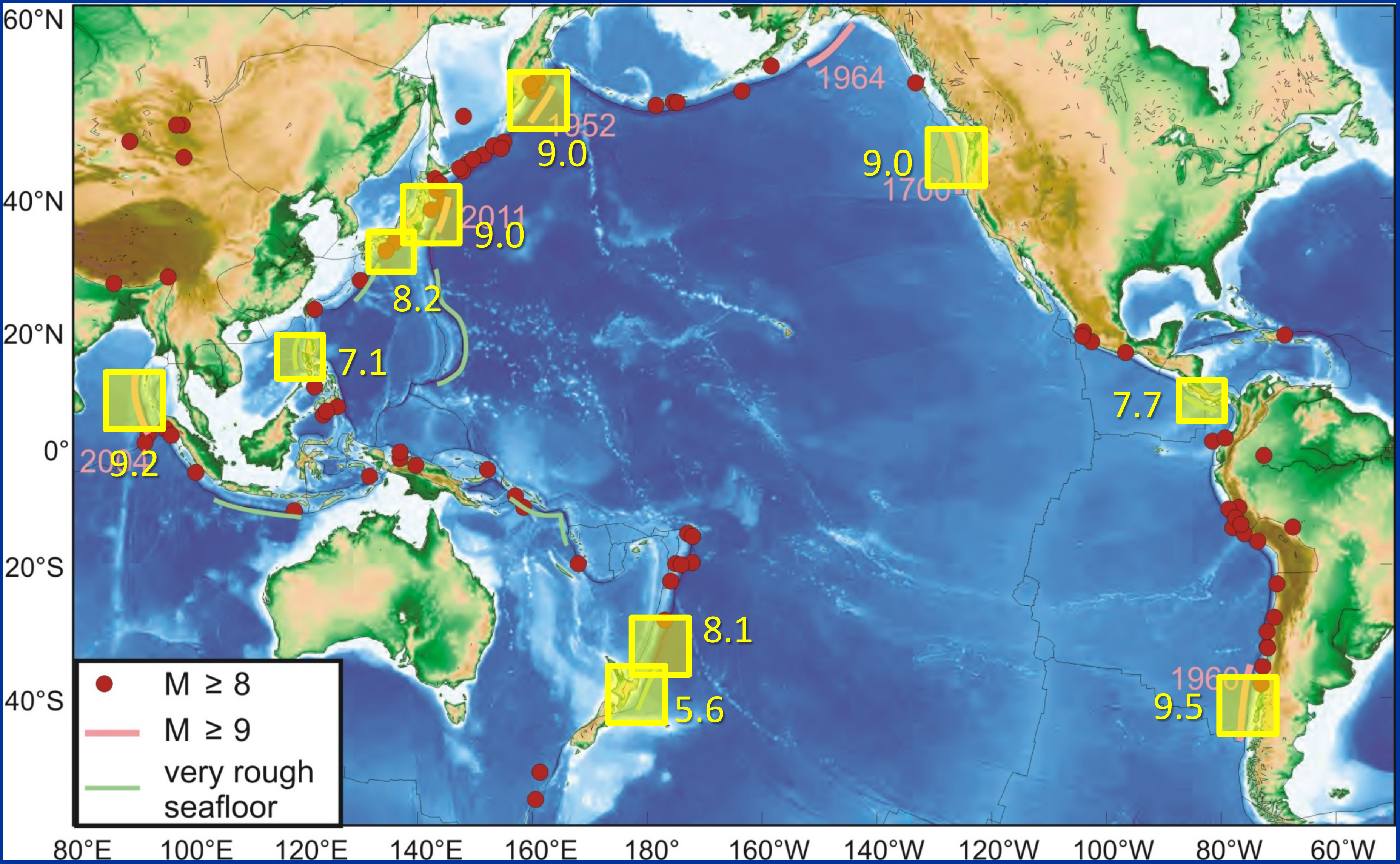
Heat flow (mW/m²)
μ' = 0.18
μ' = 0.13
μ' = 0.08
Depth (km)
100℃
200
300
400
500
Moho
Slab age: 100 Ma
Subduction rate: 45 mm/yr
Stress (MPa)
Interface shear stress
Distance from trench (km)



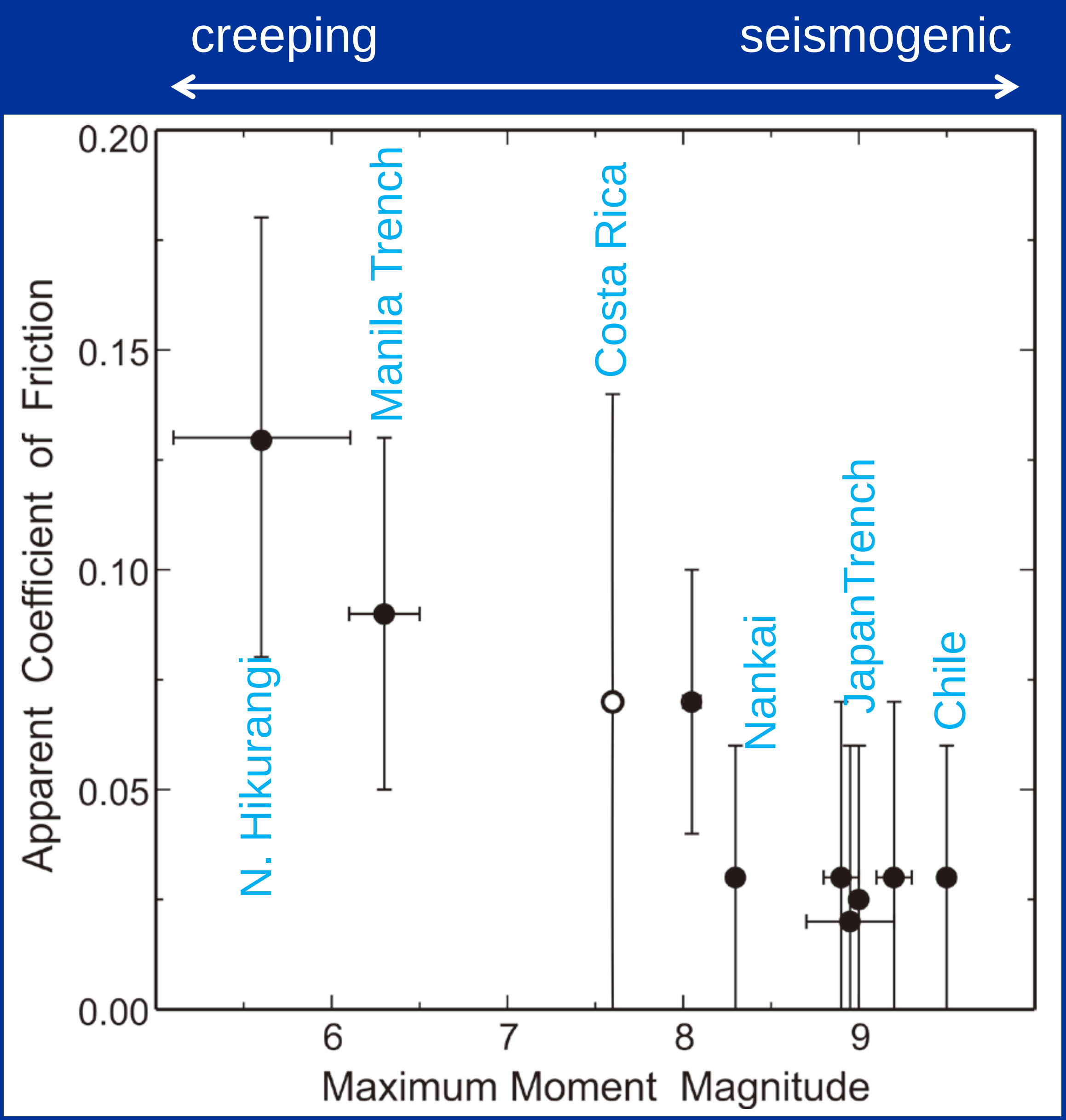
Heat flow (mW/m²)
μ' = 0.06
μ' = 0.025
μ' = 0.0
Depth (km)
100℃
200
300
400
500
Moho
Slab age: 130 Ma
Margin-normal subduction rate: 80 mm/yr
Stress (MPa)
Interface shear stress
Distance from trench (km)



Gao and Wang, Science, 2014



Subduction zones with adequate heat flow data to constrain frictional heating

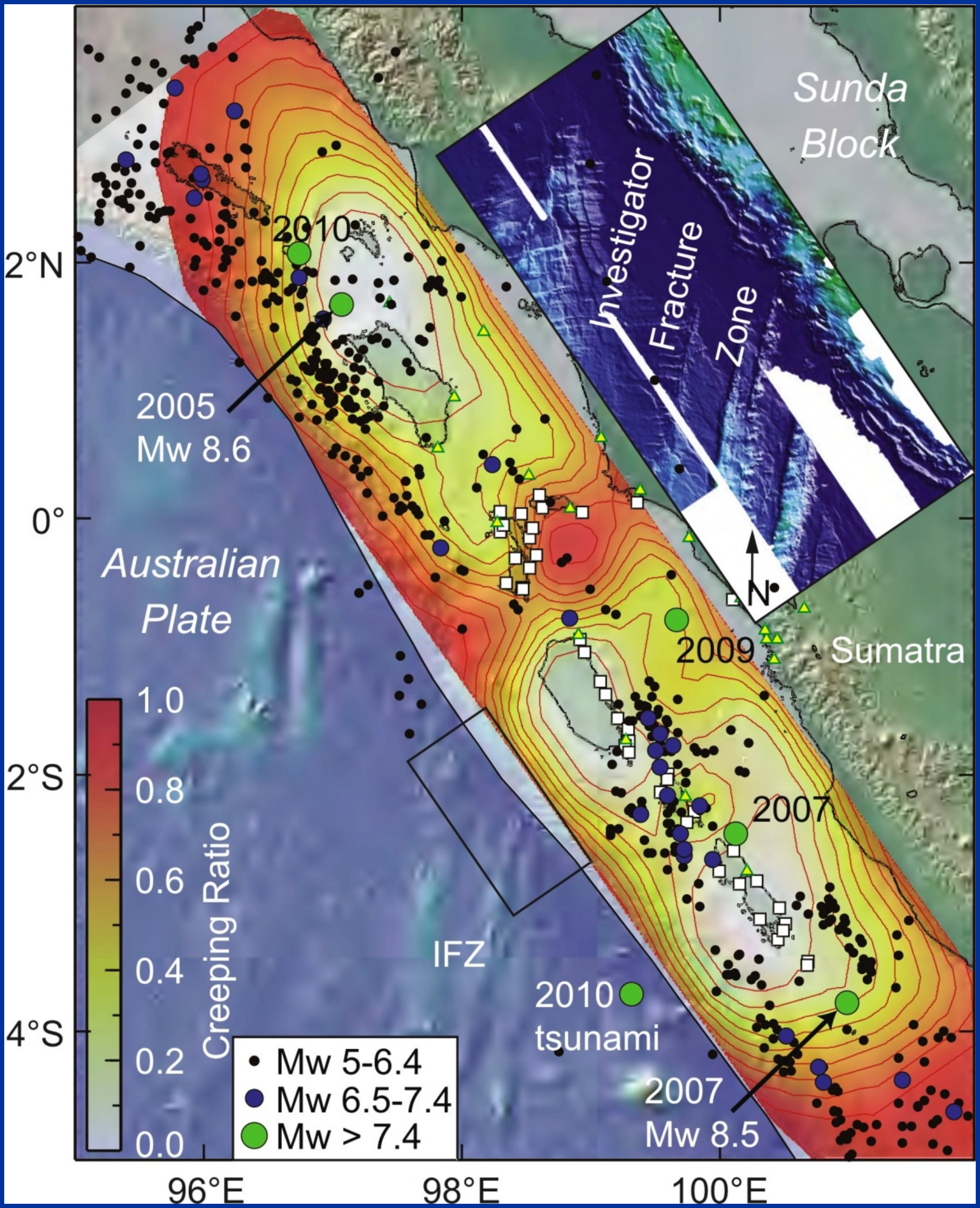


Gao and Wang, Science, 2014

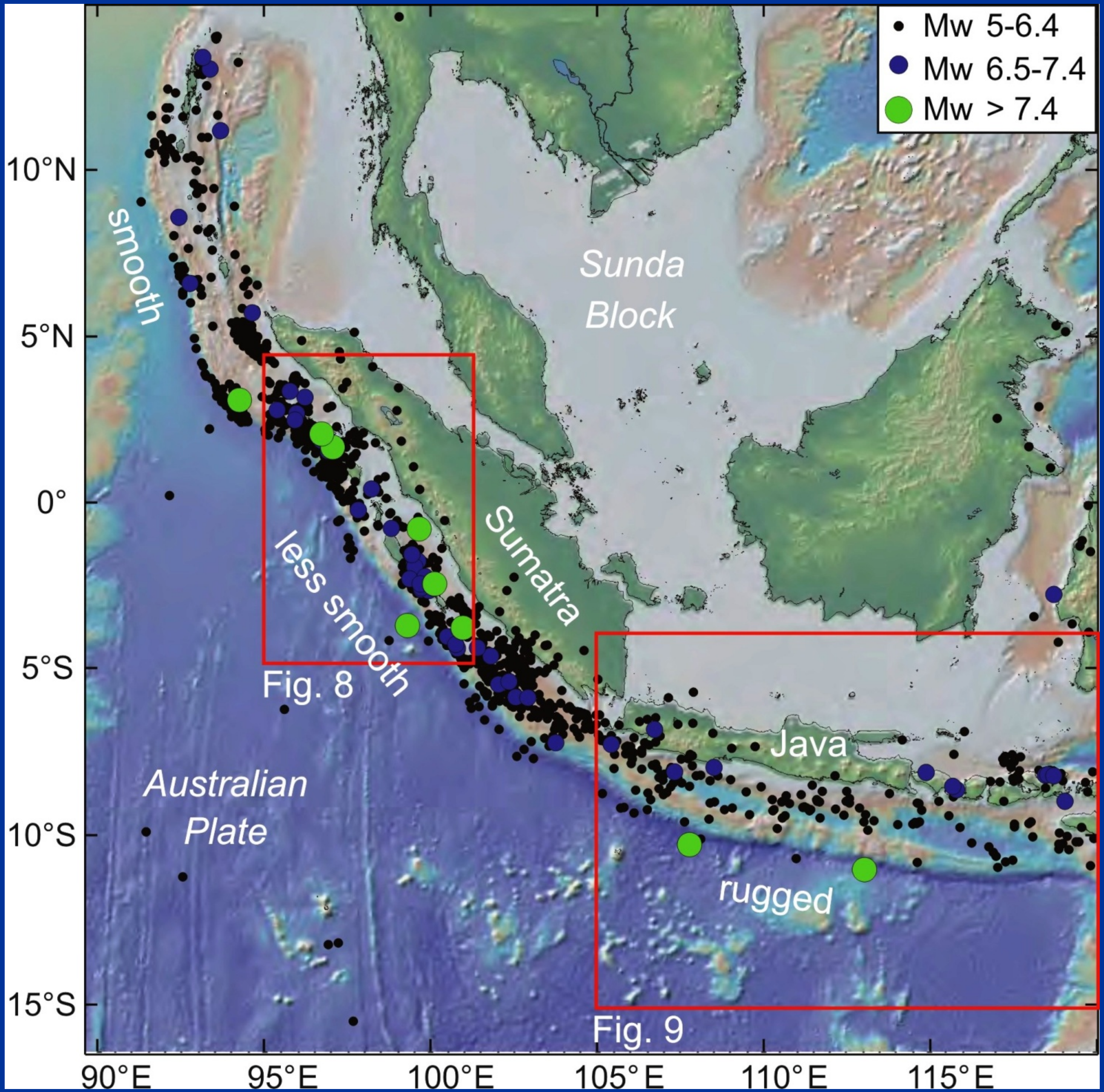
Summary

1. Strength of subduction faults (the “megathrusts”)
   – Very weak, never “strongly coupled”
2. Earthquake rupture and stress drop
   – Faults weaken in earthquakes, but not by much
3. Effect of upper plate stress
   – Results in a very fragile state of stress in the forearc
4. Smooth faults and rough faults
   – Smoother and weaker faults cause great earthquakes
5. Frictional heating of seismogenic and creeping faults
   – Creeping megathrusts often dissipate more heat (stronger)

Sumatra: Creeping Investigator Fracture Zone



Creeping ratio from Chlieh et al. (2008)



Mw 5-6.4
Mw 6.5-7.4
Mw > 7.4
10°N
5°N
0°
5°S
10°S
15°S
90°E
95°E
100°E
105°E
110°E
115°E
smooth
Sunda Block
Sumatra
less smooth
Fig. 8
Java
Australian Plate
rugged
Fig. 9