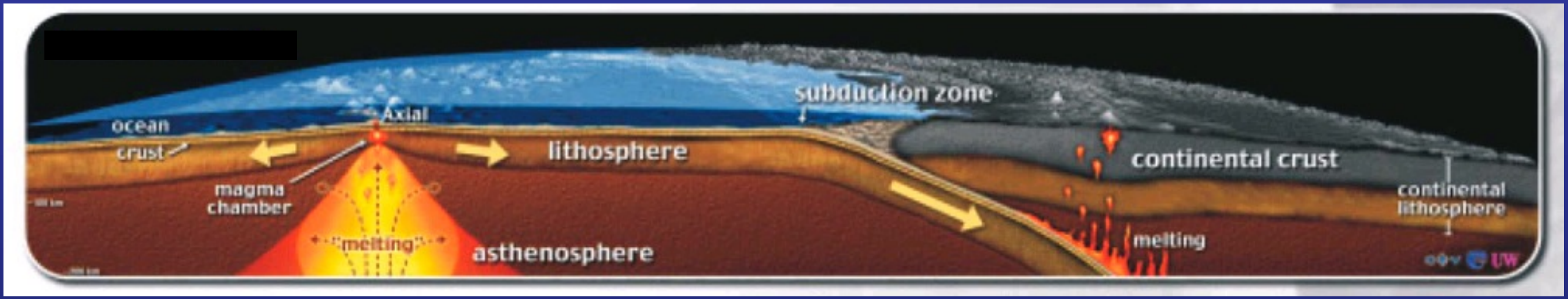
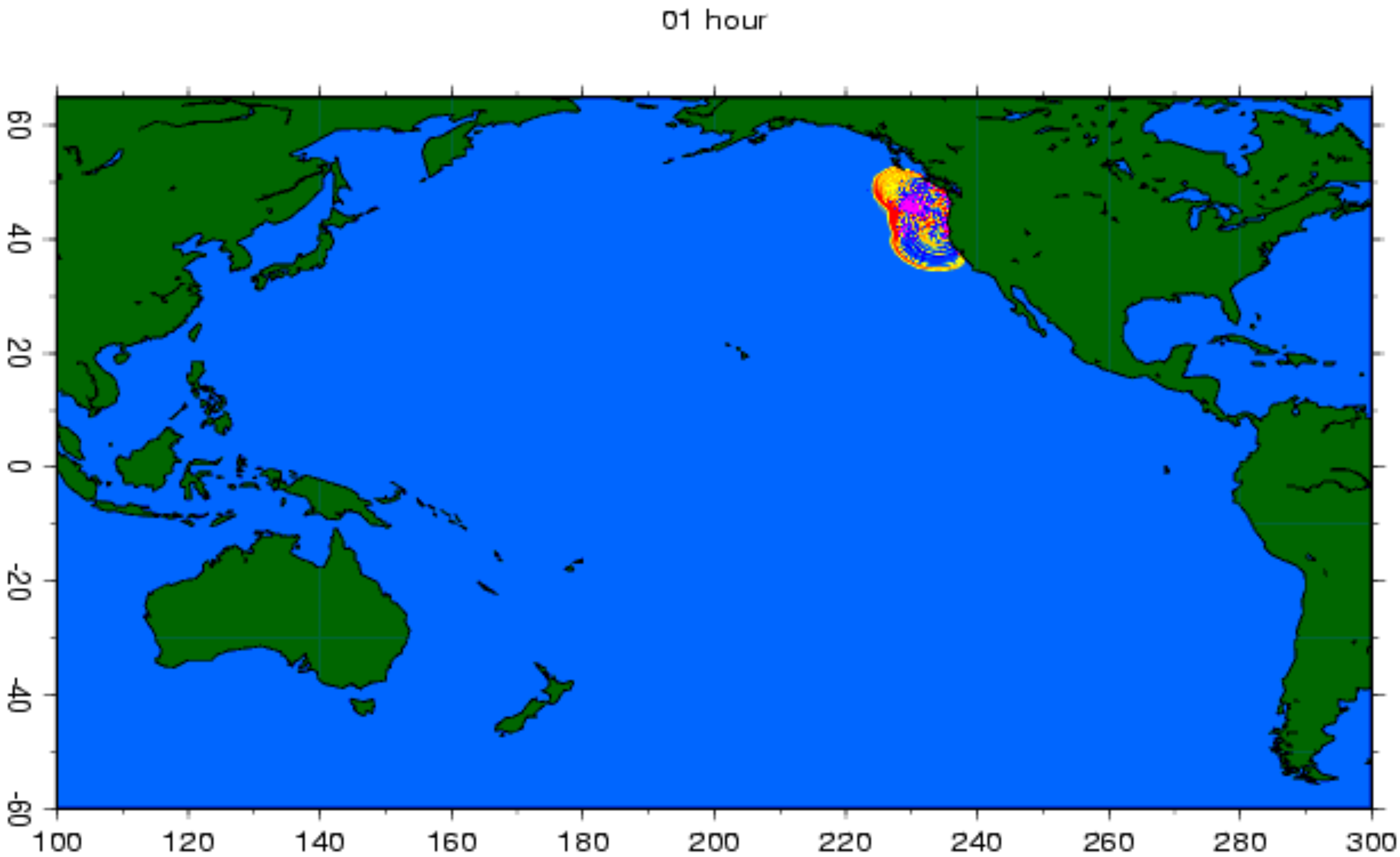
Stress and Strain in Subduction Earthquake "Cycles"

Kelin Wang

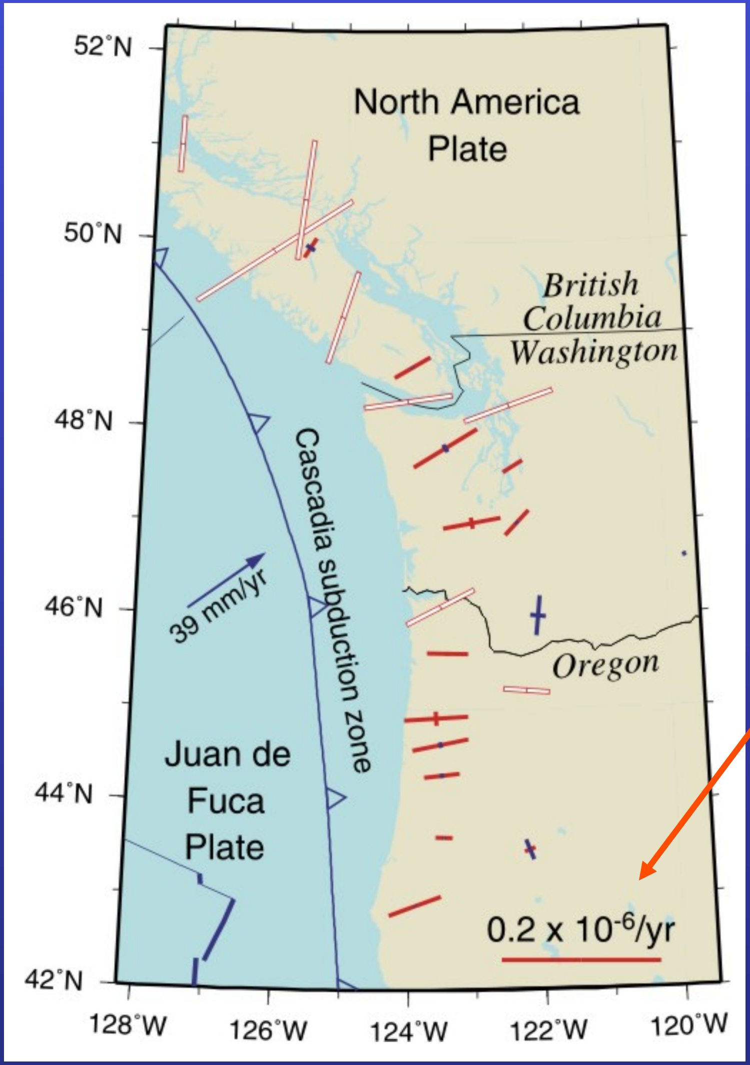
Pacific Geoscience Centre, Geological Survey of Canada

And University of Victoria, Canada



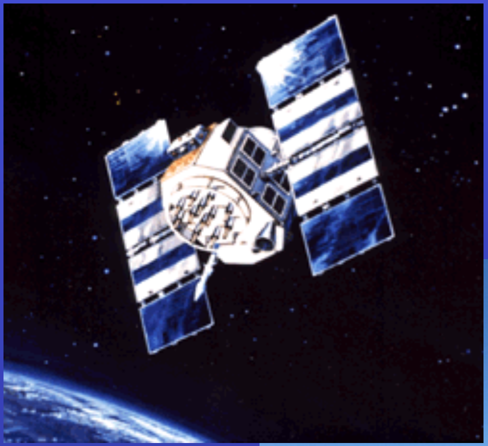


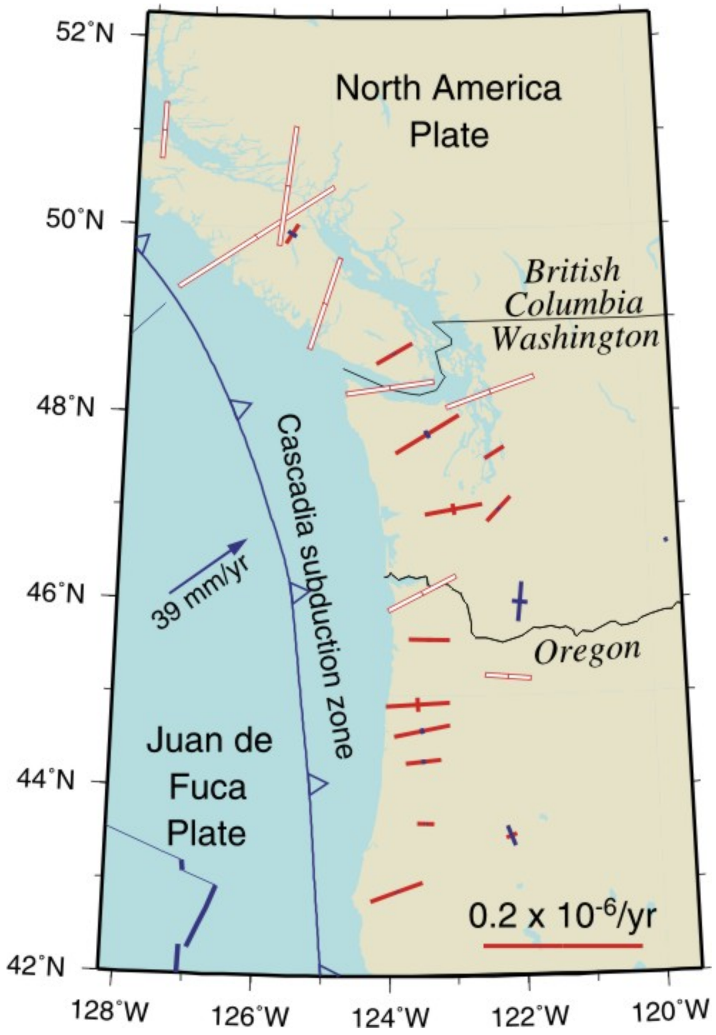
M ~ 9 Cascadia earthquake, Jan. 26, 1700 (Satake et al. 2003, JGR)



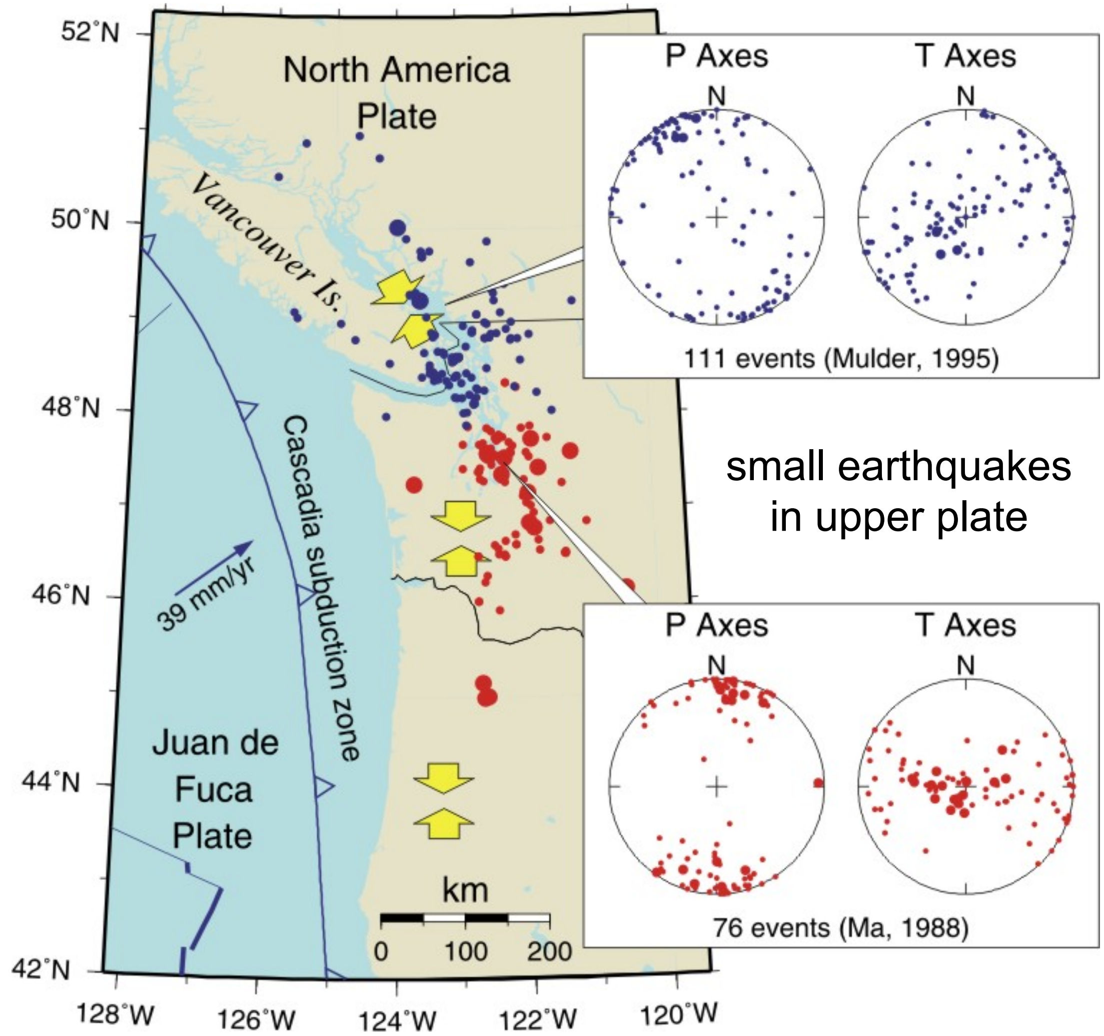
Geodetic Strain Rates

A 100-km line becomes shorter by 2 cm each year



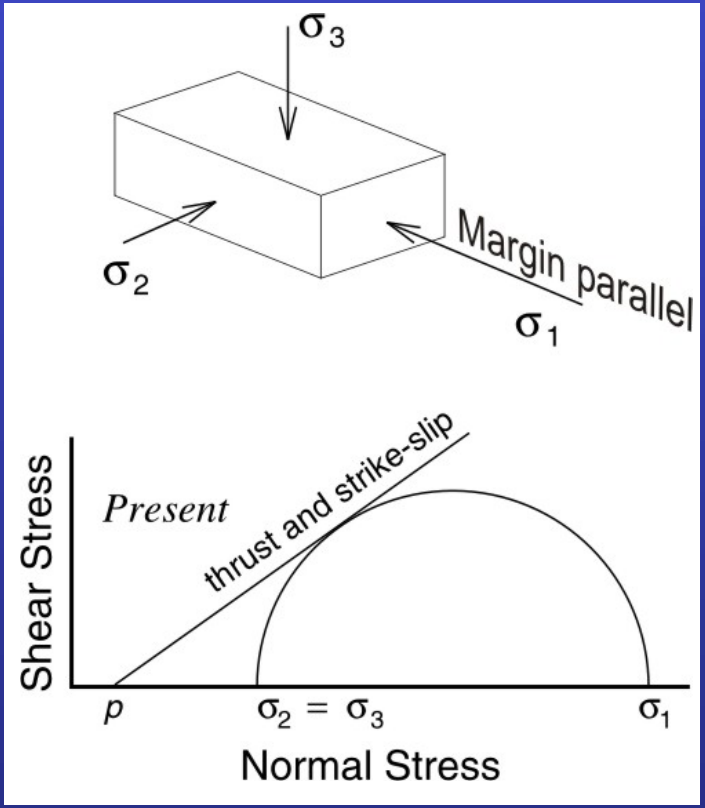


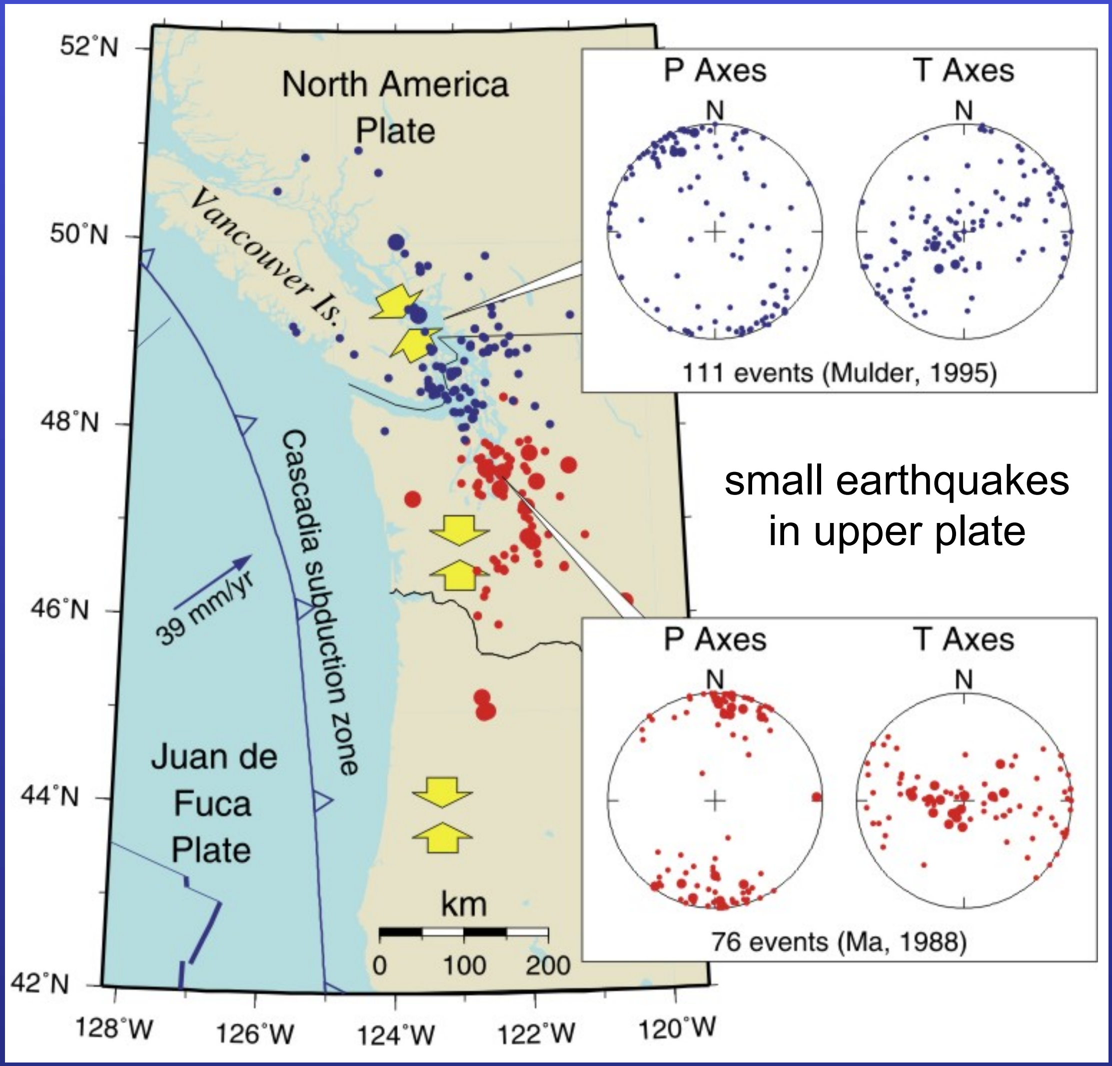
Geodetic Strain Rates



Forearc Stresses

Summary of Stresses

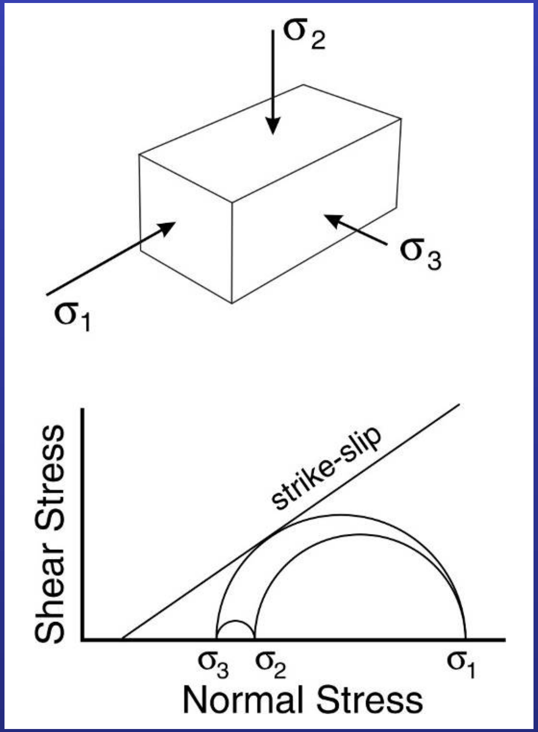


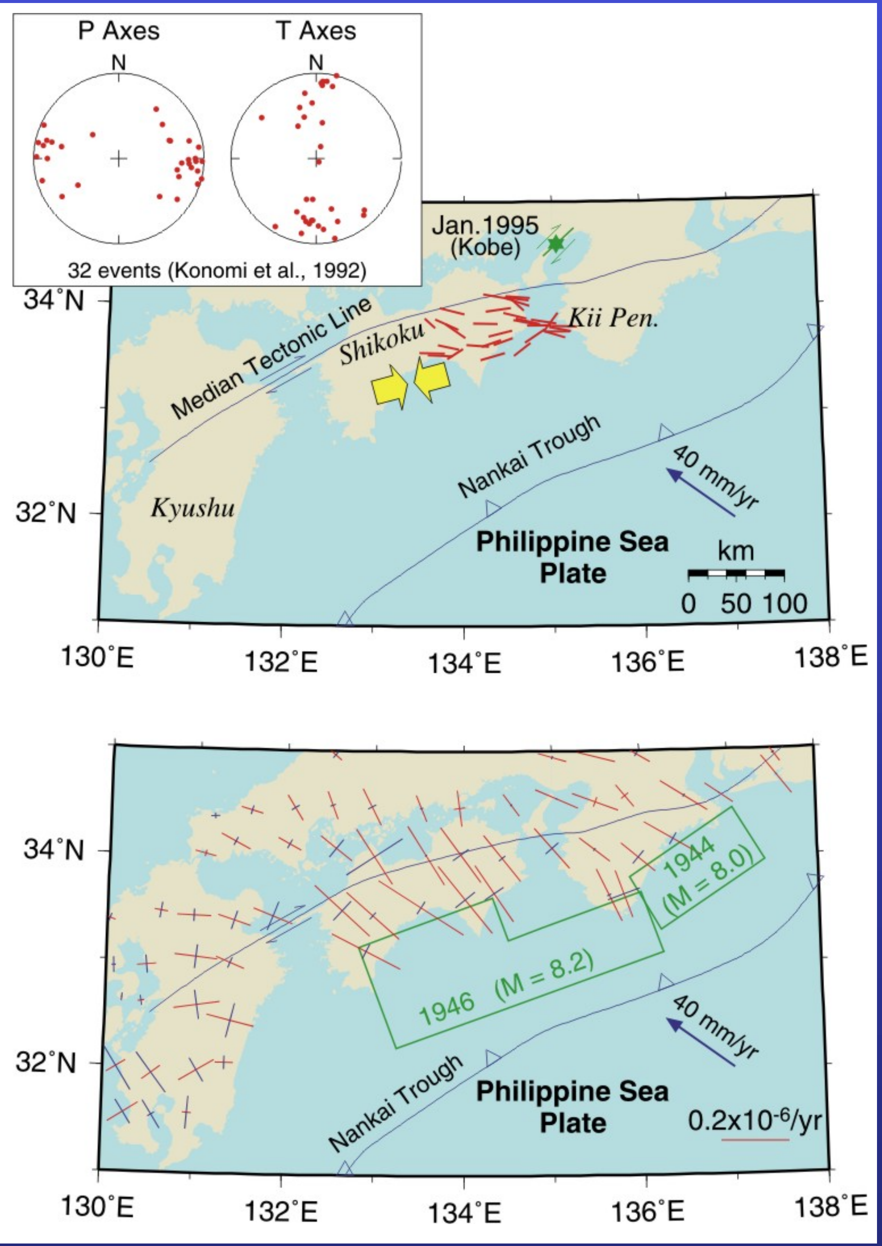


Forearc Stresses

Nankai Forearc

Stresses and geodetic strain rates are similar to Cascadia





1. Why is margin-parallel compression large?
   - Local tectonic environment

2. Why is margin-normal stress small?
   - Fundamental process

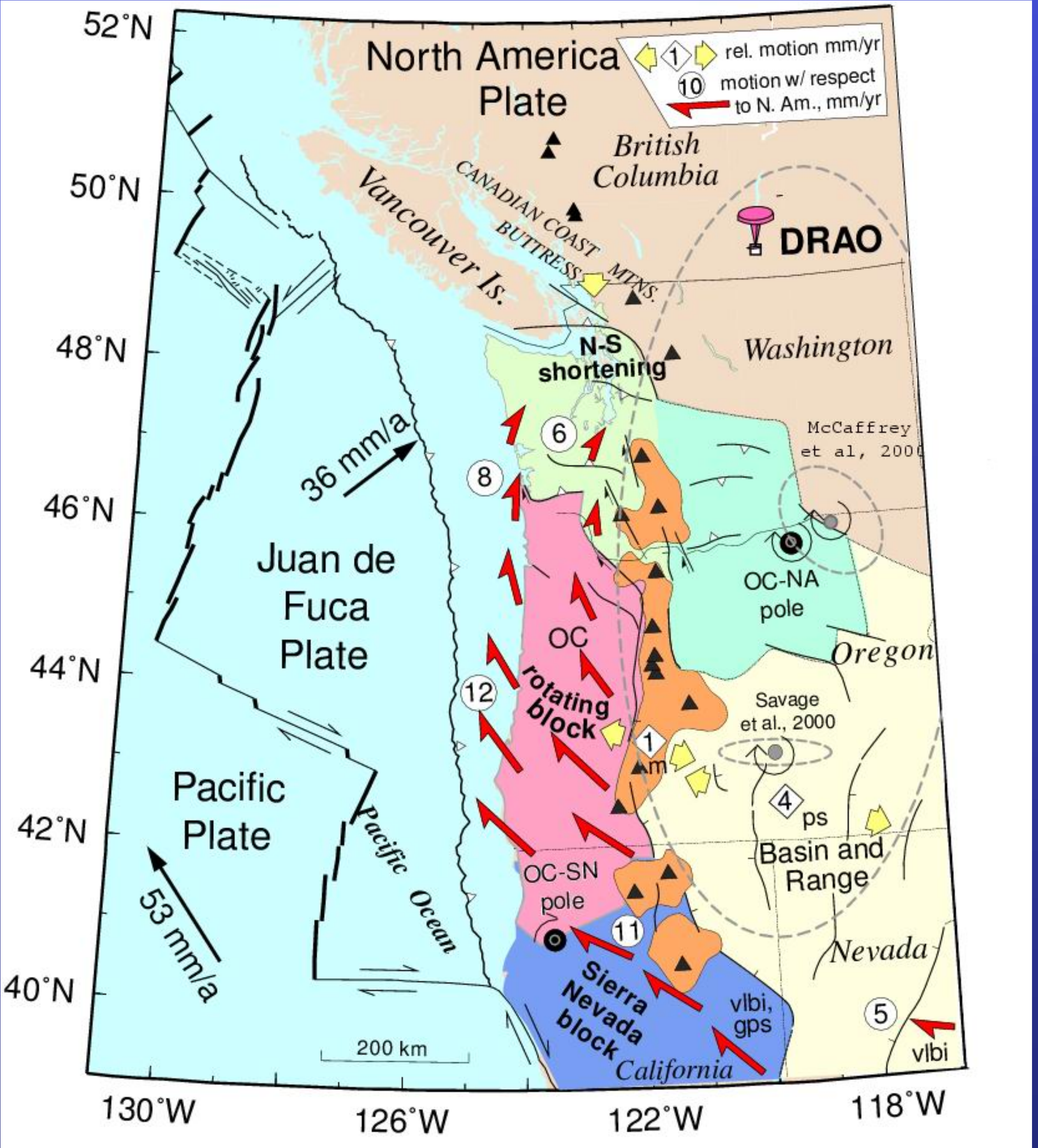
3. Why is geodetic contraction margin-normal?
   - Interseismic deformation

1. Why is margin-parallel stress large?

Secular motion of Cascadia forearc (*Modified from Wells & Simpson, 2001*).

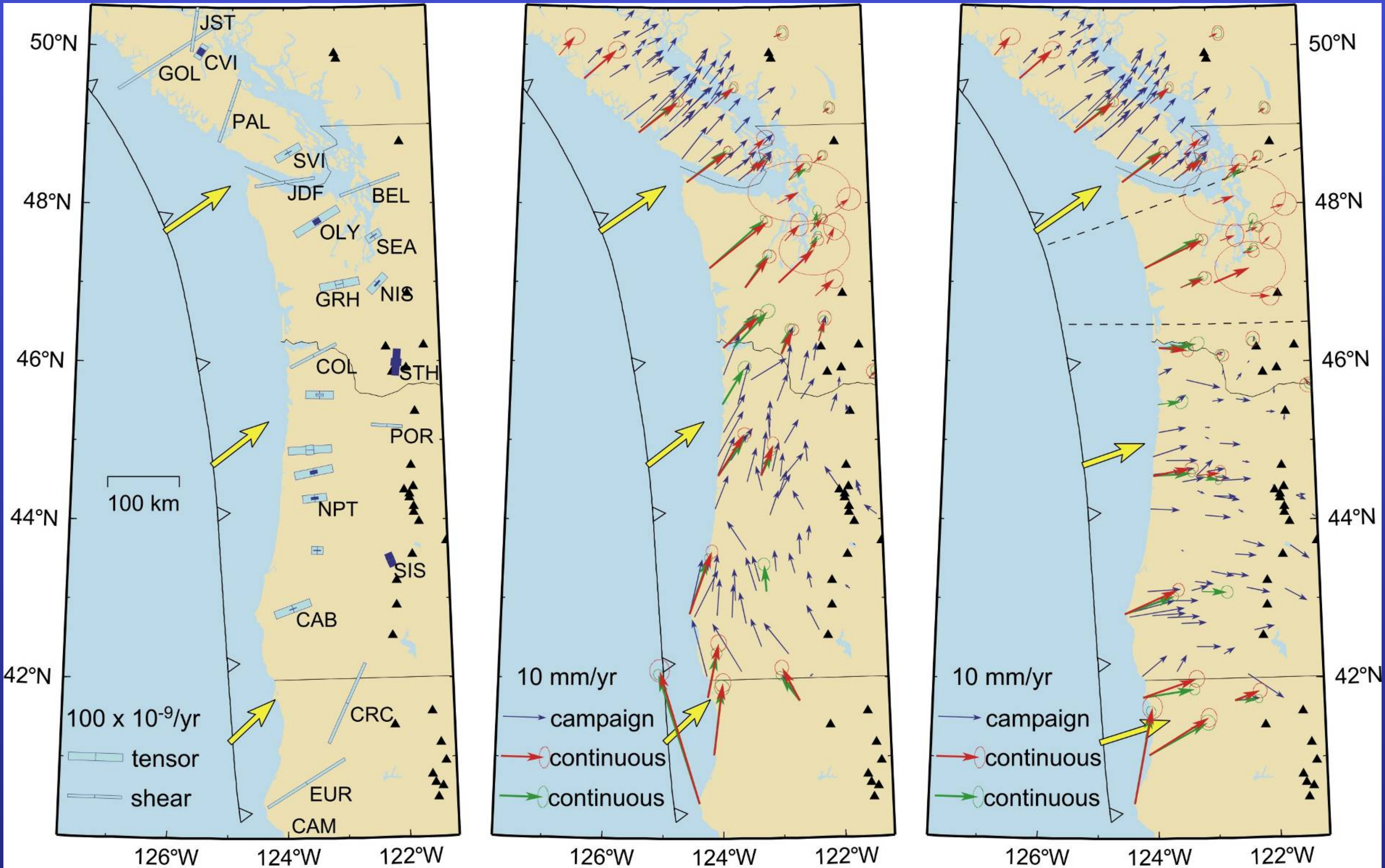
Assumed to be steady state.

To be subtracted from interseismic observations and model.

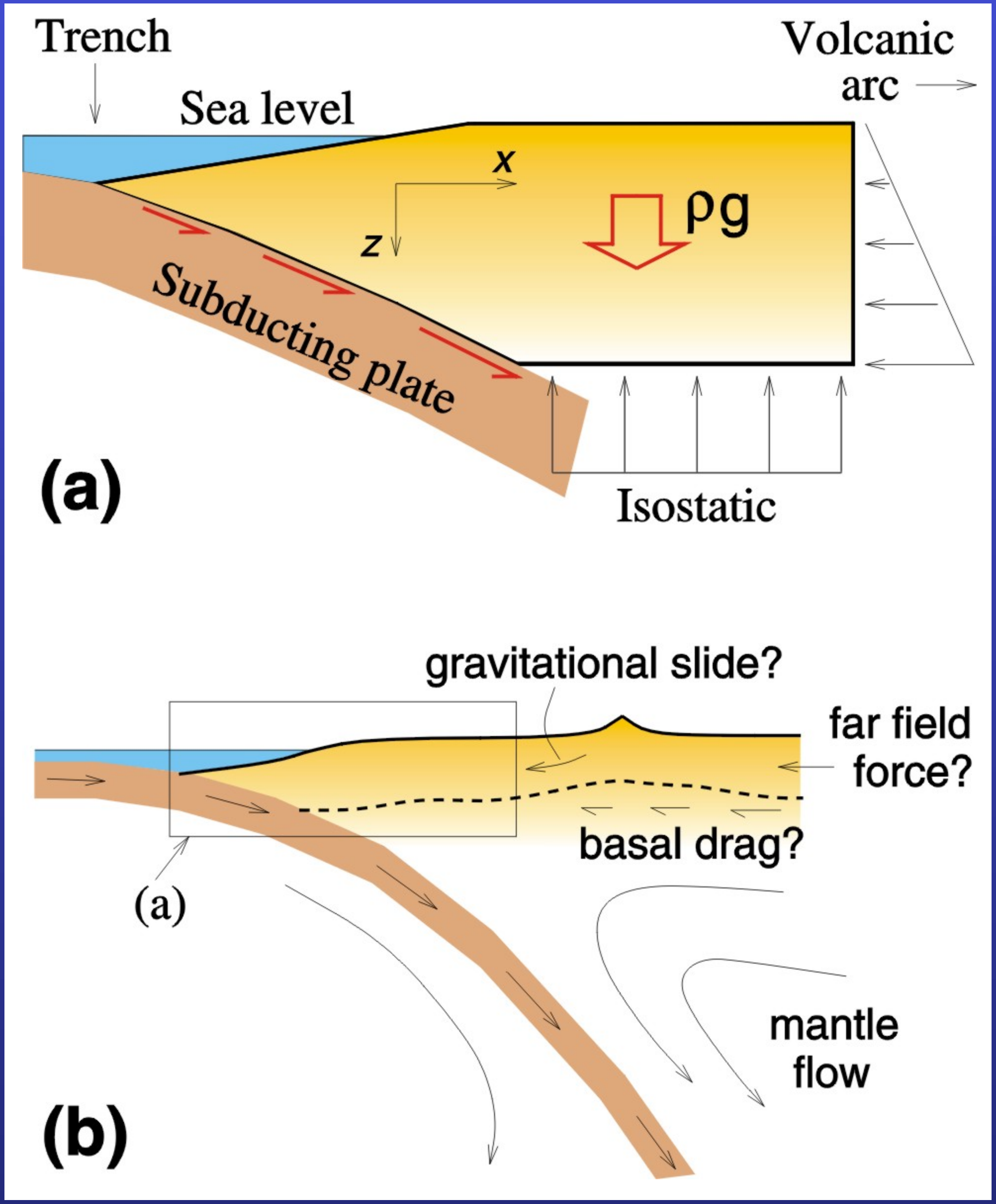


modified from Wells and Simpson, 2001

The Cascadia Subduction Zone



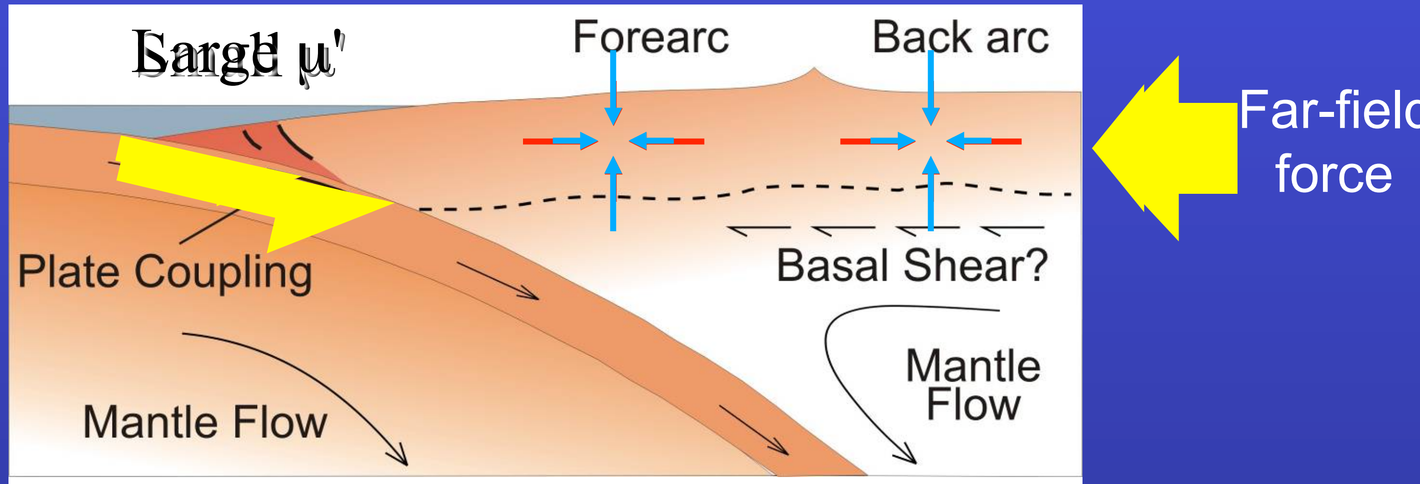
(a) Strain Rates (b) GPS Velocities (c) Corrected Velocities



2. Why is margin-normal stress small?

Margin-normal stress in forearc is controlled by two competing factors:

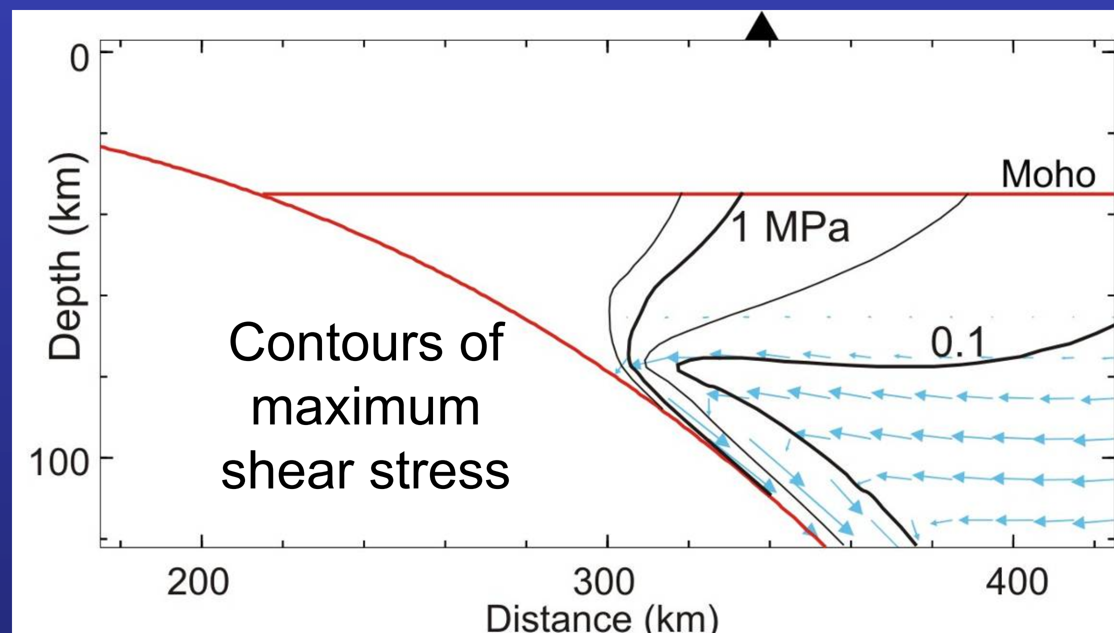
- Gravity induces horizontal tension
- Plate coupling causes compression



Fault strength:

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

Mantle wedge rheology:
Dislocation creep



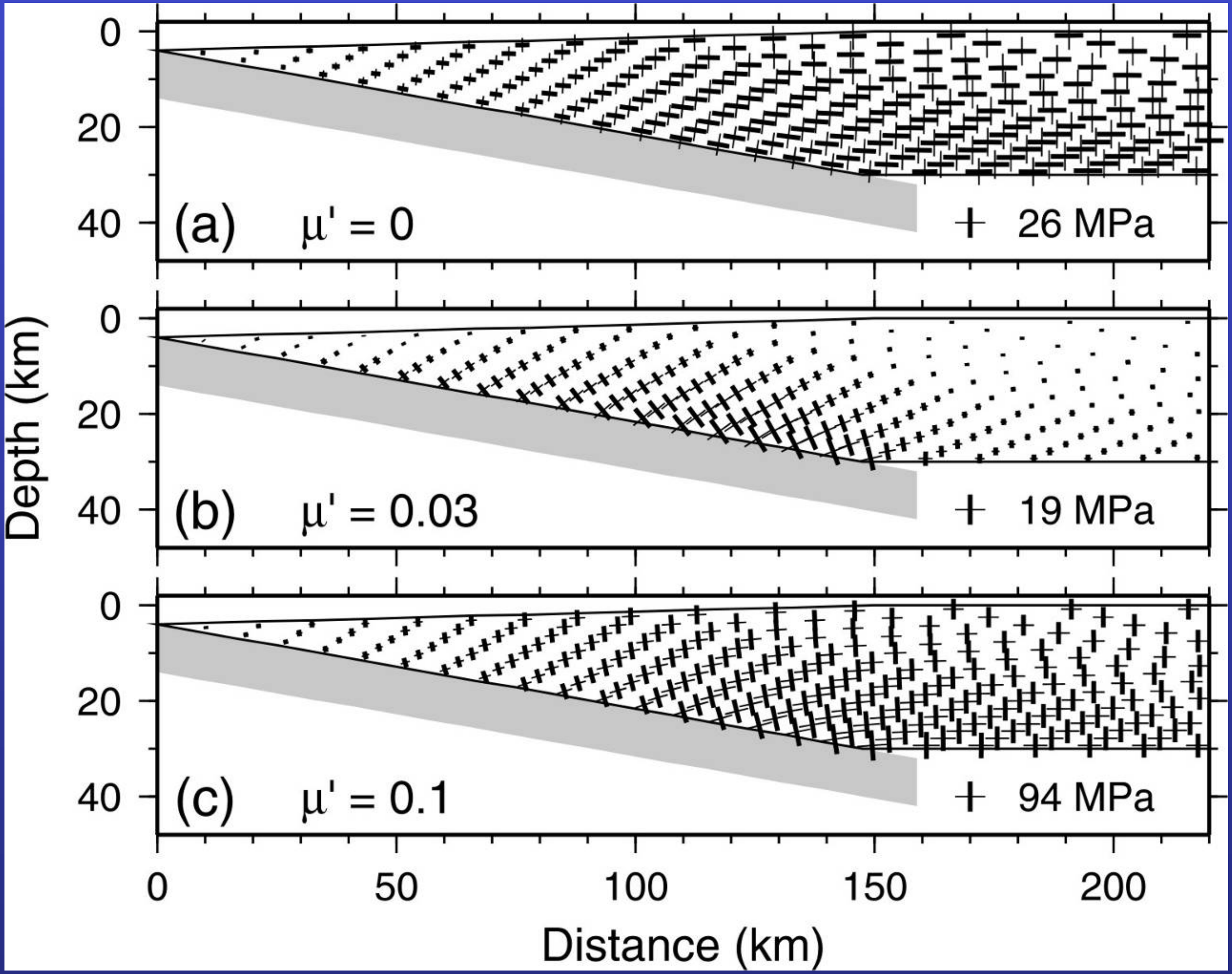
Model by Ikuko Wada

Two converging elastic plates in frictional contact $\tau = \mu' \sigma$

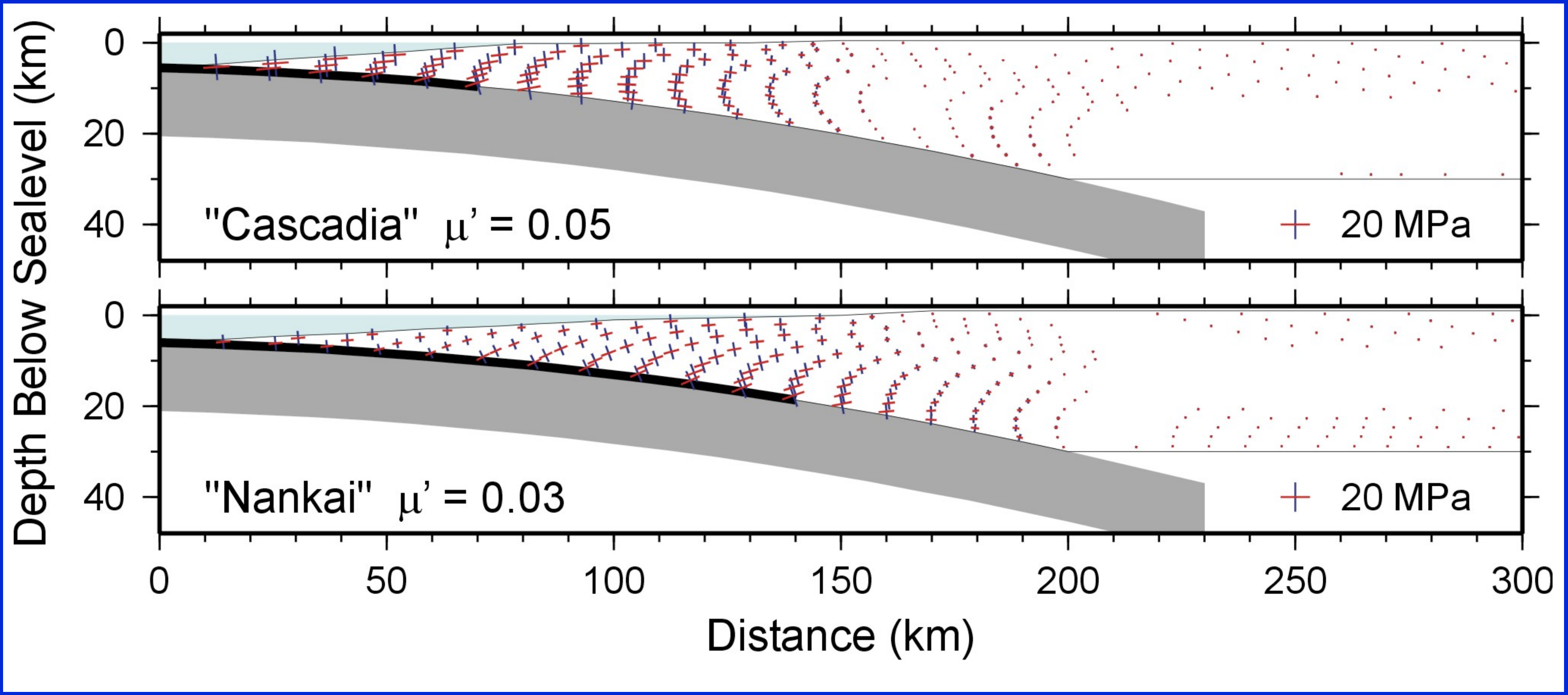
Non-lithostatic stress symbols:

Thin – compression
Thick – tension

(Finite element with Lagrange-multiplier domain decomposition)



Wang and He (1999 JGR)



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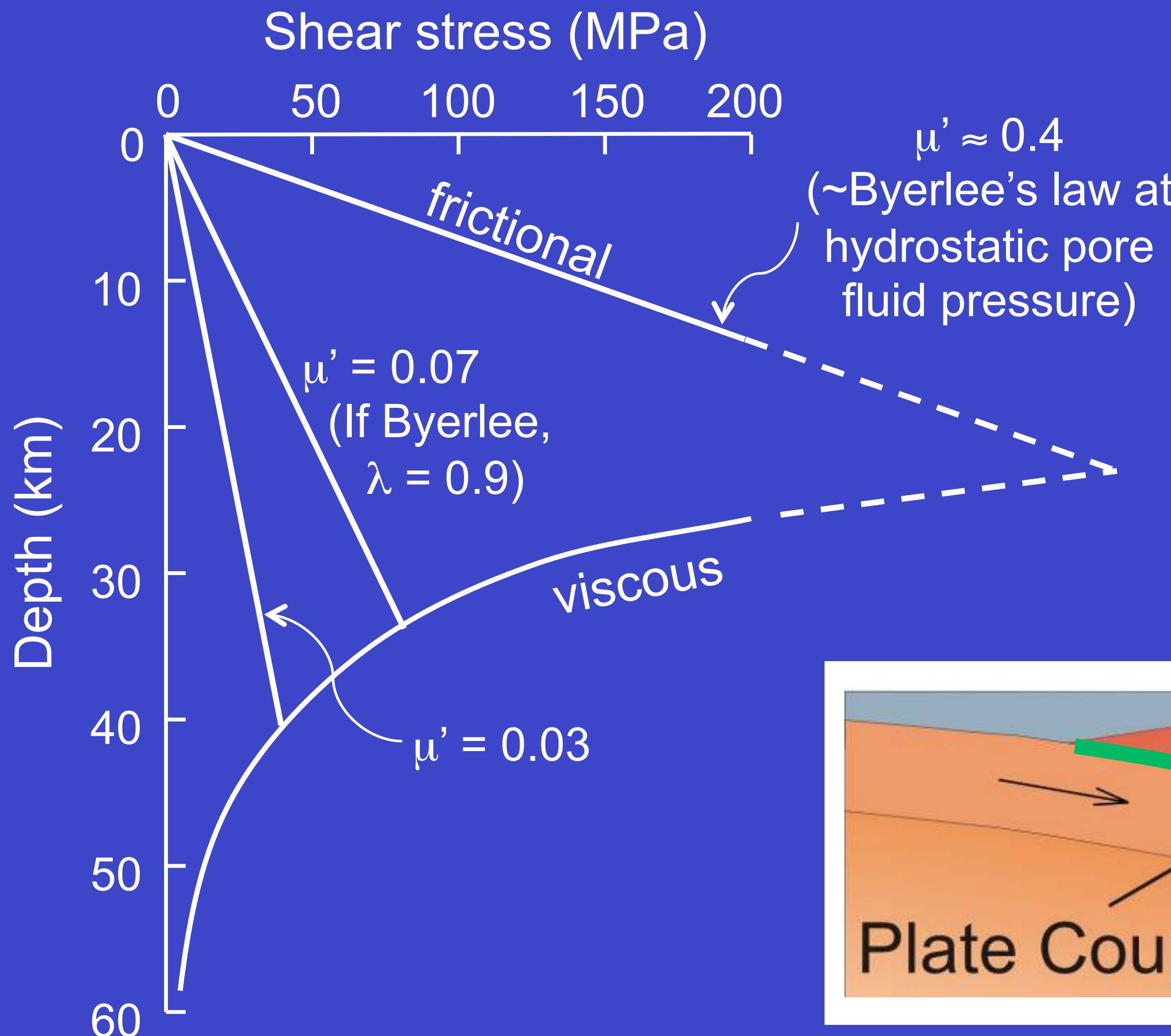
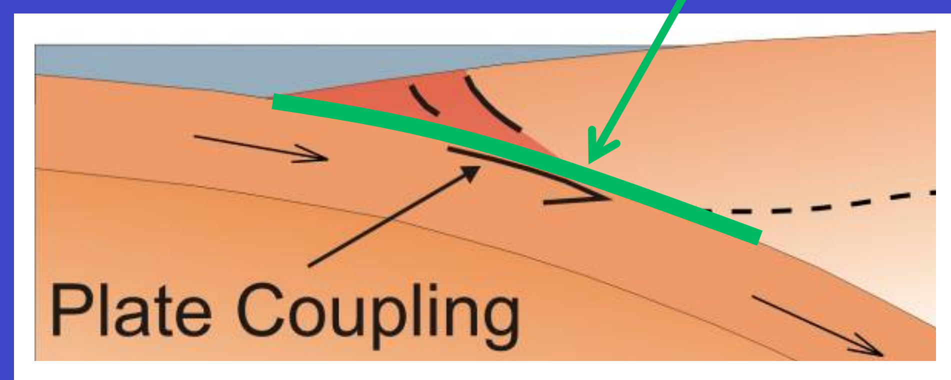
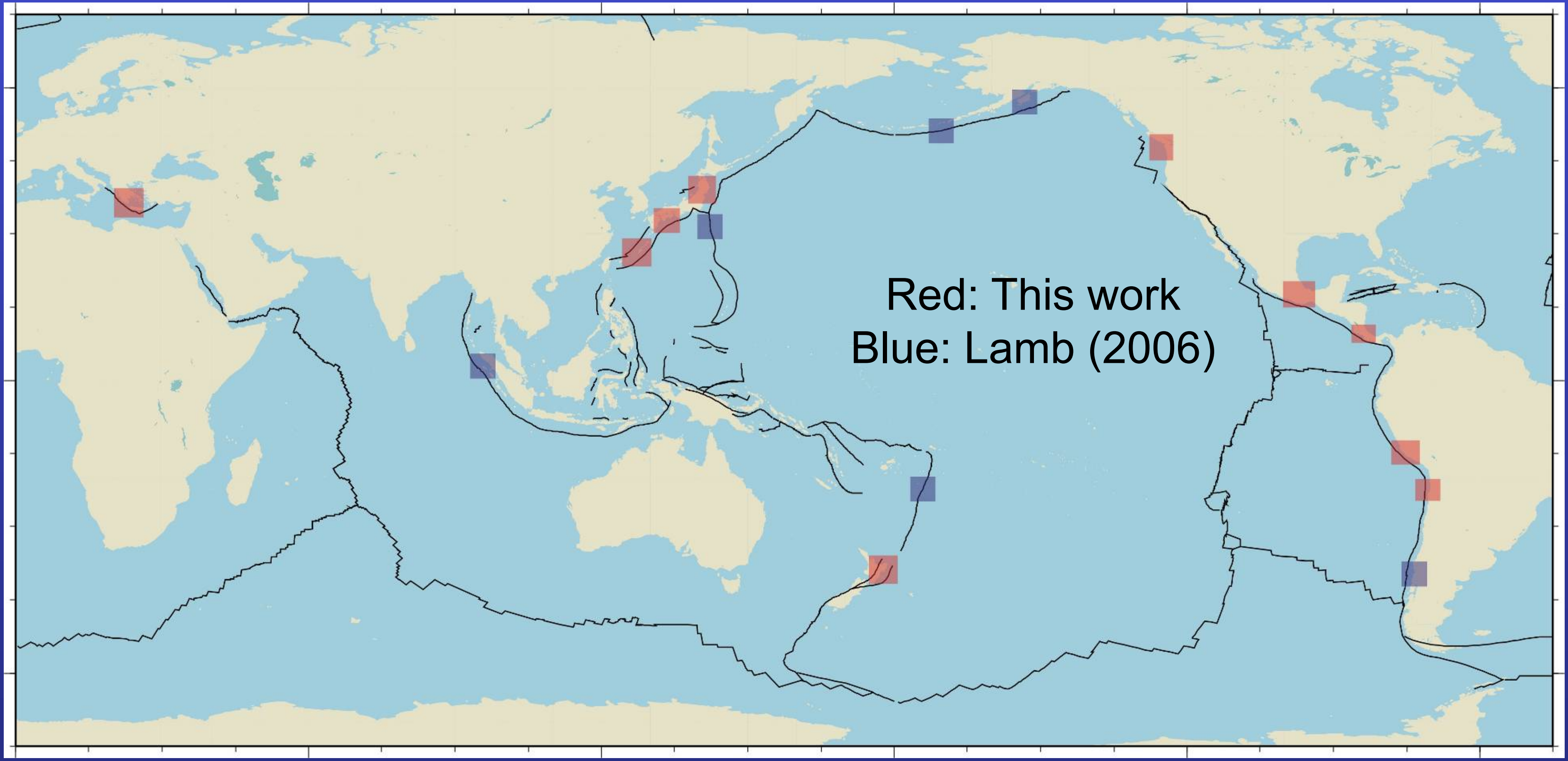


Frictional strength:

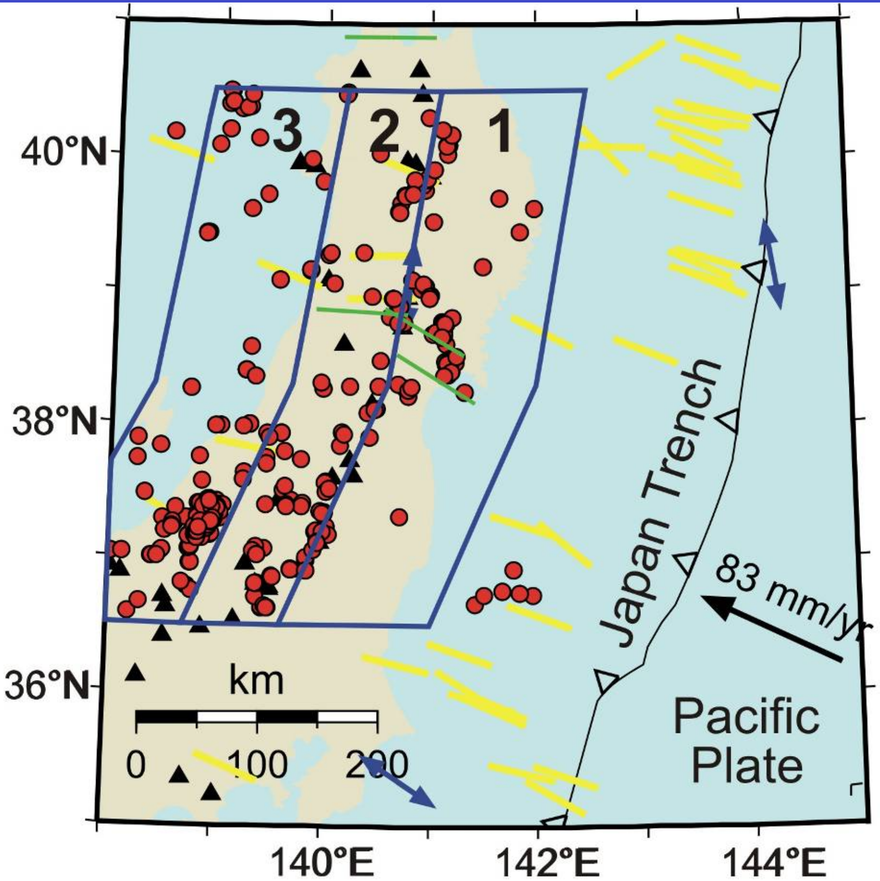
$$
\begin{aligned}
\tau &= \mu\,(\sigma_n - p) \\
&= \mu\,(1 - p/\sigma_n)\sigma_n \\
&\approx \mu\,(1 - p/\rho g h)\sigma_n \\
&= \mu\,(1 - \lambda)\sigma_n \\
&= \mu'\sigma_n
\end{aligned}
$$

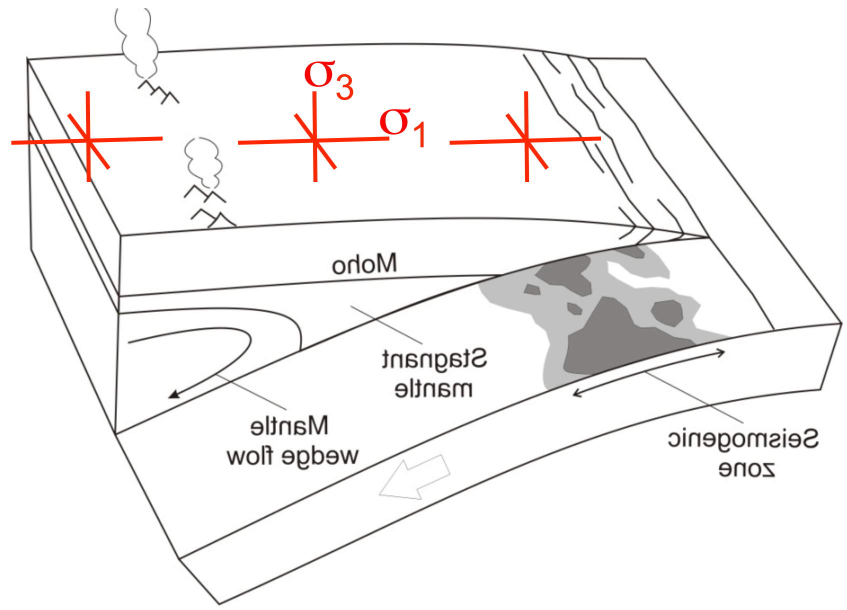


$\mu' = 0.03 - 0.06$ for most subduction zones studied



Northeast Japan before 2011 Tohoku earthquake





Shortening directions of active faults (Sato, 1984)

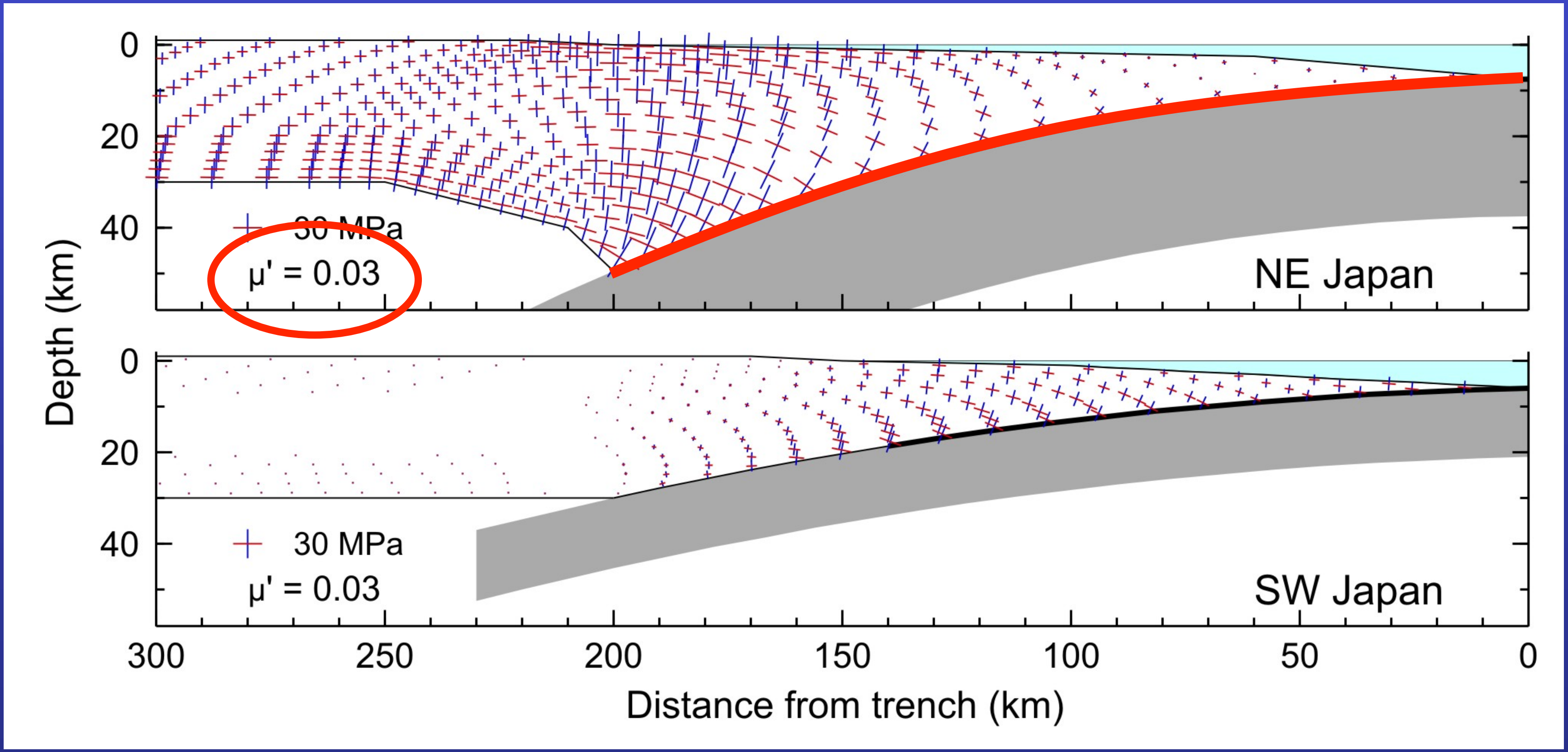
P axes

T axes

(World Stress Map)

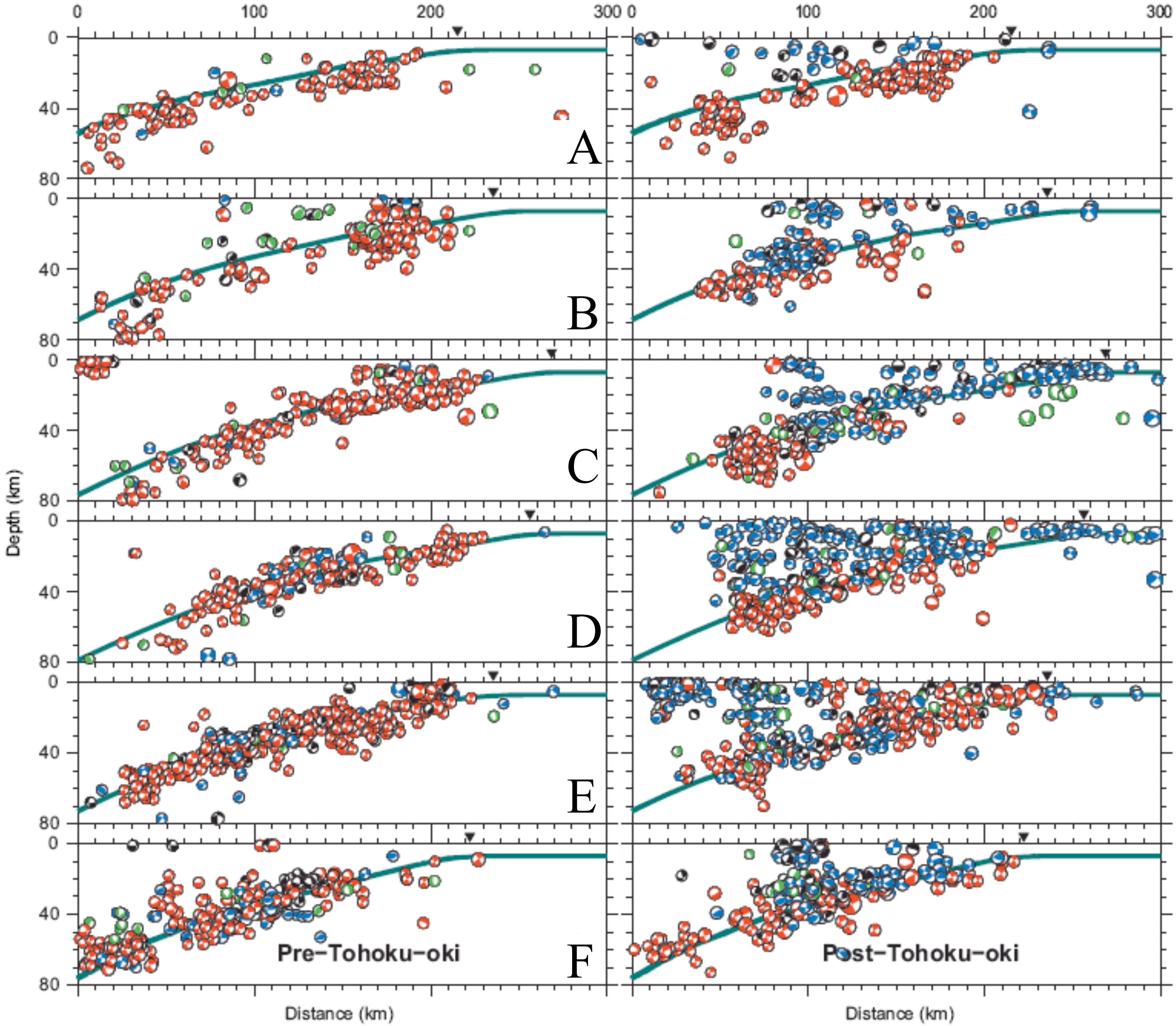
Focal mechanism solutions are from NIED and Kosuga (1999)

Deviatoric stress (red is compressive)



Wang and Suyehiro, 1999 GRL

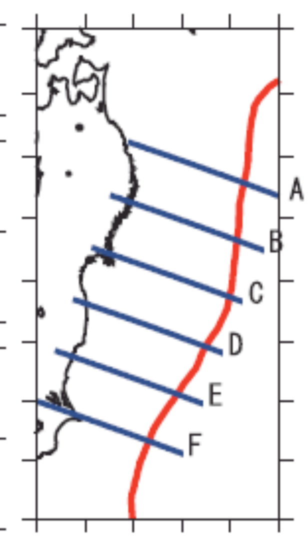
before after



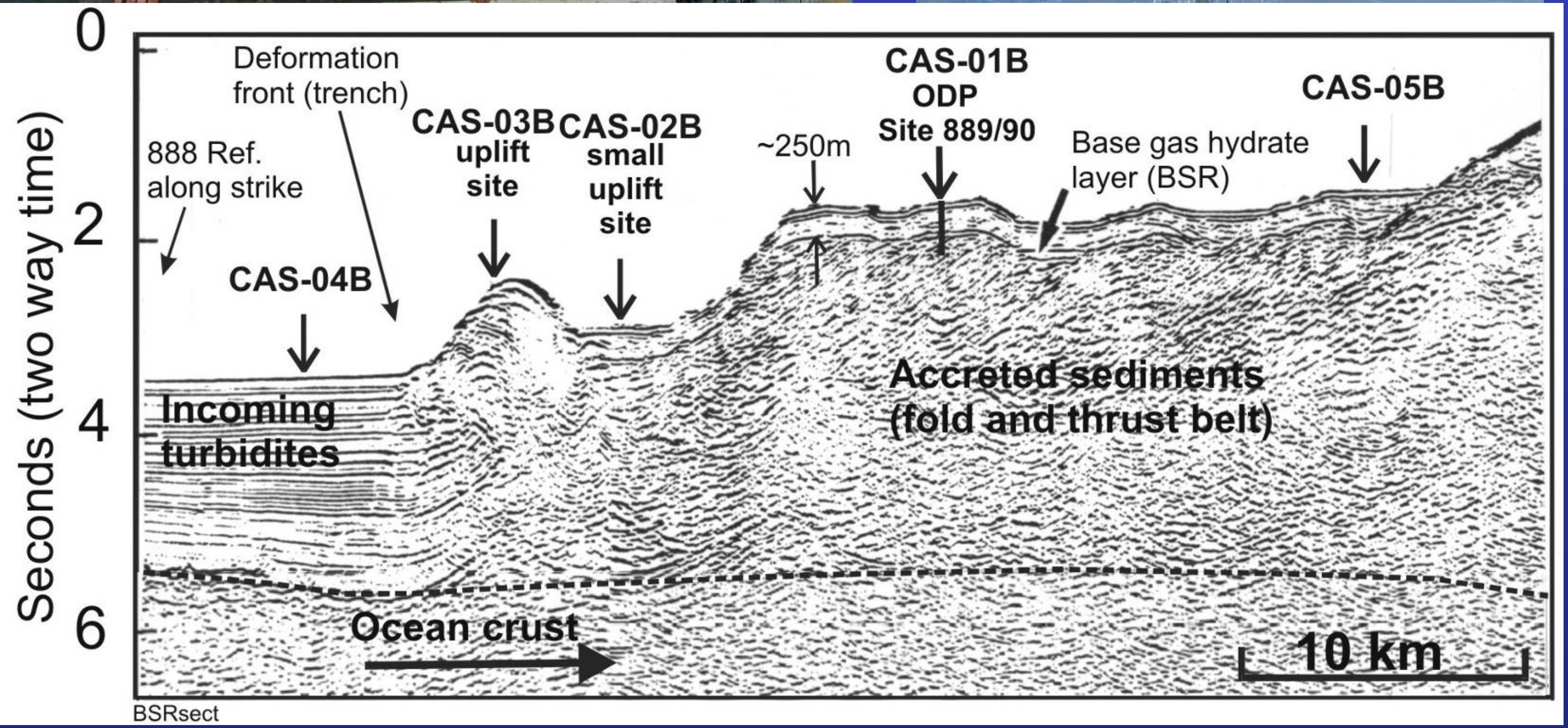
Hasegawa et al. (2012 EPSL)

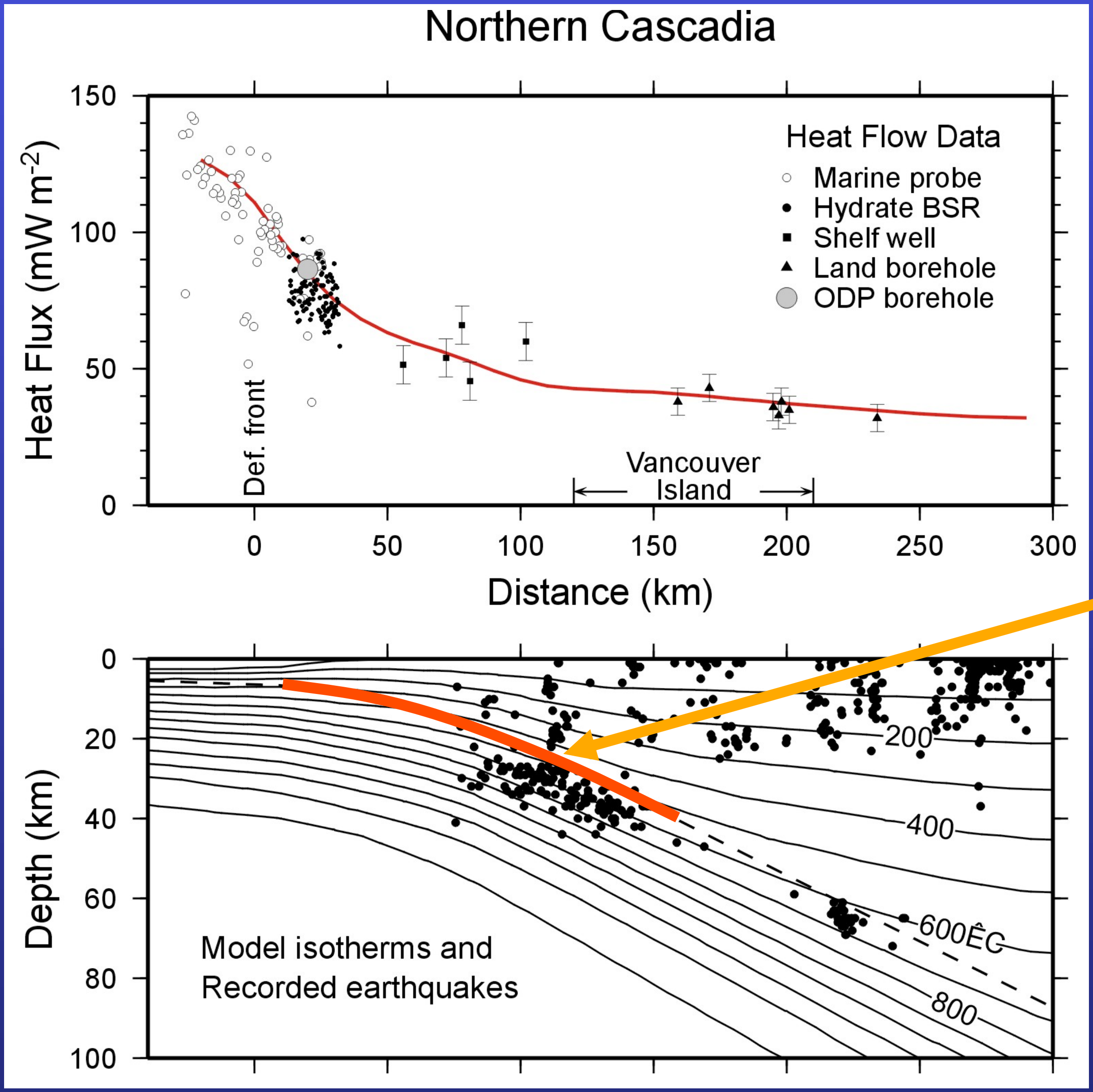
Blue: normal faulting

Red: thrust faulting

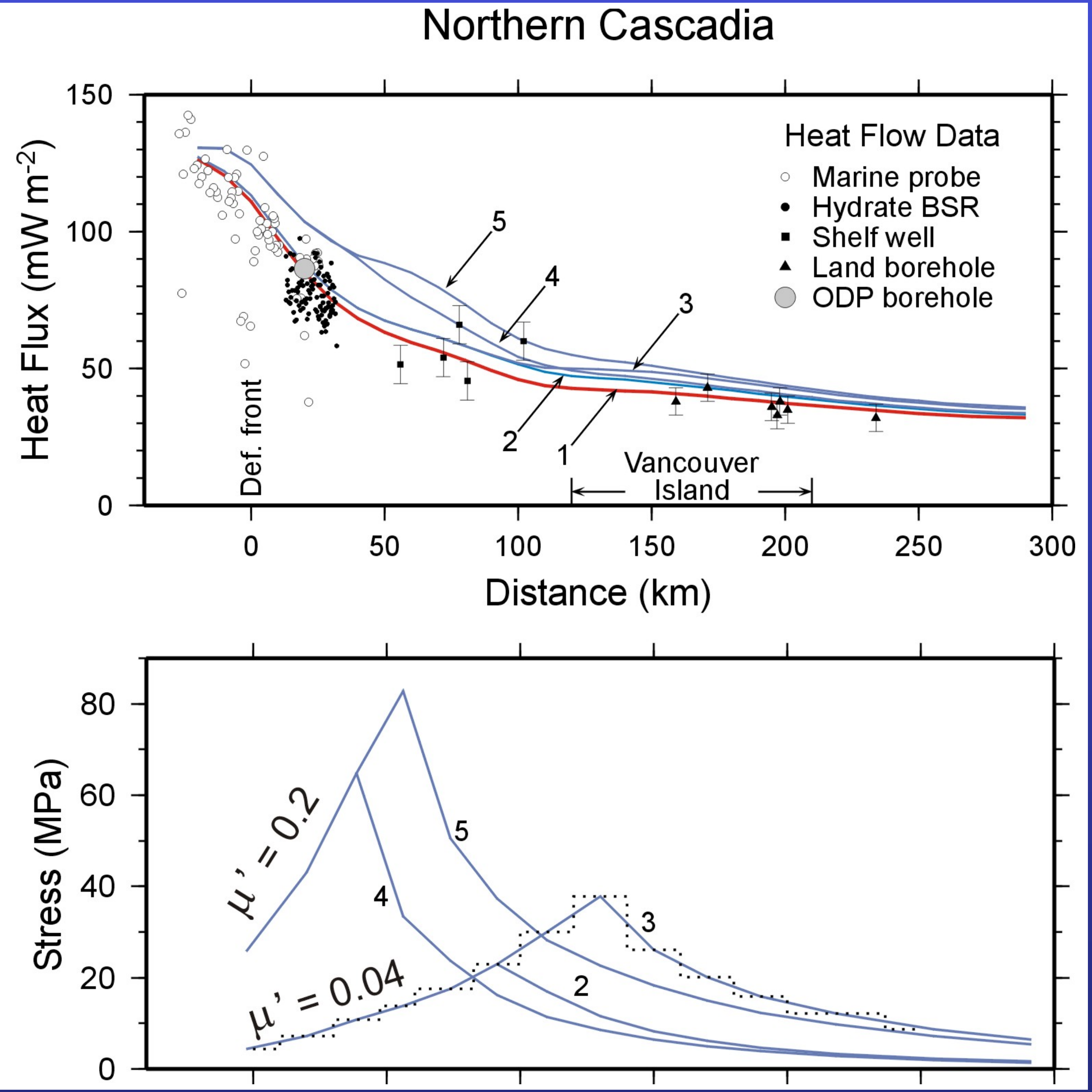


Heat Flow Measurements

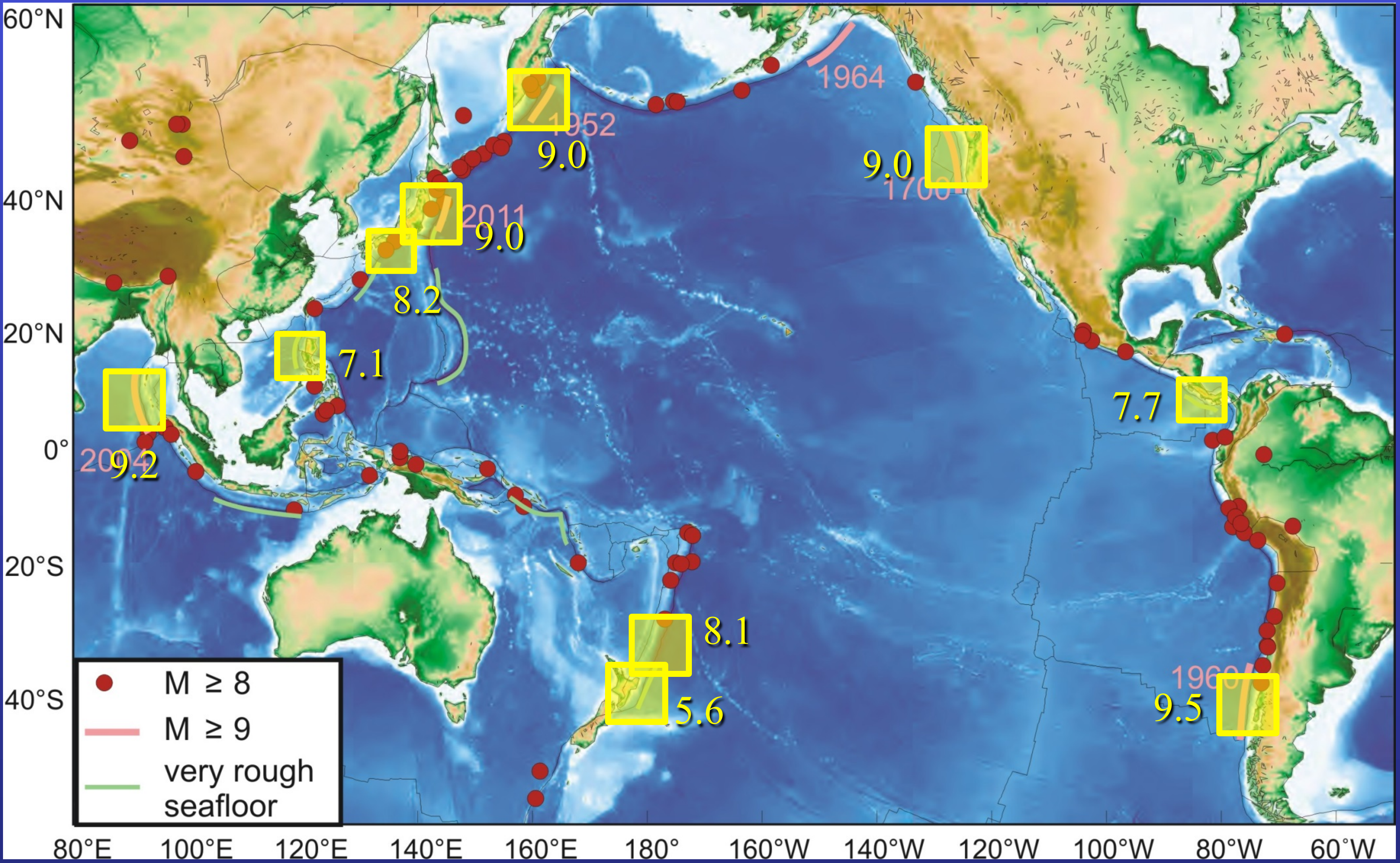




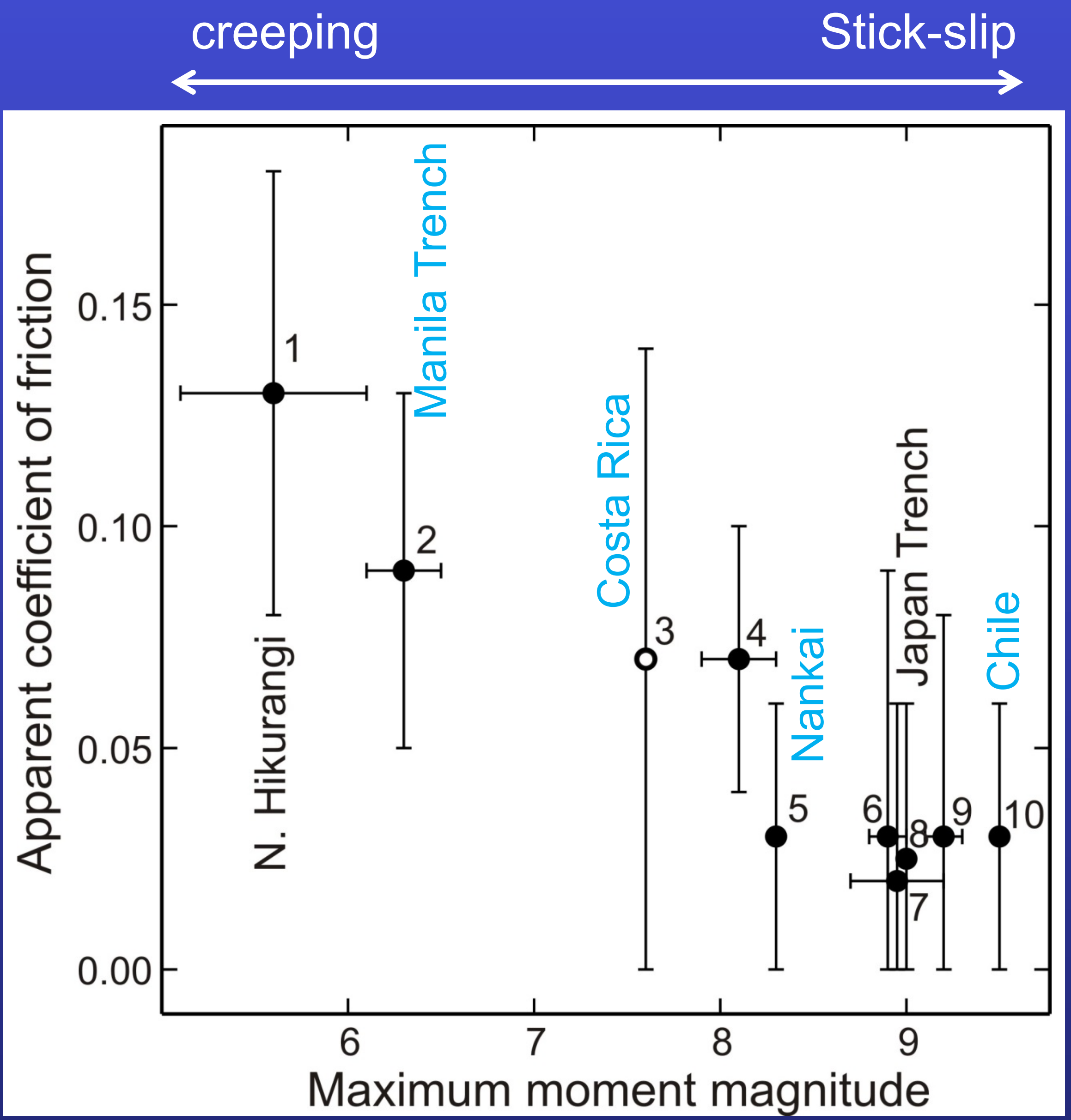
Frictional
Heating
=
Shear stress
times
Slip rate



Northern Cascadia
Heat Flux (mW m-2)
Heat Flow Data
Marine probe
Hydrate BSR
Shelf well
Land borehole
ODP borehole
Def. front
Vancouver Island
Distance (km)
Stress (MPa)
μ' = 0.2
μ' = 0.04

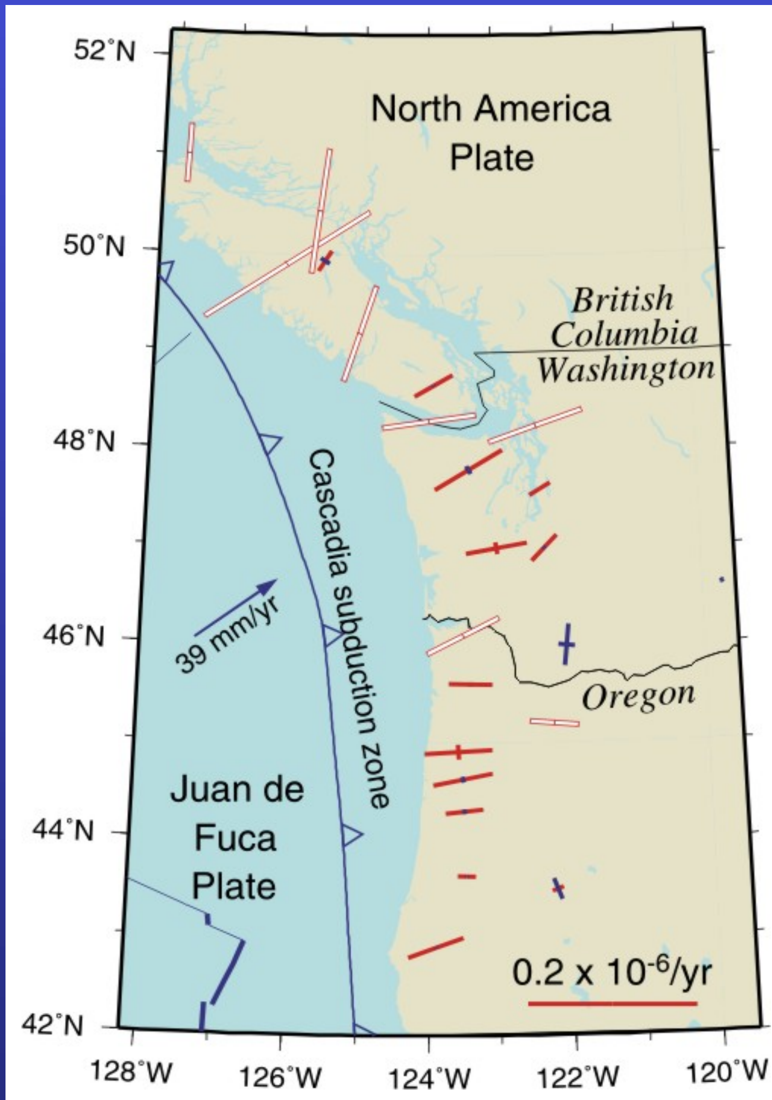


Subduction zones with adequate heat flow data to constrain frictional heating



Gao and Wang, 2014 Science

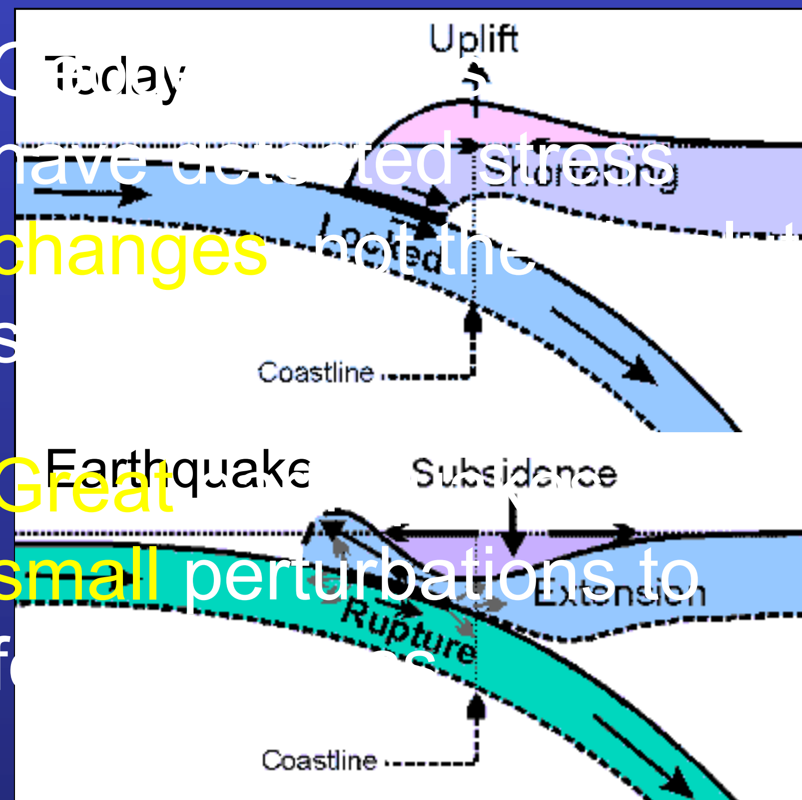
3. Why is geodetic contraction margin-normal?



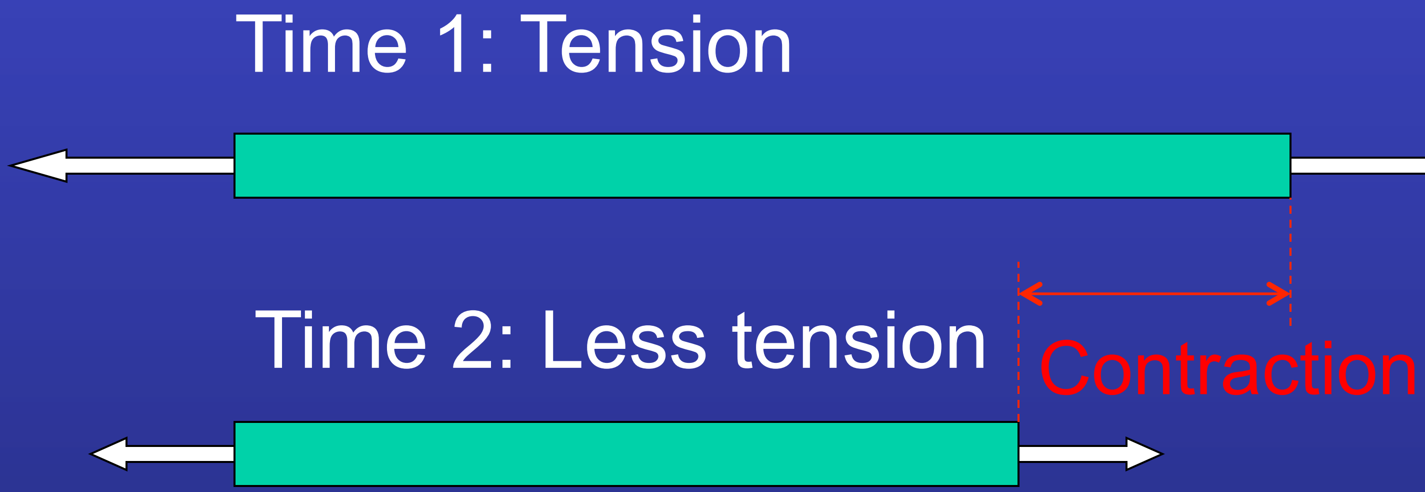
Geodetic Strain Rates

have detected stress changes, not the

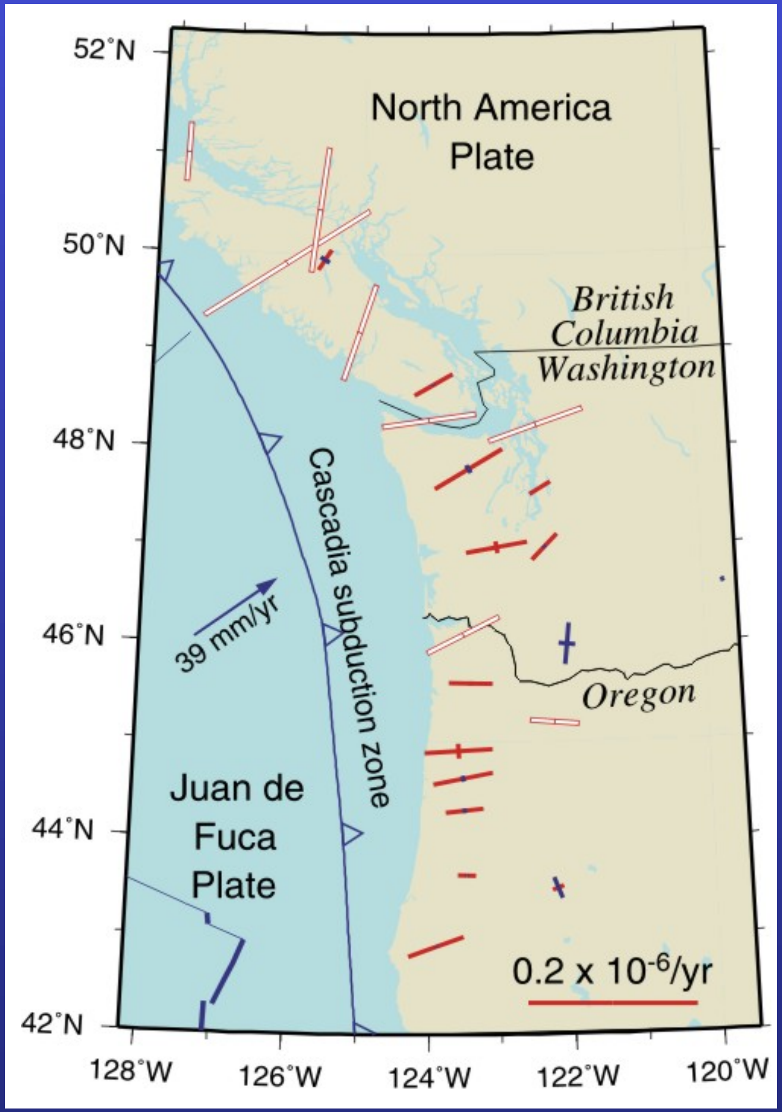
Great small perturbations to



A Stretched Elastic Band



3. Why is geodetic contraction margin-normal?

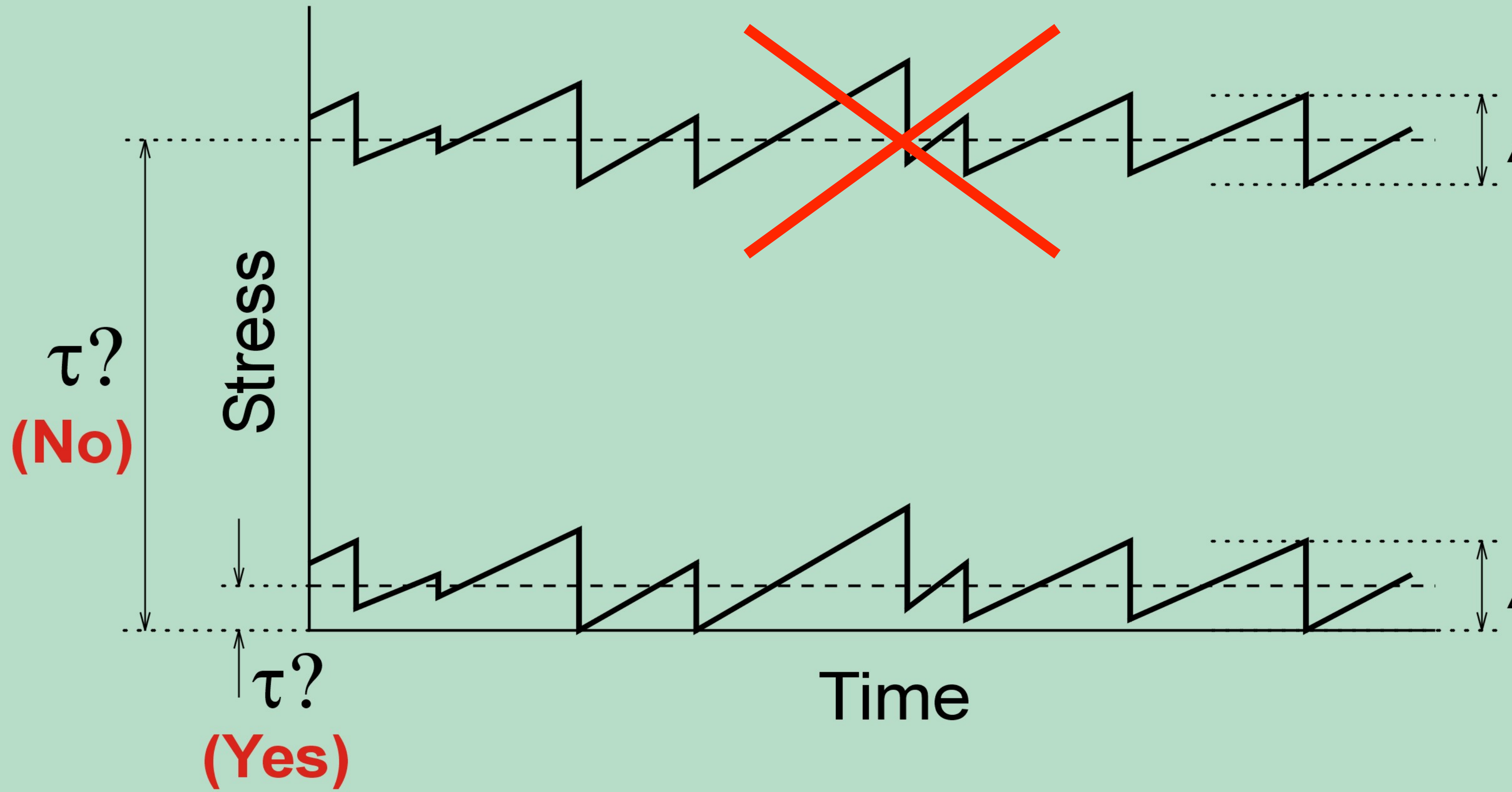


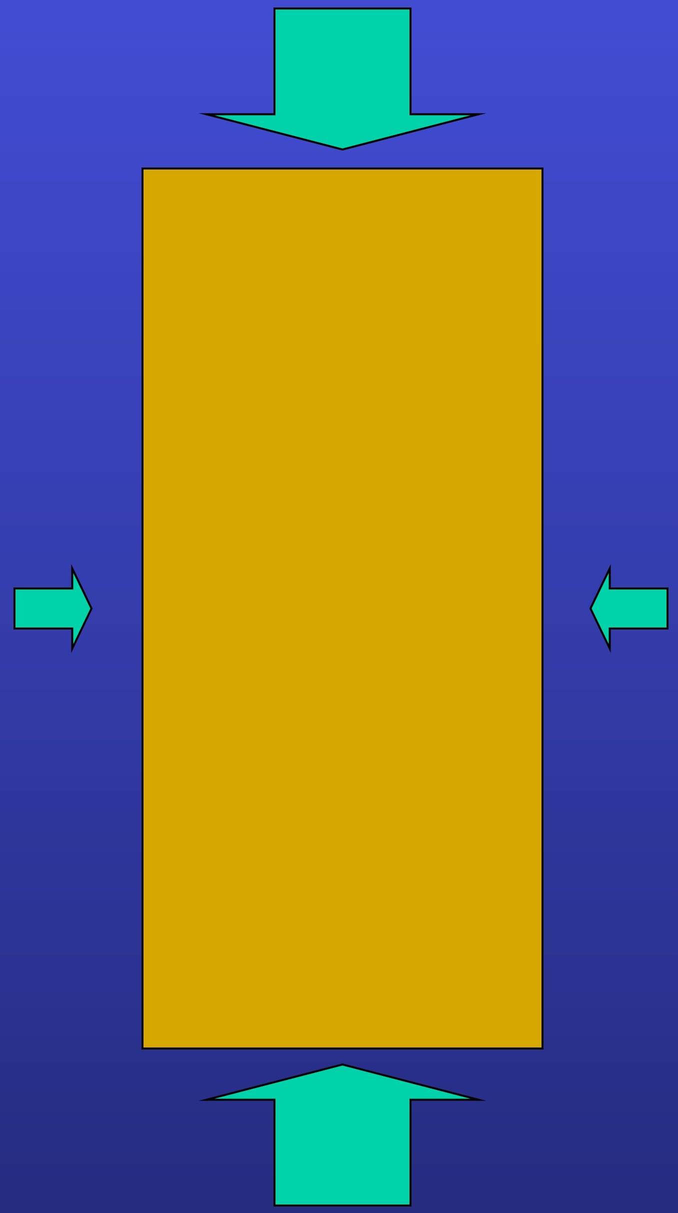
Geodetic Strain Rates

Geodetic measurements have detected stress changes, not the absolute stress.

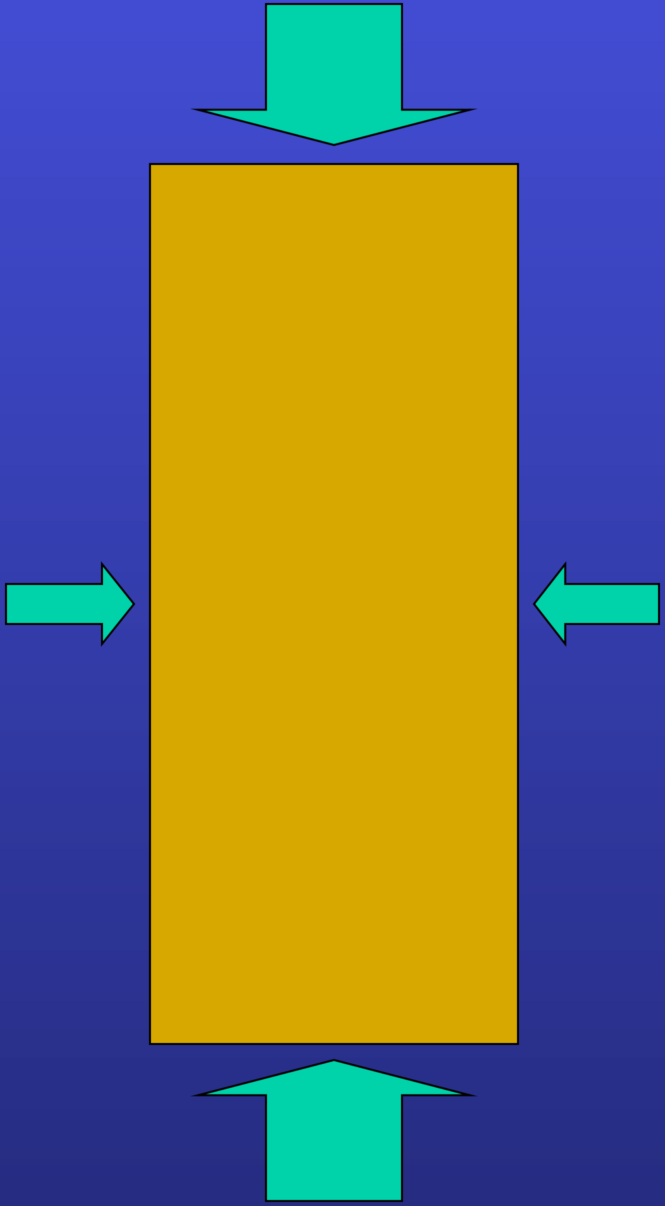
Great earthquakes cause small perturbations to forearc stress.

Shear Stress on Subduction Fault




Margin-normal stress perturbation
Margin-parallel compression

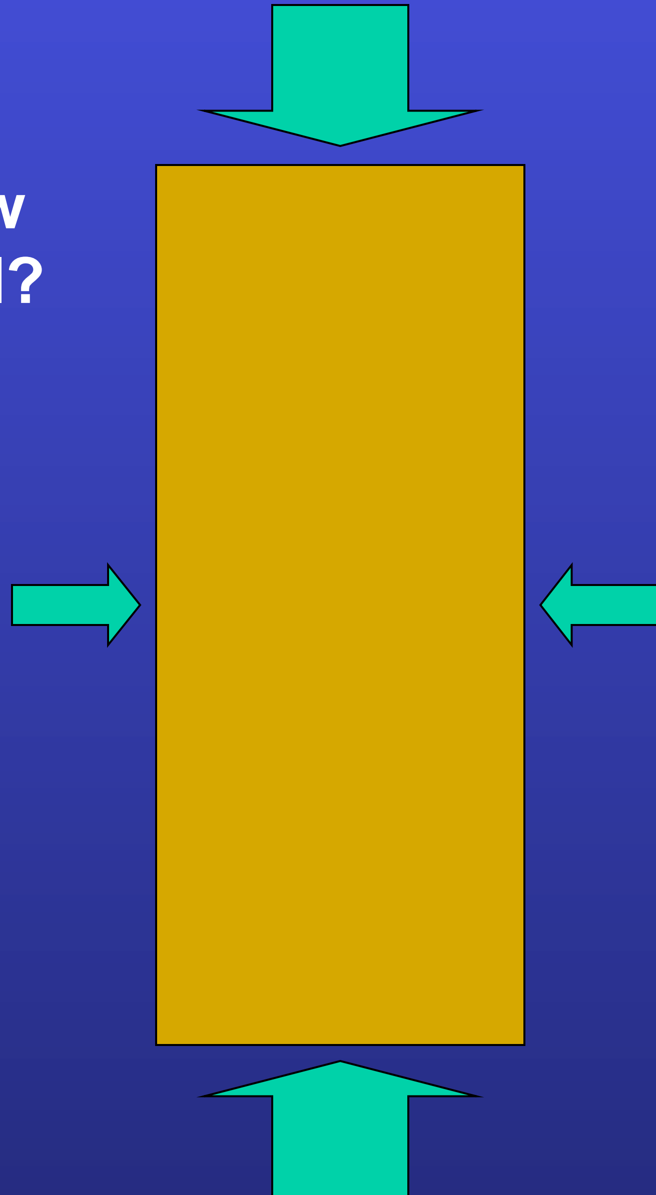
Margin-normal stress perturbation



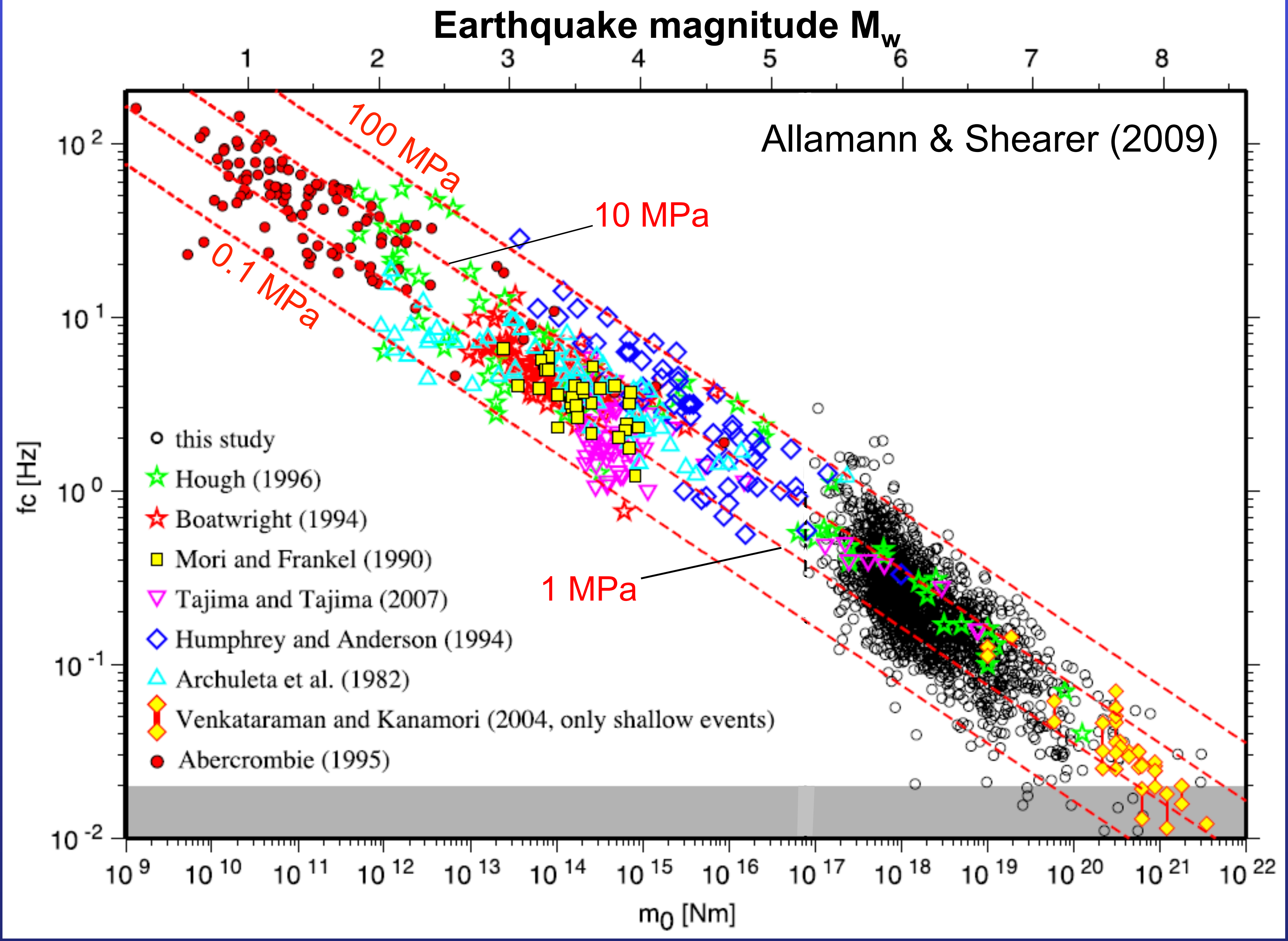
Margin-parallel compression

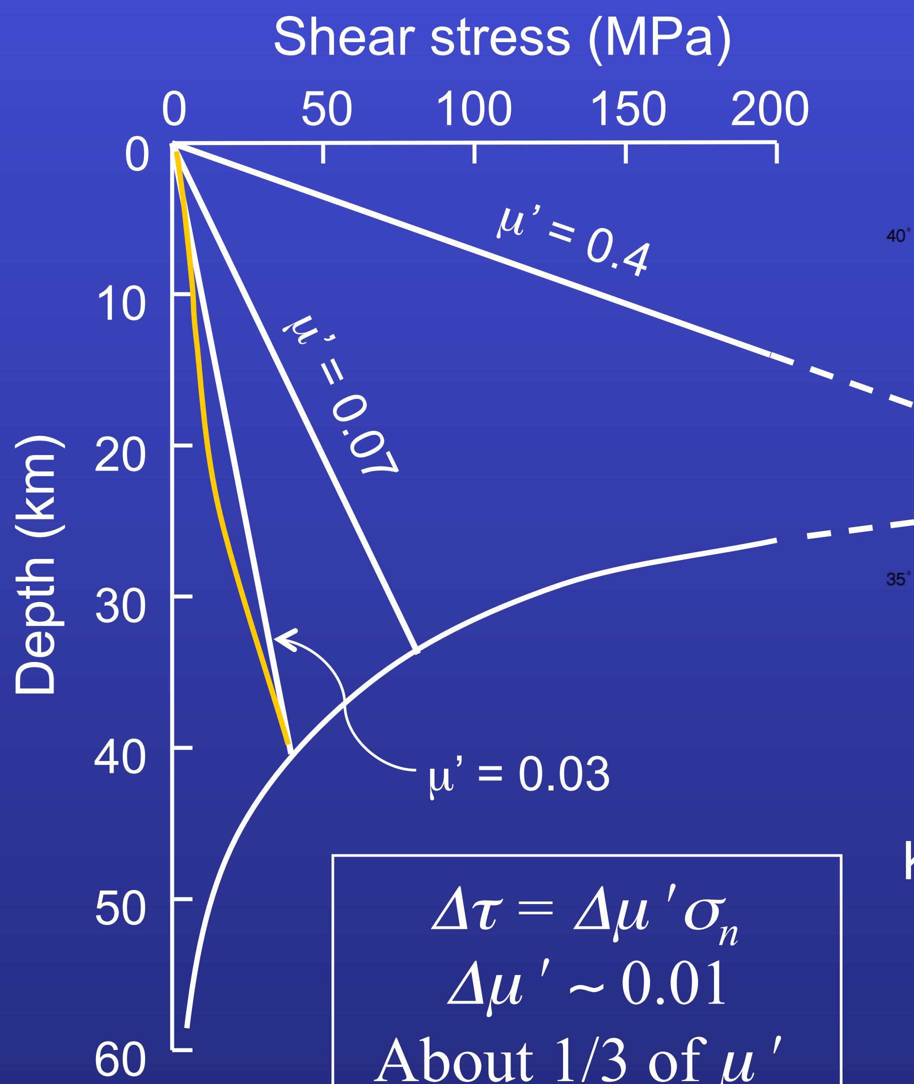
How do we know this is very small?

Margin-normal stress perturbation

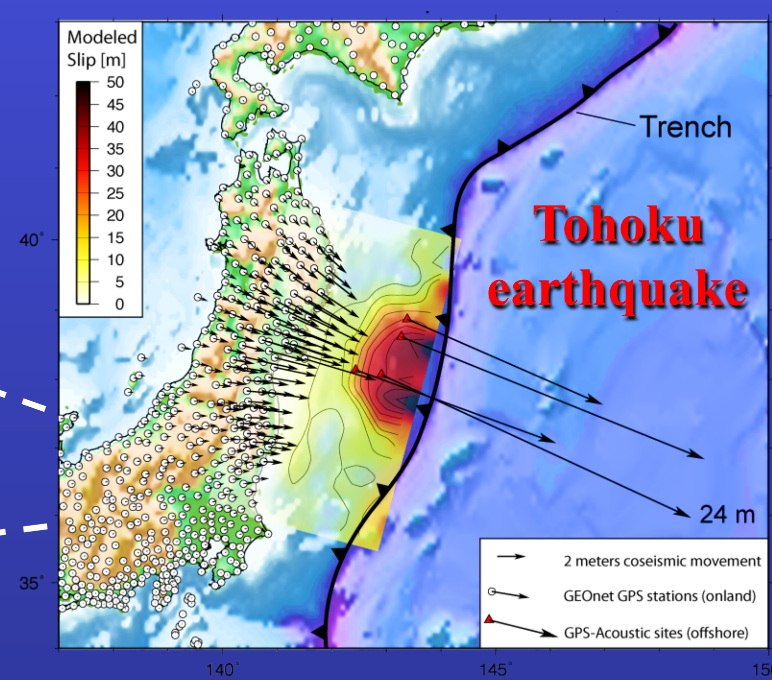


Margin-parallel compression


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]



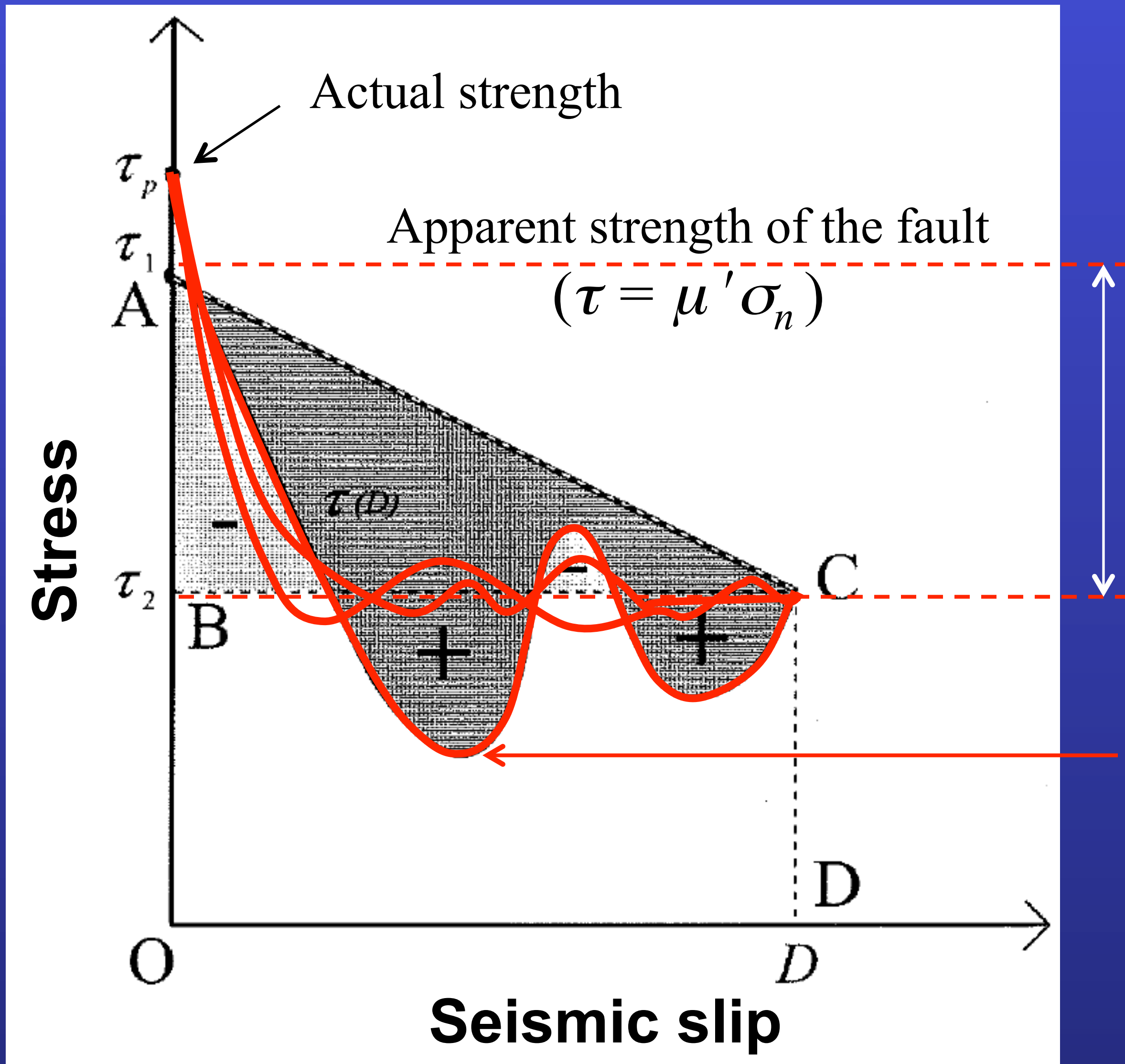
$$\Delta\tau = \Delta\mu'\sigma_n$$
$$\Delta\mu' \sim 0.01$$
About 1/3 of μ'



Stress drop estimates:

Simons et al. (2011): 2-10 MPa
Koketsu et al. (2011): 4.8 MPa
Lee et al. (2011): 7 MPa

Kumagai et al. (2012):
Locally up to 40 MPa

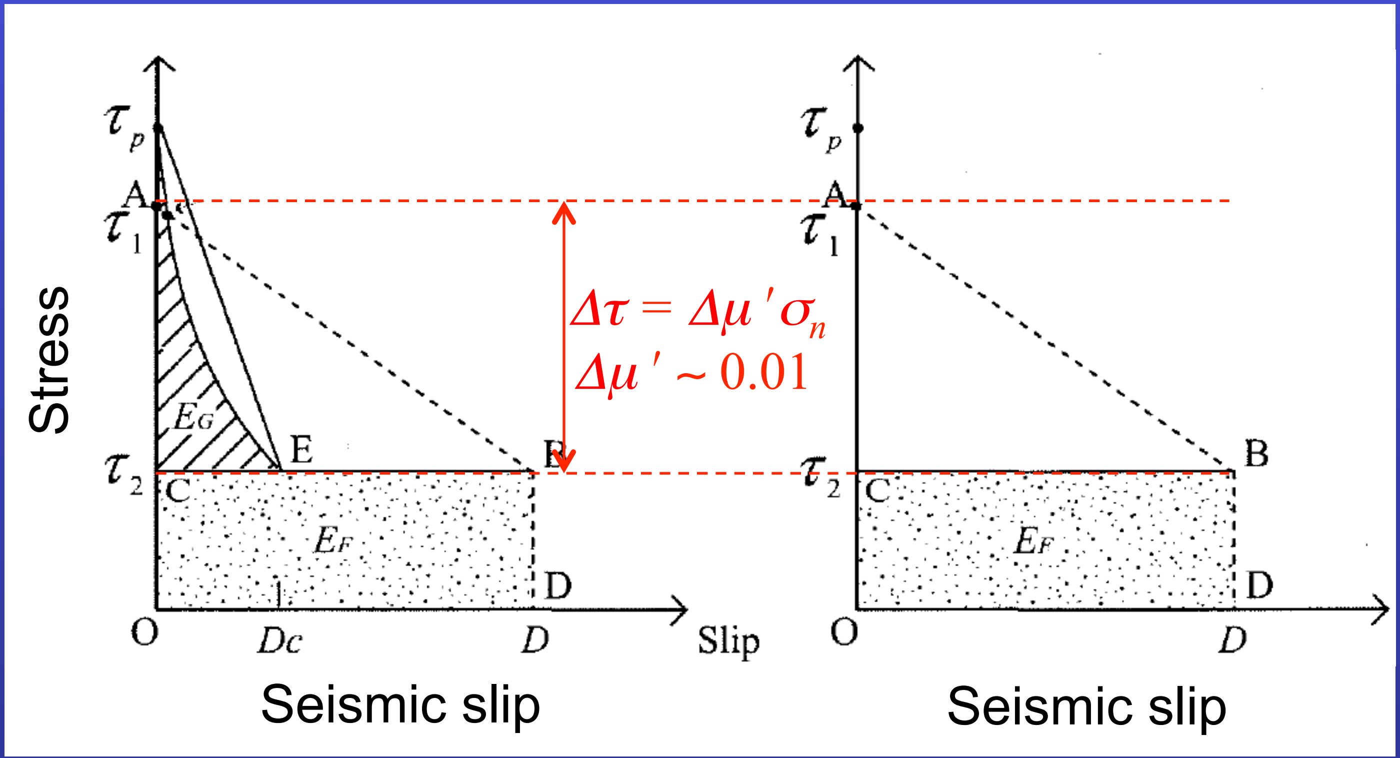


Static
stress drop

$$\boxed{\begin{aligned}\Delta\tau &= \Delta\mu' \sigma_n \\ \Delta\mu' &\sim 0.01\end{aligned}}$$

How low can it go
during the slip?

Modified from Kanamori and Rivera (2006)

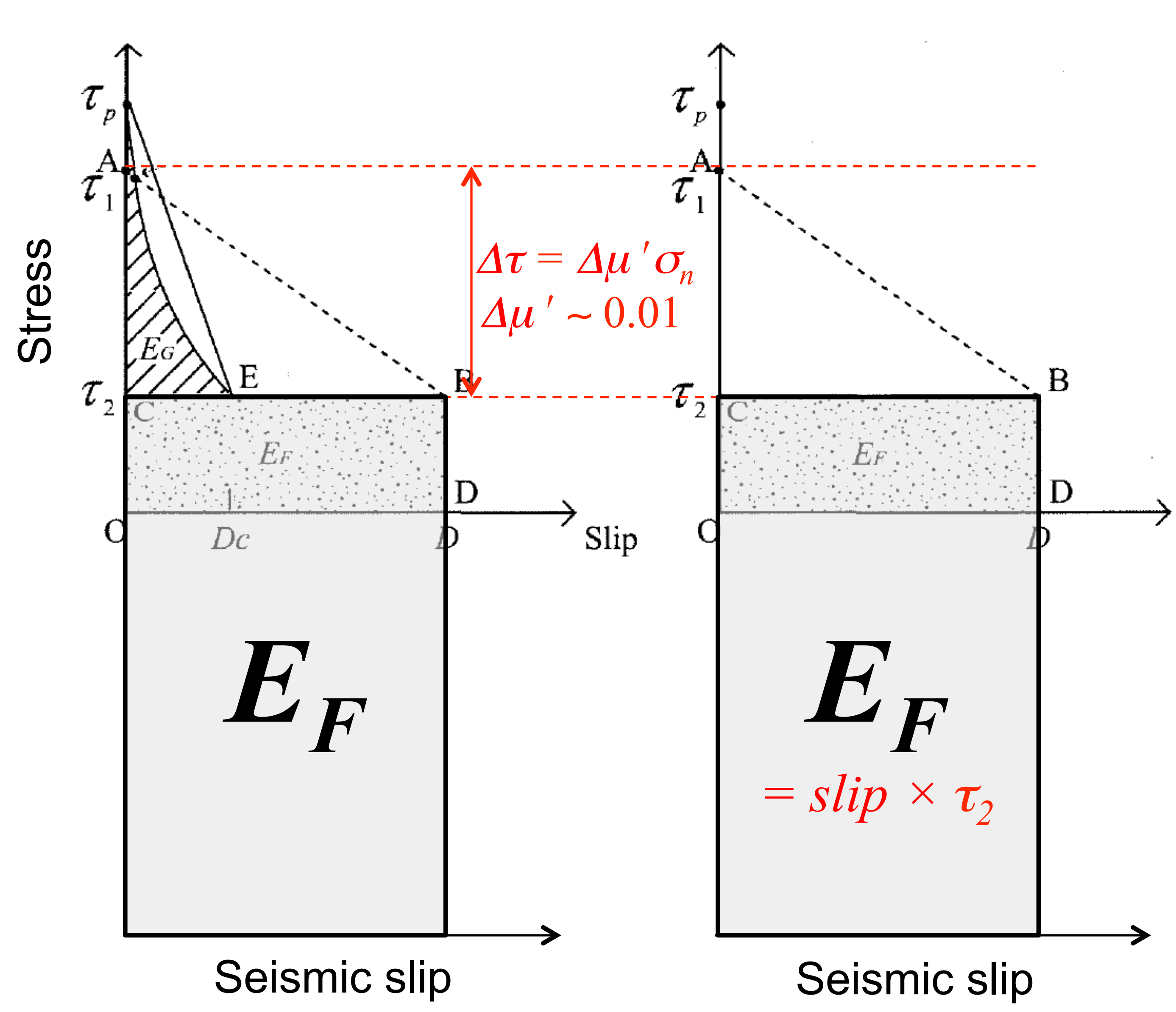


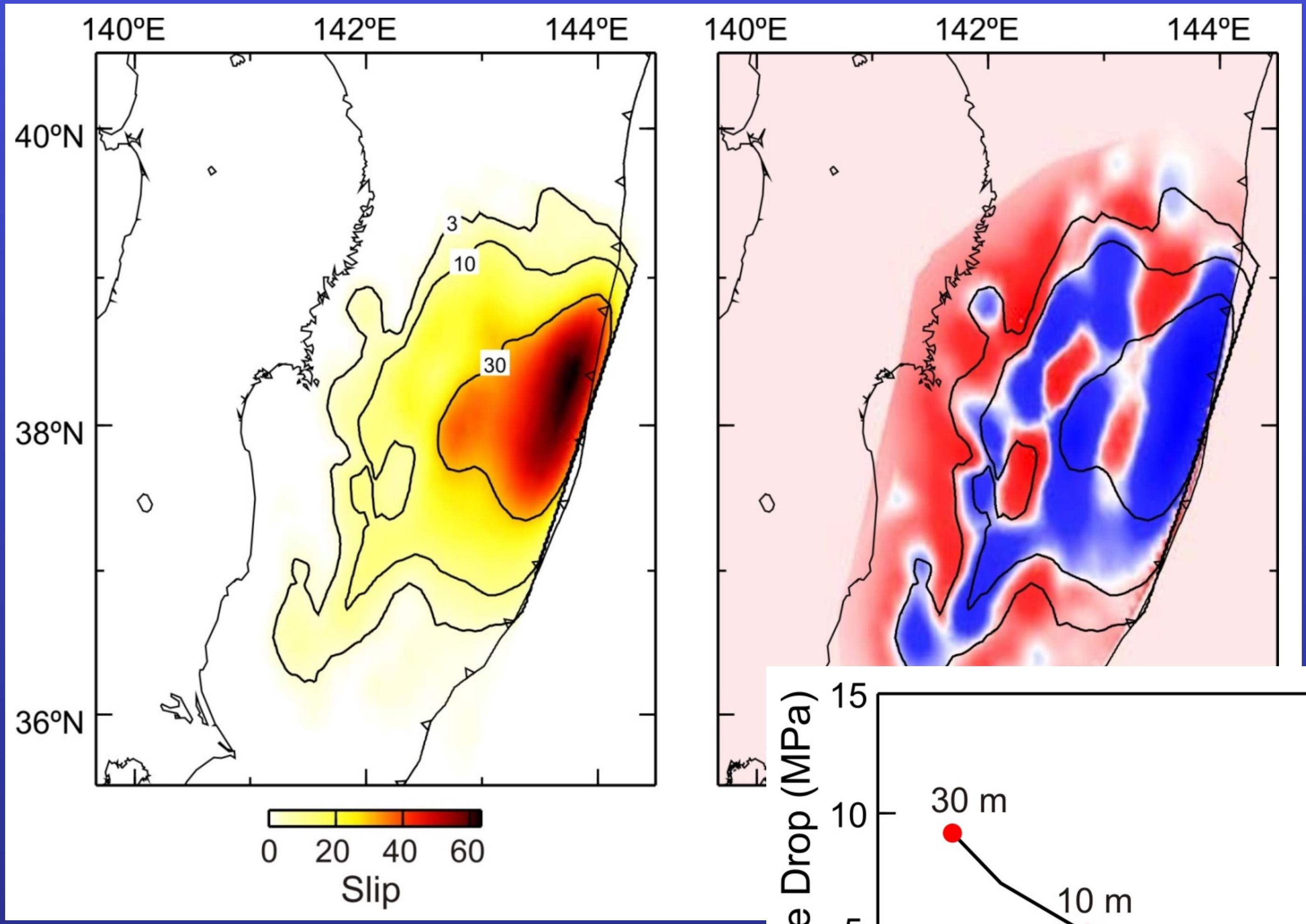
$$W = E_R + E_F + E_G$$

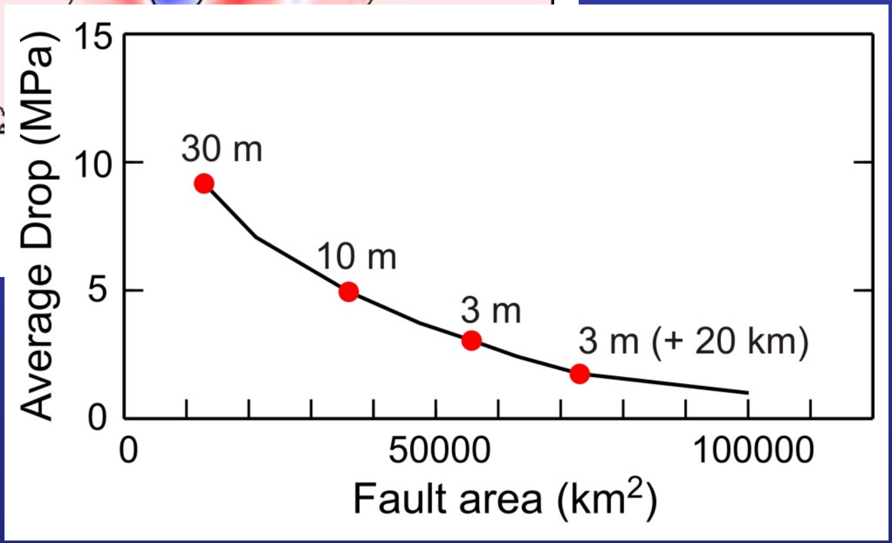
Radiated as seismic waves

Frictional heat

Energy disspated in other ways (“fracture” energy)


Stress
τ_p
A
τ_1
E_G
E
B
τ_2
C
E_F
D
O
Dc
D
Slip
$\Delta\tau = \Delta\mu'\sigma_n$
$\Delta\mu' \sim 0.01$
E_F
Seismic slip
τ_p
A
τ_1
B
τ_2
C
E_F
D
O
D
E_F
$= slip \times \tau_2$
Seismic slip

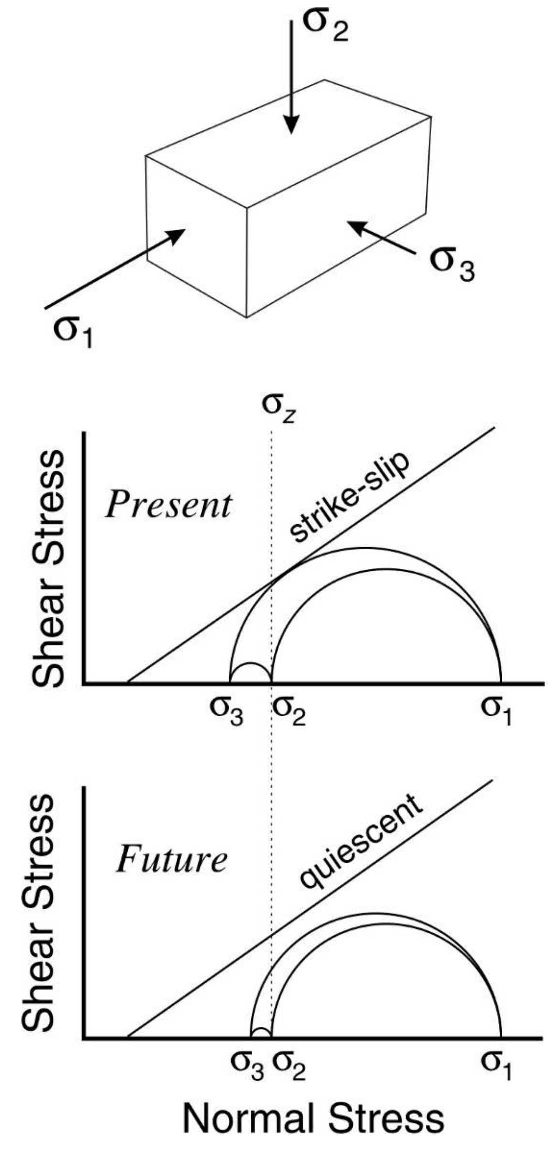


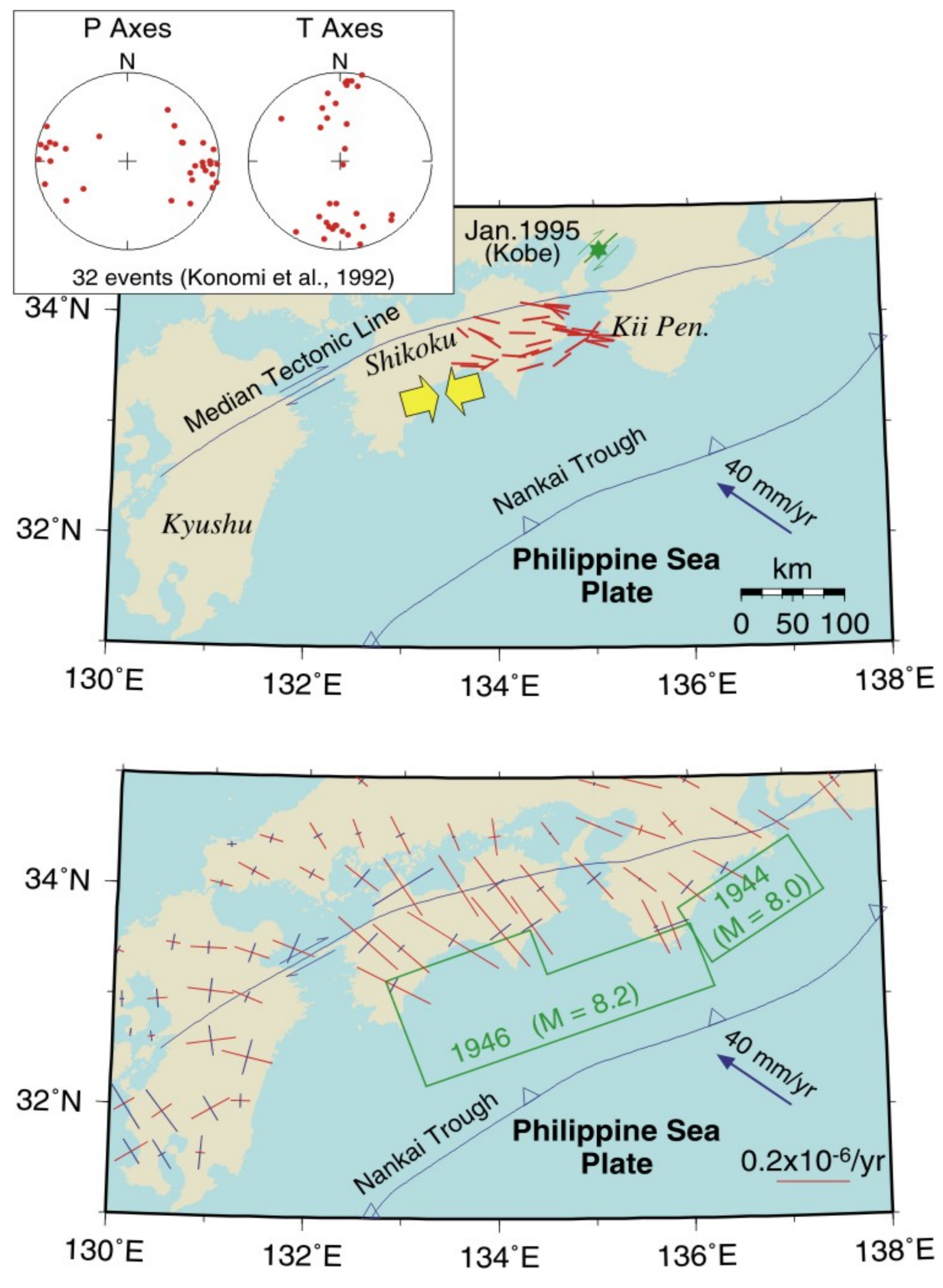


Ongoing work
(Lonn Brown)

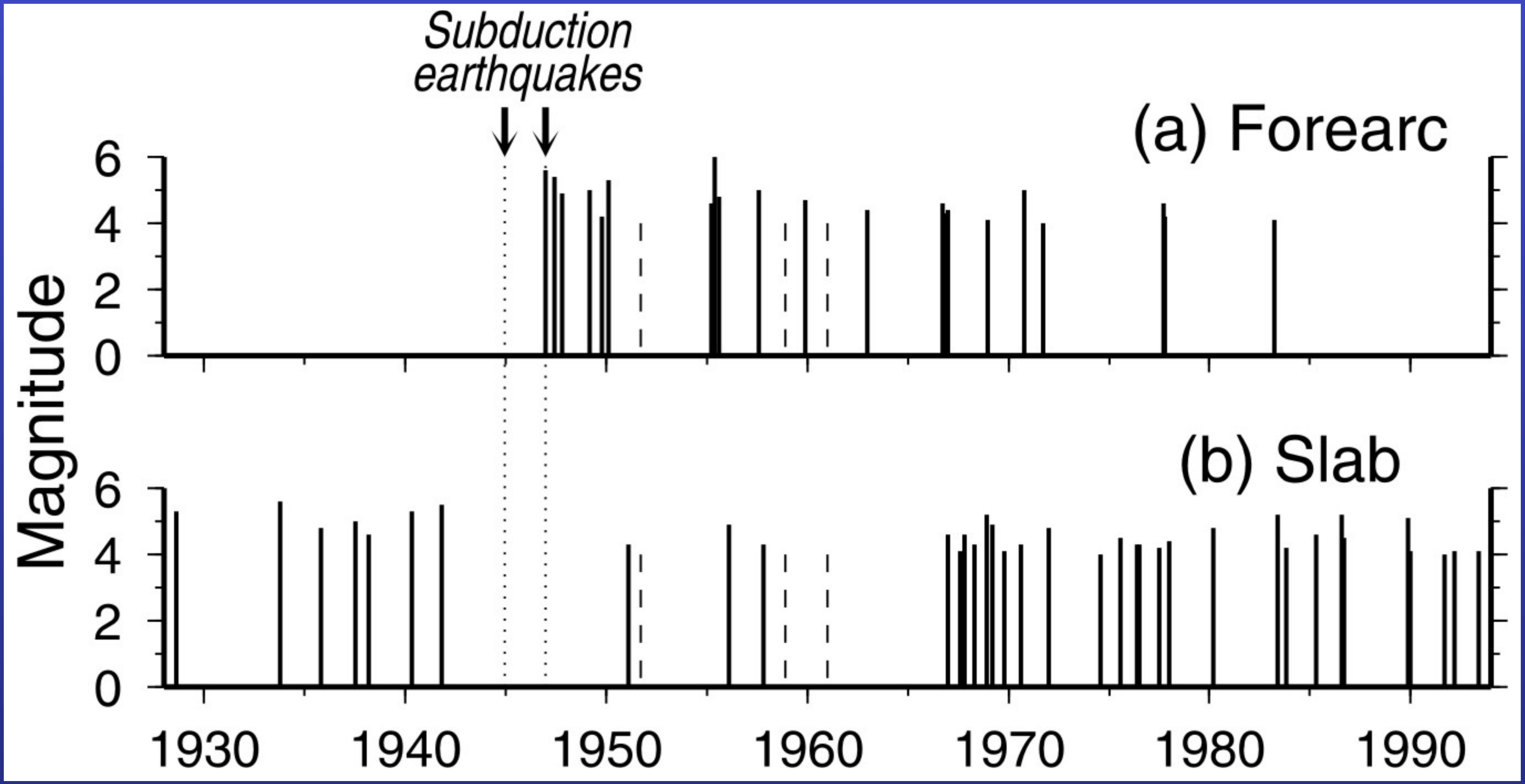
Rupture model of
Shao et al. (2012)

Nankai Forearc





Nankai forearc seismicity before and after 1944/46 earthquakes



(Kimura and Okano, 1995)

Summary

- Subduction faults are weak (μ’ 0.03 – 0.13) and are never “strongly coupled”.
  - Small margin-normal stress
  - Low frictional heating
- Rupture-zone average stress drop in great earthquakes is a fraction (< 1/3) of fault strength; local stress drop can be larger.
  - Interseismic margin-normal contraction
  - May modulate forearc seismicity
- Interseismic deformation reflects stress changes in earthquake cycles, not absolute stress.
  - Elastic deformation only reflects stress change
  - Only permanent deformation can be used to infer absolute stress