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)
A 100-km line becomes shorter by 2 cm each year.
small earthquakes in upper plate
Summary of Stresses

Forearc Stresses

small earthquakes in upper plate
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.
The Cascadia Subduction Zone
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
Far-field force

Mantle wedge rheology: Dislocation creep

Fault strength: \[ \tau = \mu' \sigma_n \]
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)
Wang and He (1999 JGR)
Frictional strength:

\[ \tau = \mu (\sigma_n - p) = \mu (1 - p/\sigma_n)\sigma_n \approx \mu (1 - p/\rho gh)\sigma_n = \mu (1 - \lambda)\sigma_n = \mu'\sigma_n \]

μ' ≈ 0.4
(\~Byerlee’s law at hydrostatic pore fluid pressure)

μ' = 0.07
(If Byerlee, \( \lambda = 0.9 \))

μ' = 0.03

Plate Coupling
\( \mu' = 0.03 - 0.06 \) for most subduction zones studied

Red: This work
Blue: Lamb (2006)
Northeast Japan before 2011 Tohoku earthquake

Focal mechanism solutions are from NIED and Kosuga (1999)

Shortening directions of active faults (Sato, 1984)

P axes

T axes

(World Stress Map)
Deviatoric stress (red is compressive)

Wang and Suyehiro, 1999 GRL
Hasegawa et al. (2012 EPSL)

Blue: normal faulting
Red: thrust faulting

before

after

A
B
C
D
E
F

Pre-Tohoku-oki
Post-Tohoku-oki
Heat Flow Measurements
Frictional Heating = Shear stress times Slip rate
Subduction zones with adequate heat flow data to constrain frictional heating
Chile
Manila Trench
Costa Rica
Nankai
creeping
Stick-slip

Gao and Wang, 2014 Science
3. Why is geodetic contraction margin-normal?

Great earthquakes cause small perturbations to forearc stress. Geodetic measurements have detected stress changes, not the absolute stress.
A Stretched Elastic Band

Time 1: Tension

Time 2: Less tension

Contraction
3. Why is geodetic contraction margin-normal?

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

Great earthquakes cause small perturbations to forearc stress.
Shear Stress on Subduction Fault

Stress vs. Time

\( \tau \) (No)

\( \tau \) (Yes)
Margin-normal stress perturbation

Margin-parallel compression
Margin-normal stress perturbation

Margin-parallel compression
Margin-parallel compression

Margin-normal stress perturbation

How do we know this is very small?
Earthquake magnitude $M_w$

Allamann & Shearer (2009)

- 100 MPa
- 10 MPa
- 0.1 MPa
- 1 MPa

- 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)
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

\[ \Delta \tau = \Delta \mu' \sigma_n \]
\[ \Delta \mu' \sim 0.01 \]

About 1/3 of \( \mu' \)
Stress

Seismic slip

Modified from Kanamori and Rivera (2006)

Apparent strength of the fault

\( (\tau = \mu'\sigma_n) \)

Actual strength

Static stress drop

\[ \Delta\tau = \Delta\mu'\sigma_n \]
\[ \Delta\mu' \sim 0.01 \]

How low can it go during the slip?

\( \Delta\tau = \Delta\mu'\sigma_n \)
\[ \Delta\mu' \sim 0.01 \]
Stress
Seismic slip

$W = E_R + E_F + E_G$

Radiated as seismic waves

Frictional heat

Energy dissipated in other ways ("fracture" energy)

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

$\Delta \mu' \sim 0.01$
\[ \Delta \tau = \Delta \mu' \sigma_n \]
\[ \Delta \mu' \sim 0.01 \]
Rupture model of Shao et al. (2012)

Ongoing work (Lonn Brown)
Nankai Forearc

Shear Stress

Present

strike-slip

Future

quiescent

Normal Stress
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