Viscoelastic Deformation Models for Subduction Earthquake Cycles

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Stress and Strain
The Cascadia Subduction Zone

Forearc stresses

Geodetic strain rates

small earthquakes in upper plate
Summary of Stresses

small earthquakes in upper plate

Shear Stress

\( p \) \( \sigma_2 = \sigma_3 \) \( \sigma_1 \)
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

(a) Strain Rates
(b) GPS Velocities
(c) Corrected Velocities
Margin-normal stress is small because it is controlled by two competing factors:

- Gravity induces horizontal tension in the forearc.
- Plate coupling causes compression.

Why is margin-normal stress small?
Two converging elastic plates in frictional contact $\tau = \mu' \sigma$

Non-lithostatic stress symbols:
Thin – compression
Thick – tension

Method:
Finite element with Lagrange-multiplier domain decomposition

(a) $\mu' = 0$ + 26 MPa
(b) $\mu' = 0.03$ + 19 MPa
(c) $\mu' = 0.1$ + 94 MPa
Thermal model for Cascadia (Finite element)

Very little fictional heating is required to fit surface heat flow observations, indicating very low shear stress.

Frictional heating
Static friction:
Loading followed by stress drop on locked zone

Method:
Finite element with Lagrange-multiplier domain decomposition
Time dependent deformation
Inter-seismic deformation rate

Post-seismic deformation rate

Co-seismic displacement
Fault slip vs. stress relaxation
Rupture

After-slip
Afterslip: ~ 1 – 10 years?
Relaxation: ~ decades? Hopefully effects of transient and/or nonlinear rheology also become less pronounced
Backslip model for fault locking
Locked

Locked =

Backslip + Steady Subduction
Viscoelastic model:
earthquake (foreslip)
followed by fault locking
(backslip)
Red: Locked (rupture)
Orange: transition

This accounts for
some afterslip in
a crude way
Finite element model; 27-node elements; Maxwell viscoelastic
50 years after earthquake

(a) Strain Rates
(b) Velocities
(c) Uplift Rates (mm/yr)
300 years after earthquake (today)
Prolonged post-seismic deformation and stress relaxation
Alaska GPS campaigns (1993-1997)

Freymueller et al. (2000, JGR)
Savage et al. (1999, GRL)
3D finite element model of mantle stress relaxation; an earthquake (foreslip) followed by fault locking (backslip)

GPS data at Chile margin
~ 35 years after the 1960 great earthquake (Mw 9.5)
(Klotz et al., EPSL, 2001)
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8-node finite elements; Maxwell viscoelastic
3D Viscoelastic model of post-seismic deformation (mantle viscosity $2.5 \times 10^{19} \text{ Pa s}$) (Hu et al., JGR, 2004)

GPS data at Chile margin ~ 35 years after the 1960 great earthquake (Mw 9.5) (Klotz et al., EPSL, 2001)
3D Viscoelastic model of crustal deformation following 1960 (M 9.5) Chile earthquake (Hu et al., JGR, 2004)
Importance of along-strike rupture length and slip magnitude (35 years after earthquake; mantle viscosity $2.5 \times 10^{19}$ Pa s) (Hu et al., 2004)
Summary

• A great subduction earthquake is the rupture of a weak plate boundary fault; earthquake cycles cause small stress changes but large strain rates

• Afterslip (or interseismic slip) and stress relaxation cannot always be distinguished (model-dependent)

• Mantle wedge viscosity required in stress relaxation models is $\sim 10^{19}$ Pa s

• Prolonged seaward motion of inland GPS sites can be explained as post-seismic deformation following long-rupture great earthquakes
Effect of oceanic mantle viscosity (Pa s)

Time After Earthquake (year)

uplift (m)

$10^{20}$

$10^{19}$
Developer: Jiangheng He

Preprocessing:
Software: academic version of VisualFEA (S. Korea) or GID (Spain)
2D: Direct use of above software
3D: Use above software to create 2D meshes on plate interface and other important surfaces, then extrapolate into 3D

Visualization:
ParaView

Parallelization:
Elemental computing: Metis (Parmetis ready) (graphic partition)
Iterative solver: Aztec, Petsc
Direct solver: SuperLU