Viscoelastic Deformation Models for Subduction Earthquake Cycles

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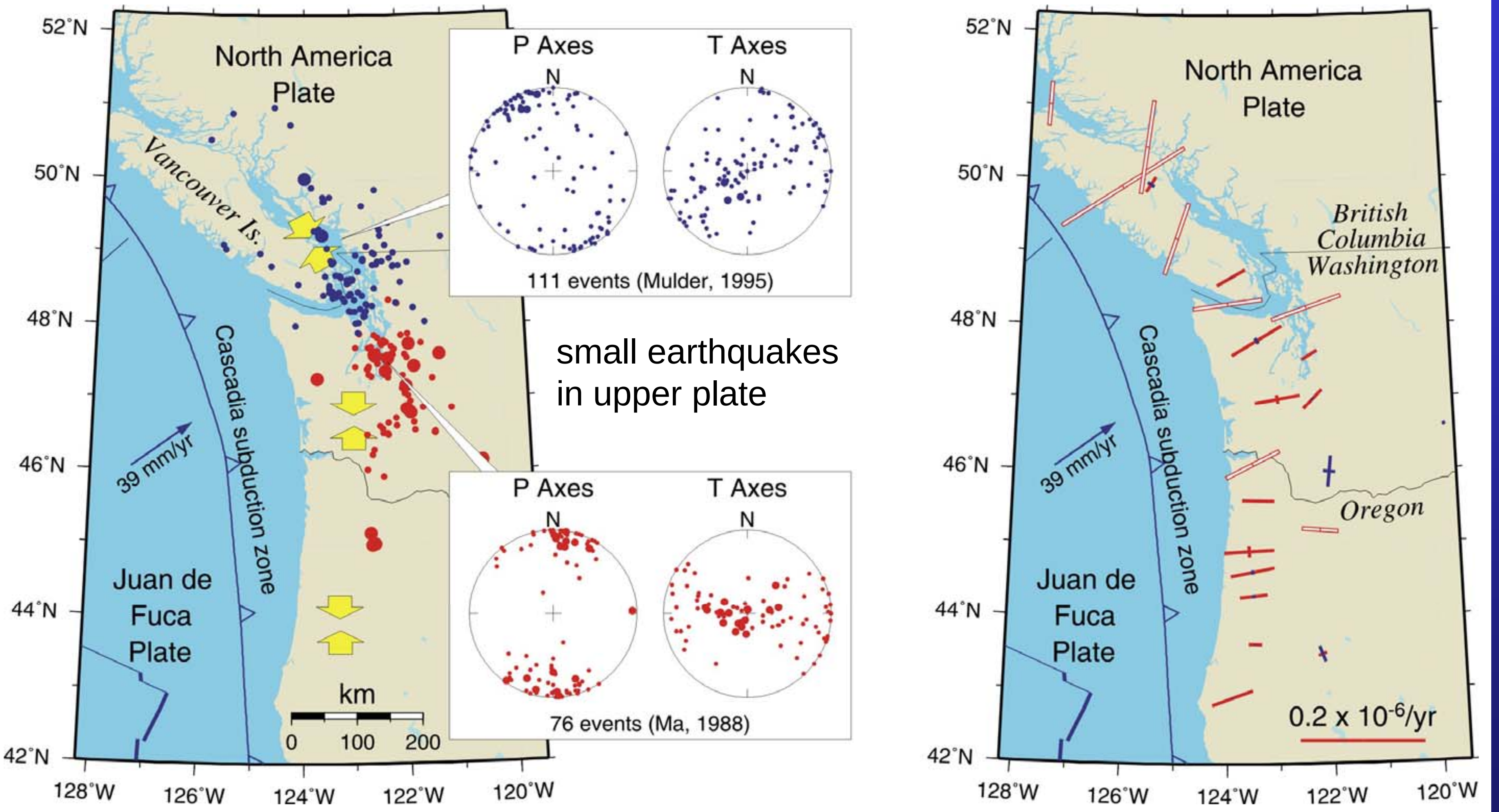
Stress and Strain

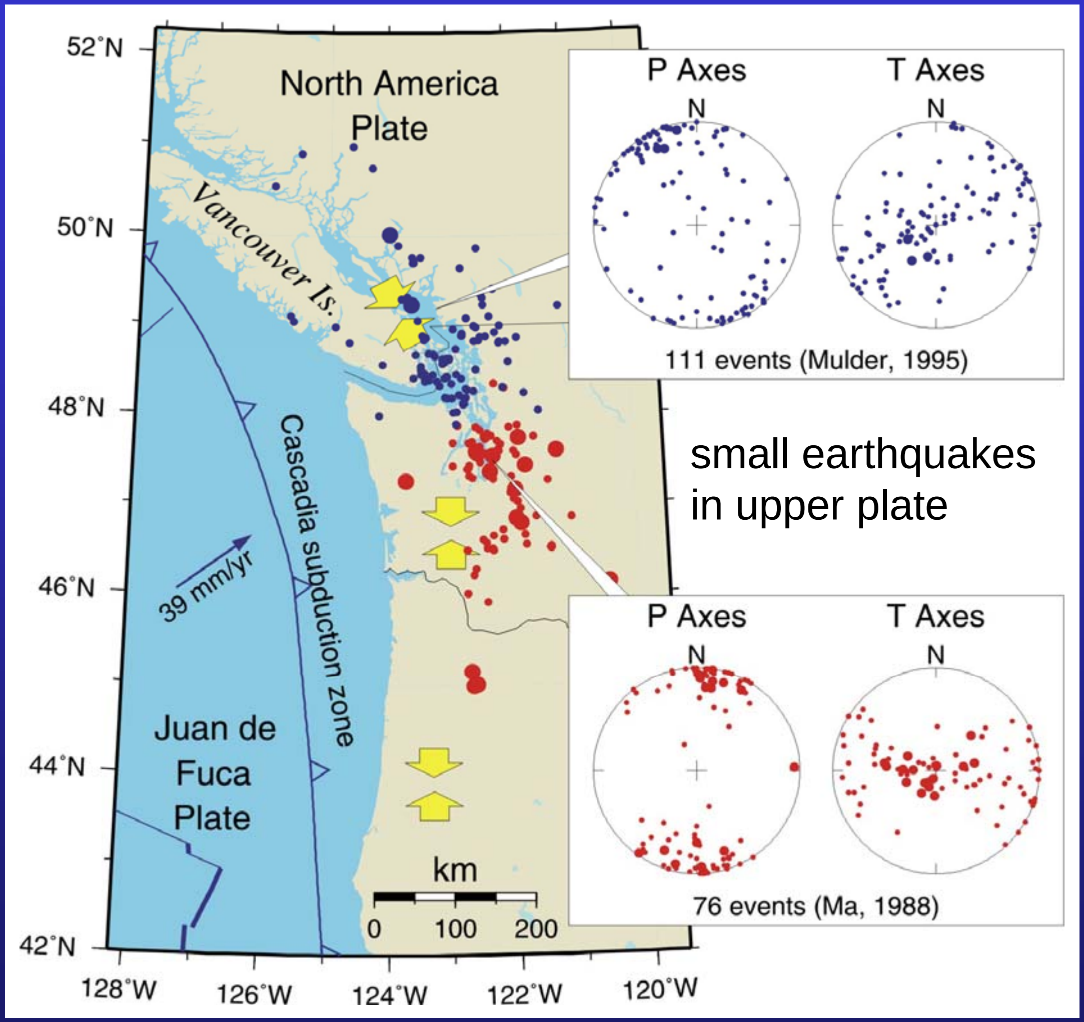
The Cascadia Subduction Zone

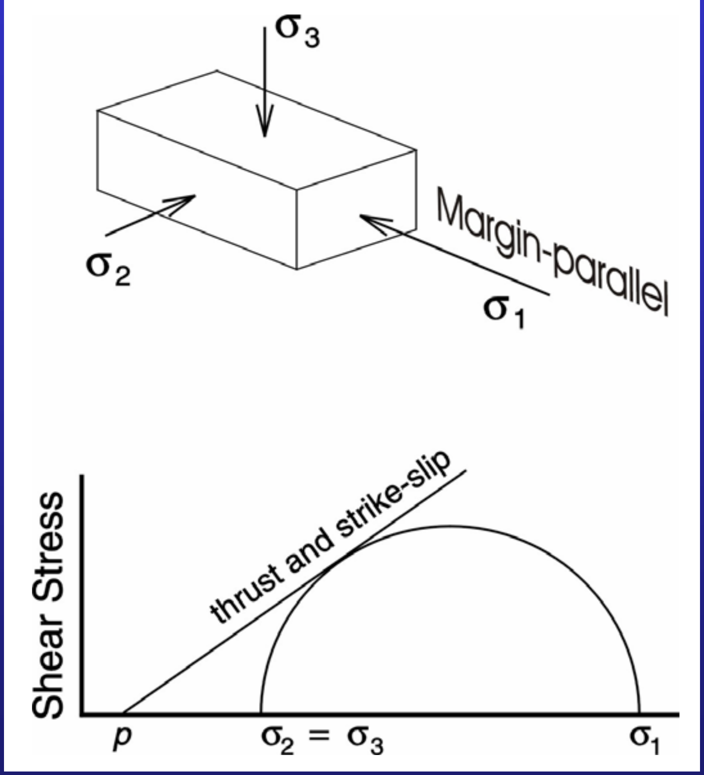


Forearc stresses

Geodetic strain rates

Summary of Stresses



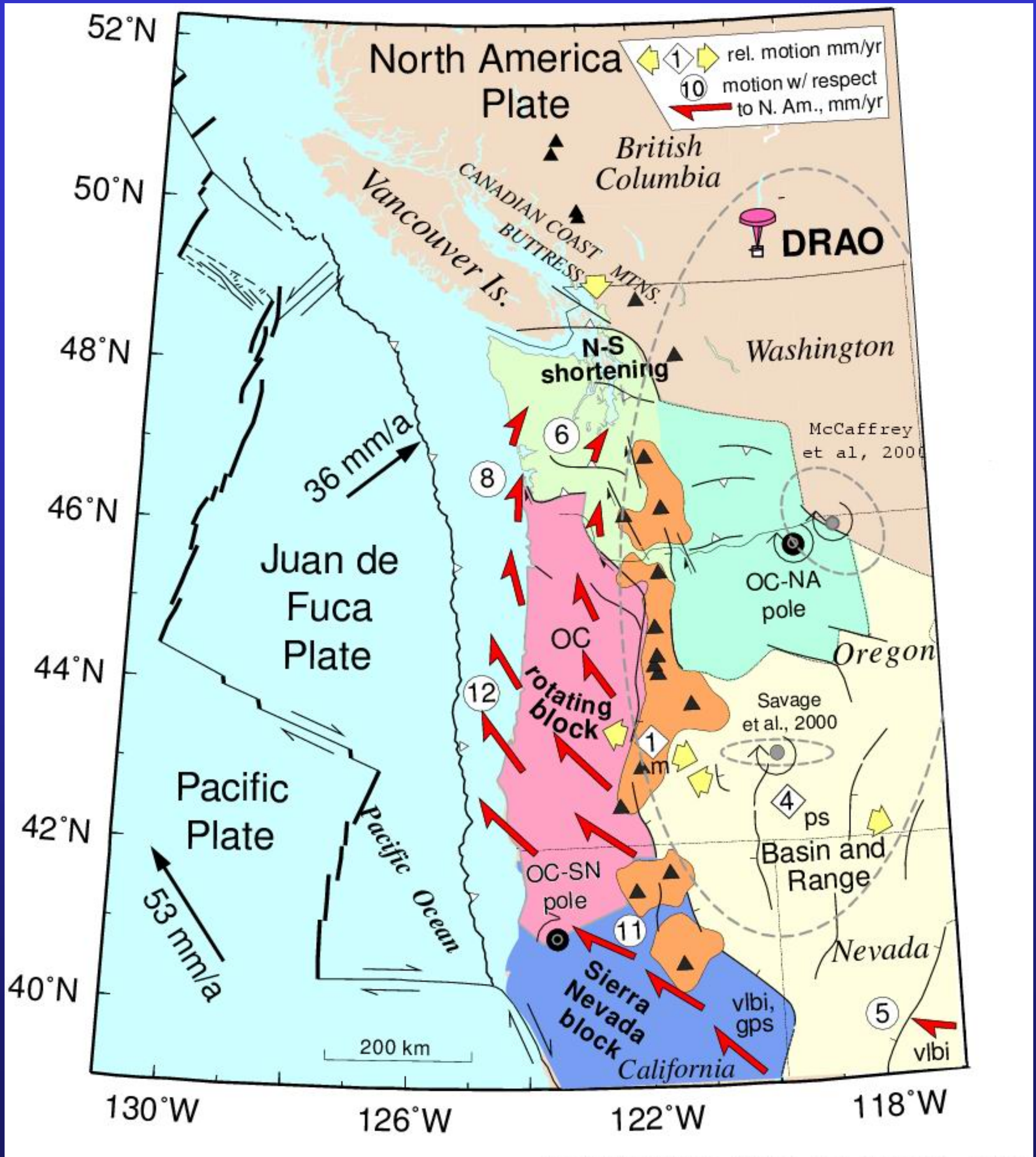


Why is margin-parallel stress large?

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

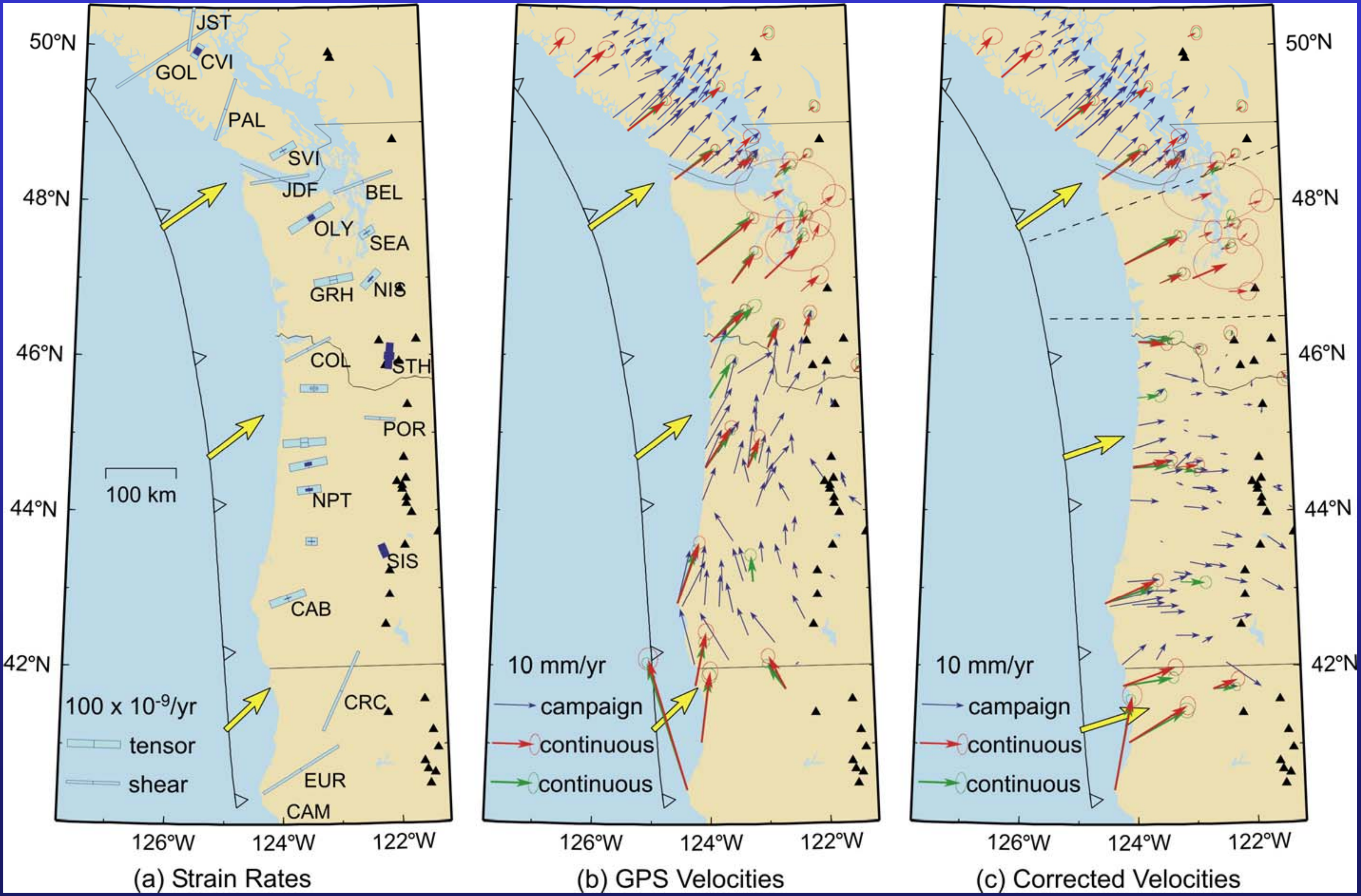
Assumed to be steady state.

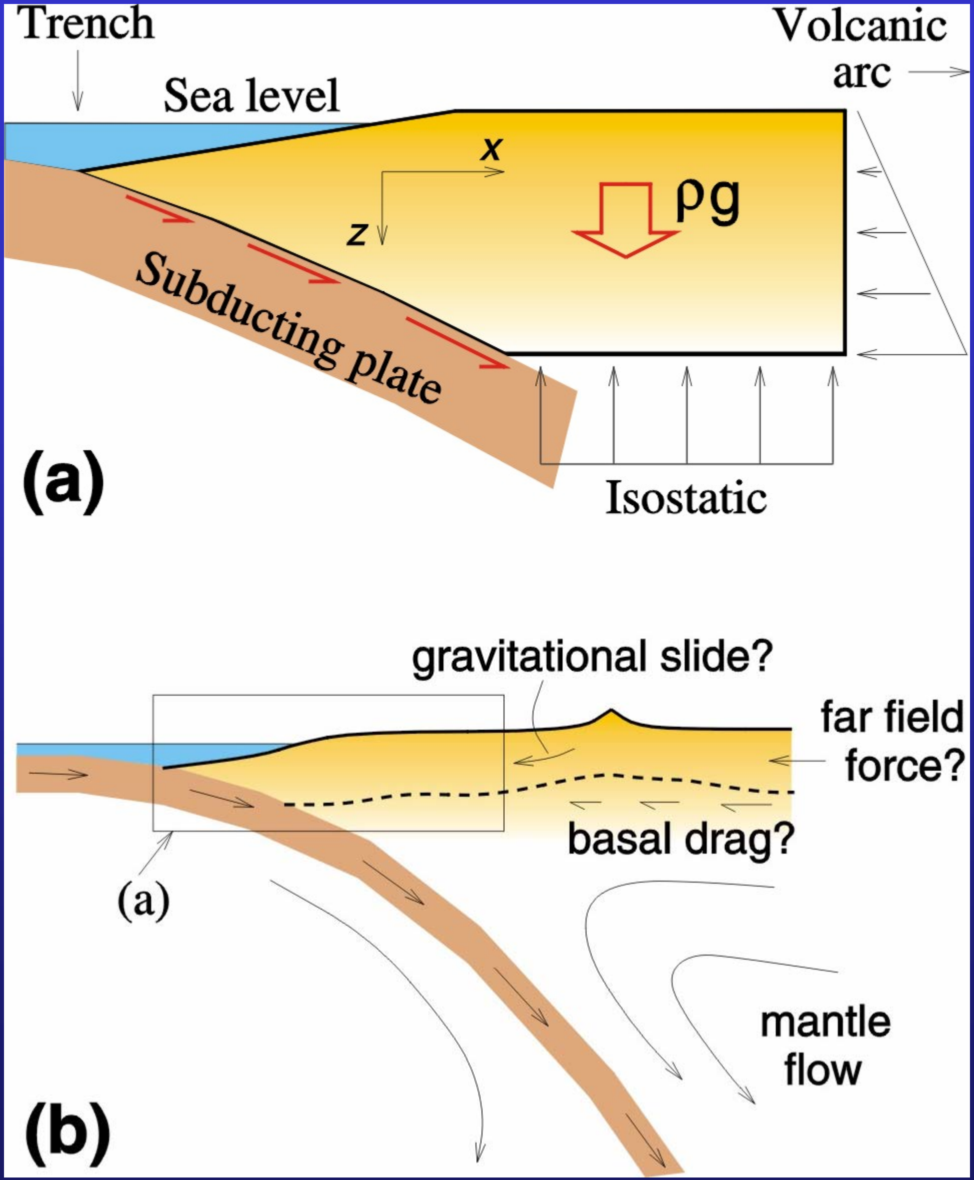
To be subtracted from interseismic observations and model.



modified from Wells and Simpson, 2001

The Cascadia Subduction Zone





Why is margin-normal stress small?

Margin-normal stress controlled by two competing factors:

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

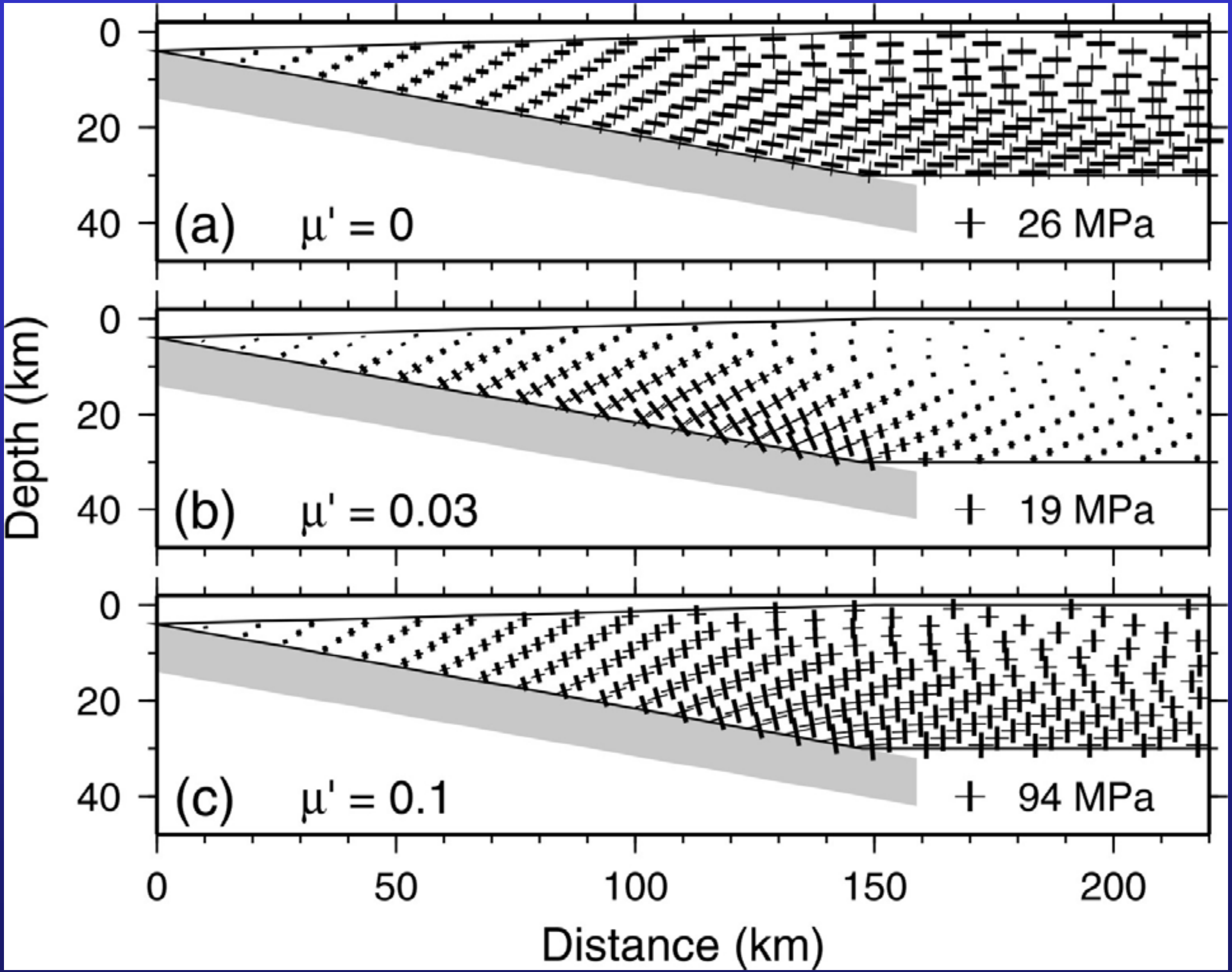
Two converging elastic plates in frictional contact $\tau = \mu'\sigma$

Non-lithostatic stress symbols:

Thin – compression
Thick – tension

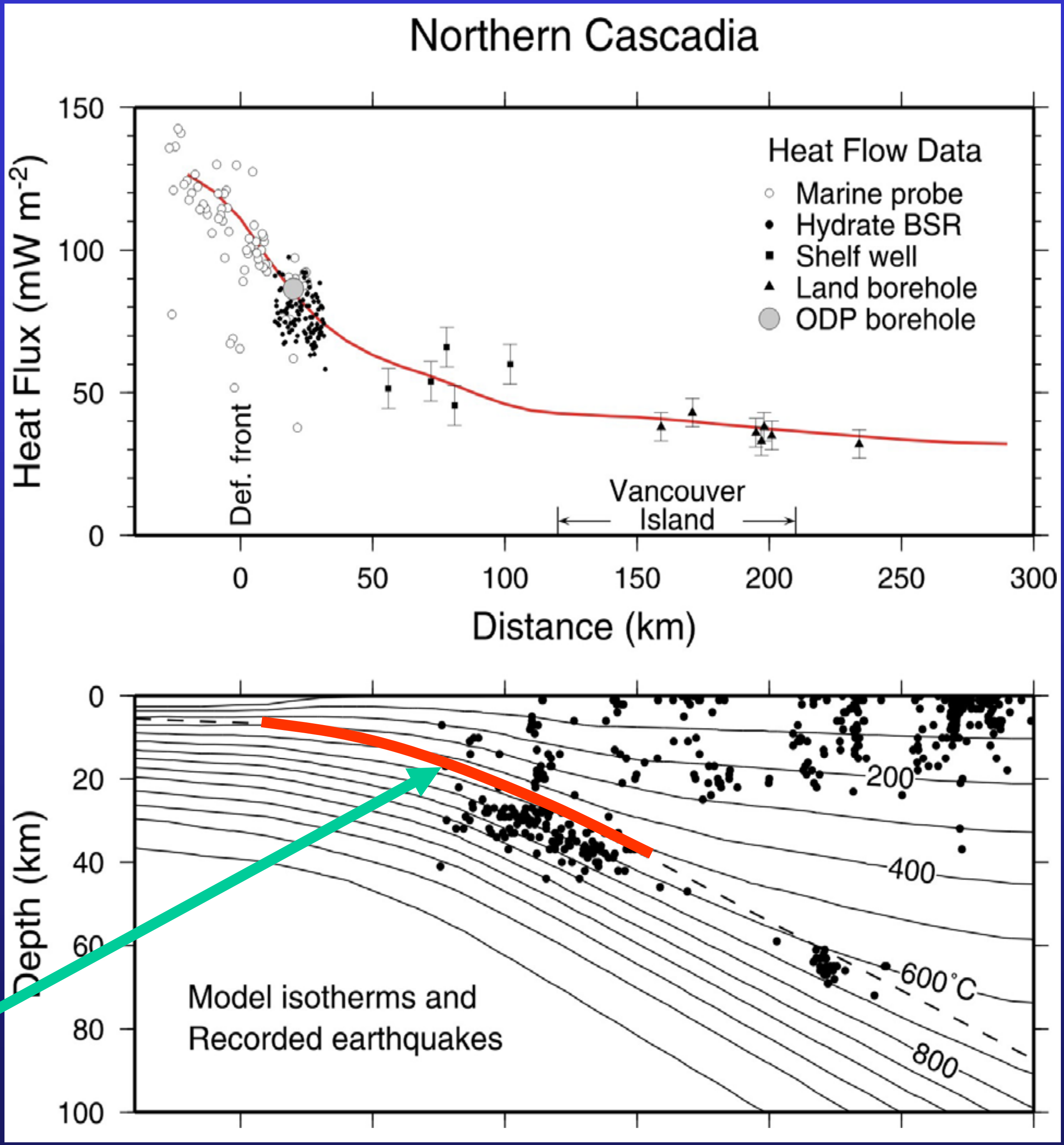
Method:

Finite element with Lagrange-multiplier domain decomposition



Thermal model for Cascadia
(Finite element)

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



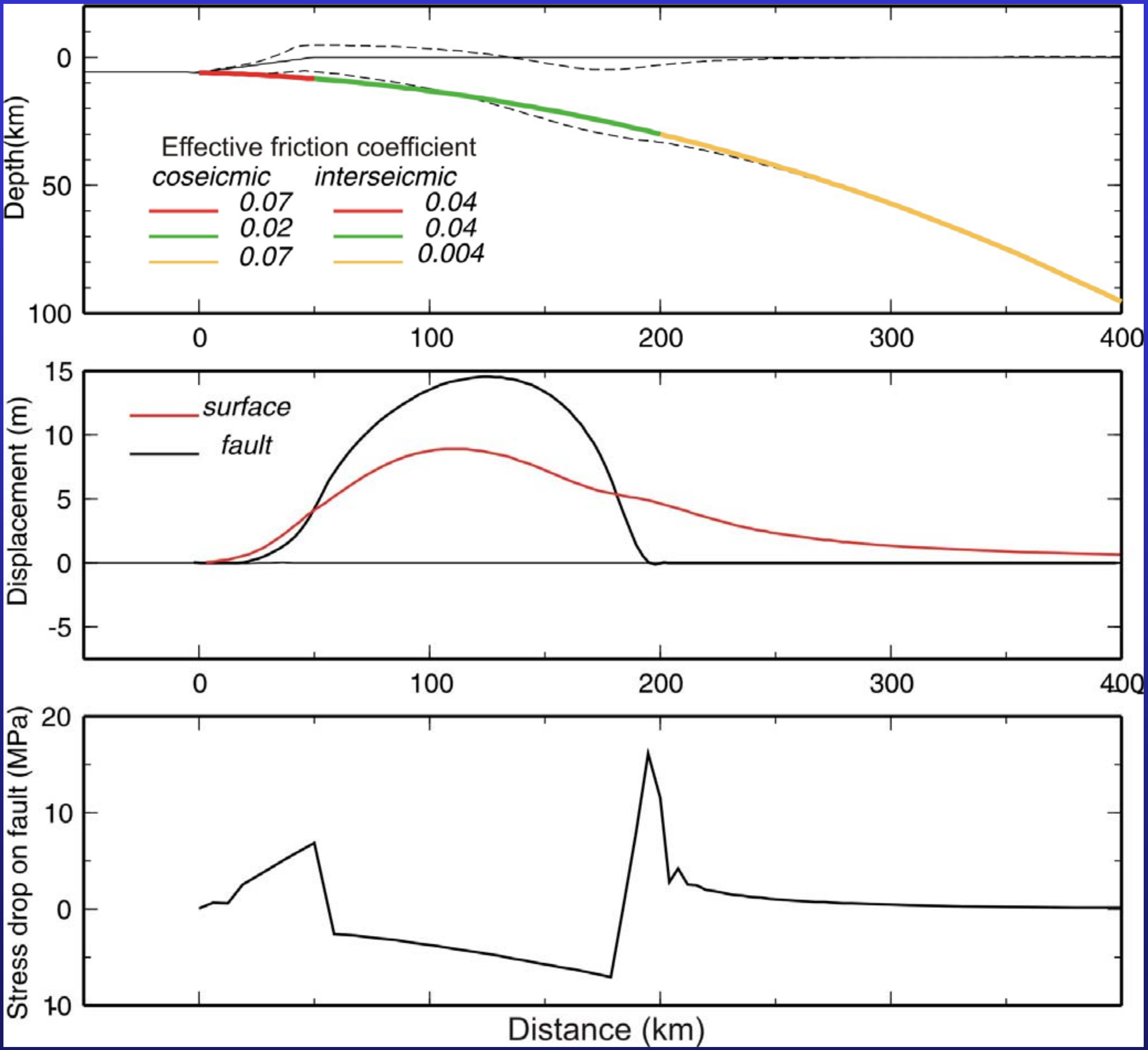
Frictional heating

Static friction:

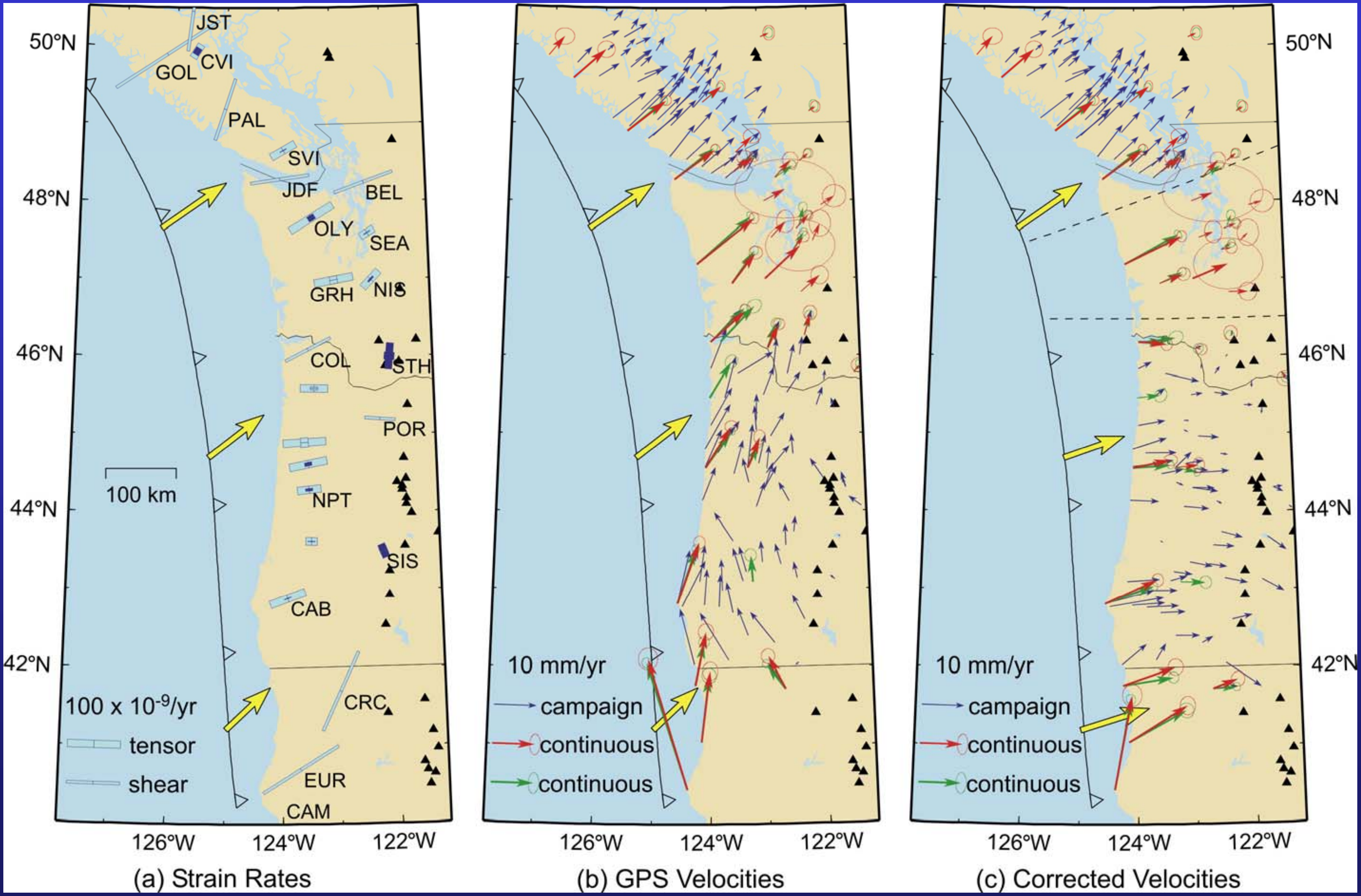
Loading followed by stress drop on locked zone

Method:

Finite element with Lagrange-multiplier domain decomposition



The Cascadia Subduction Zone

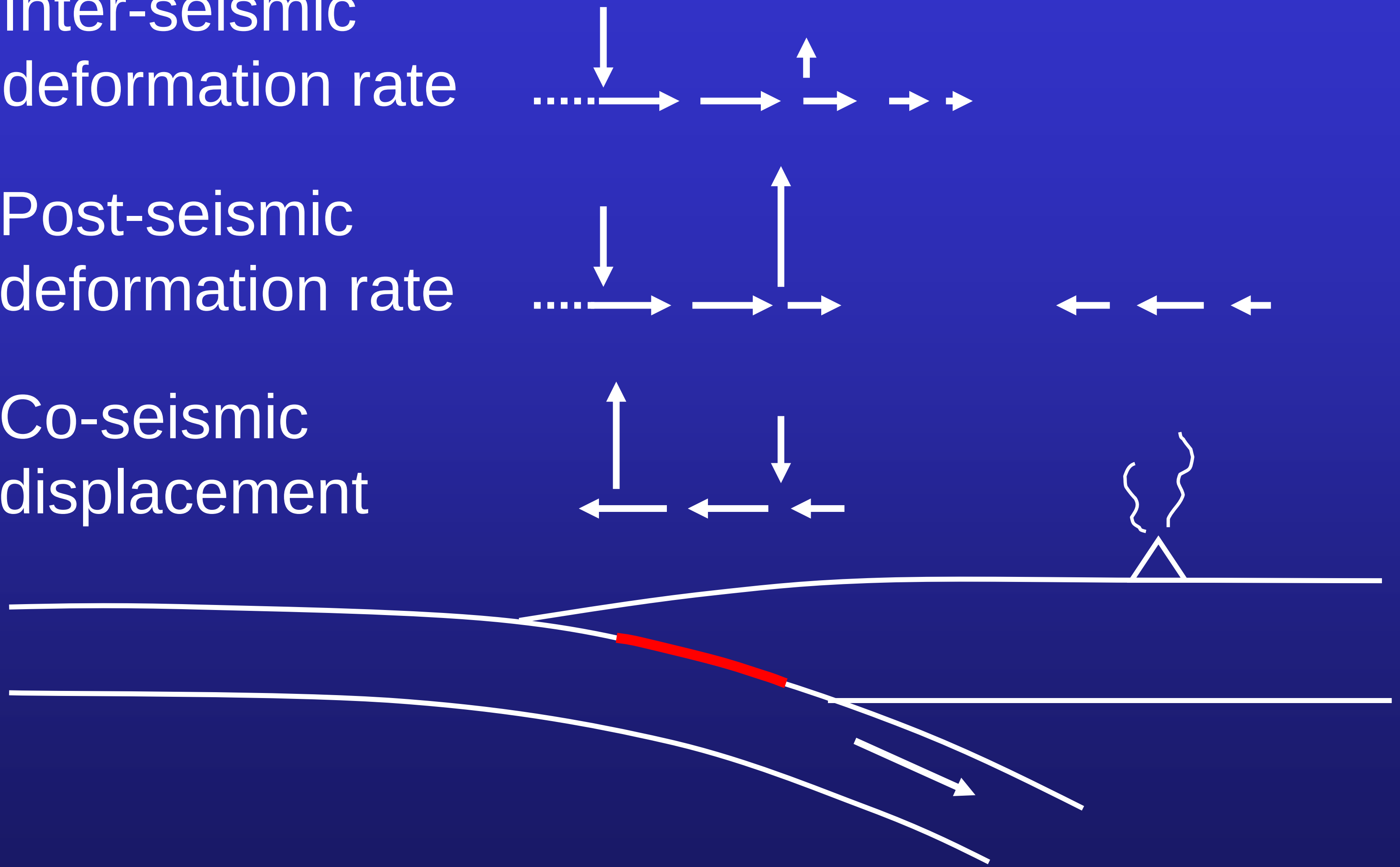


Time dependent deformation

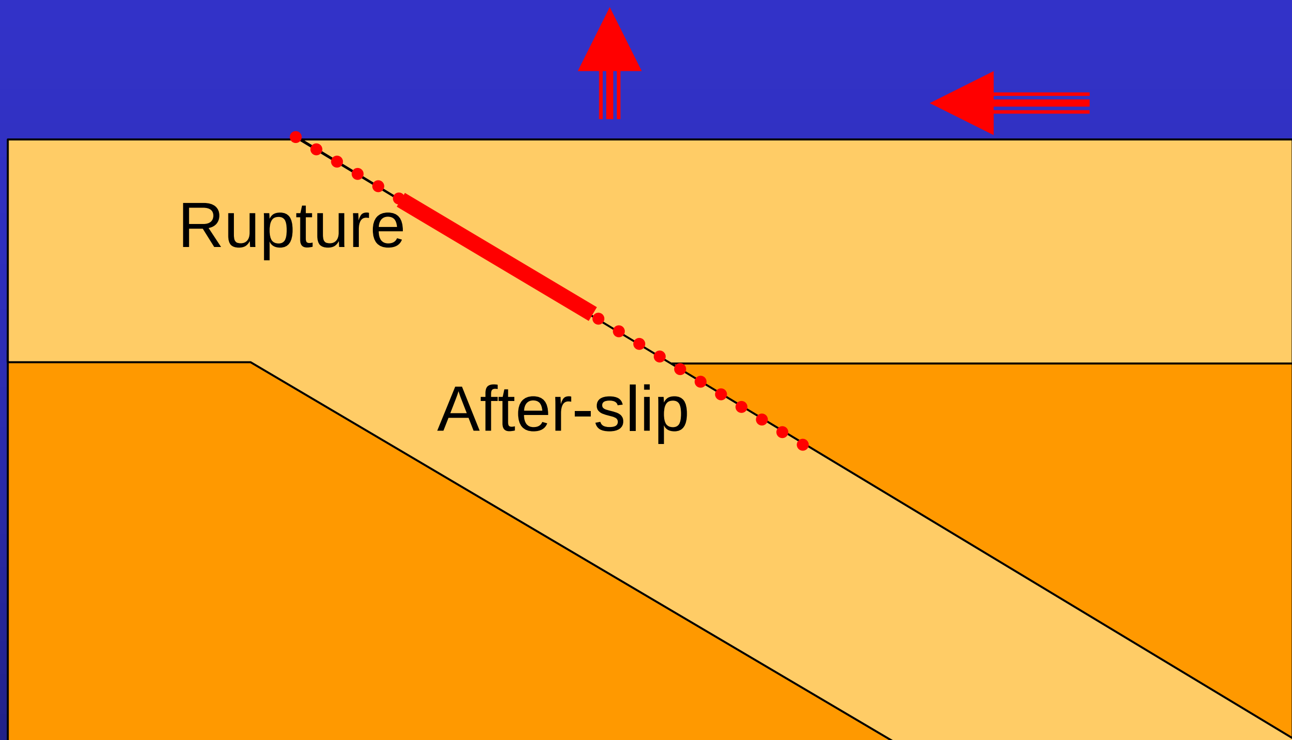
Inter-seismic
deformation rate

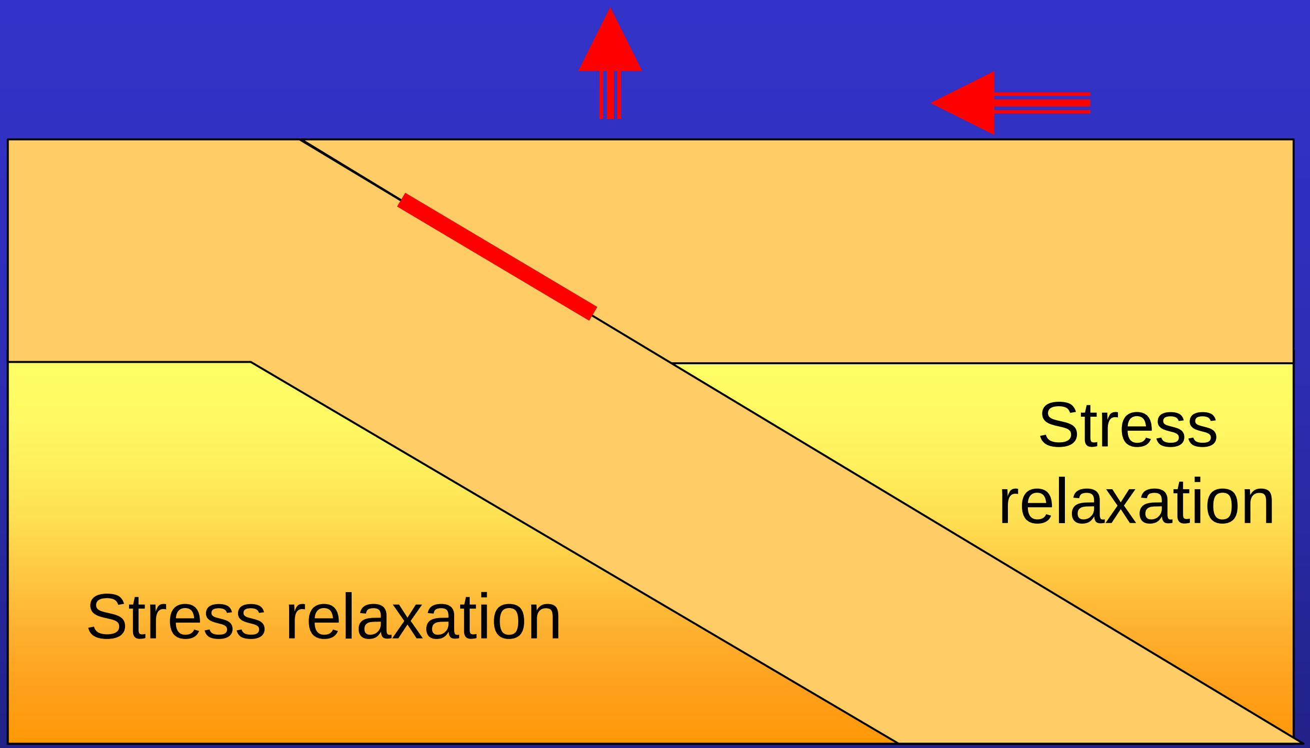
Post-seismic
deformation rate

Co-seismic
displacement



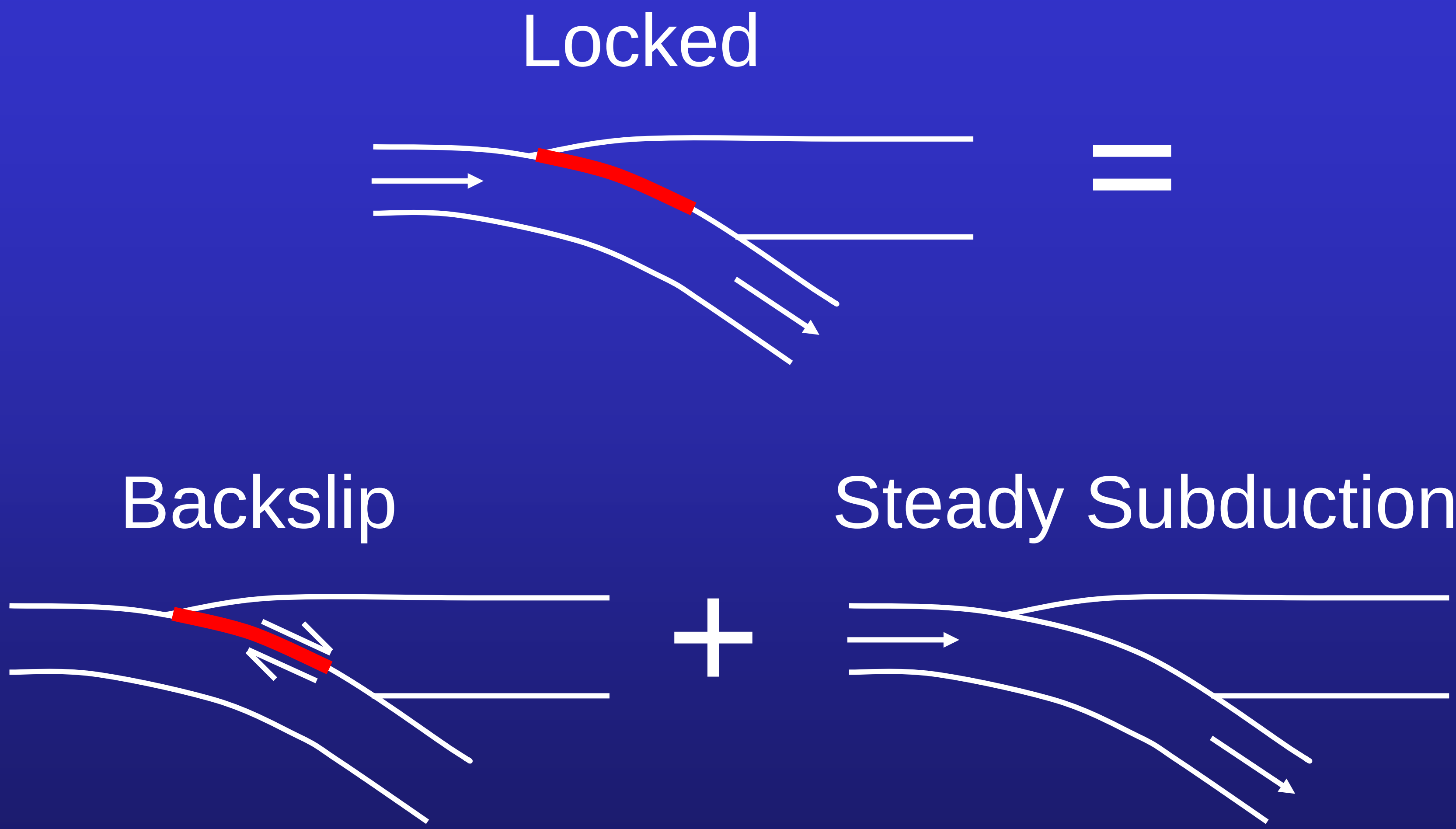
Fault slip vs. stress relaxation

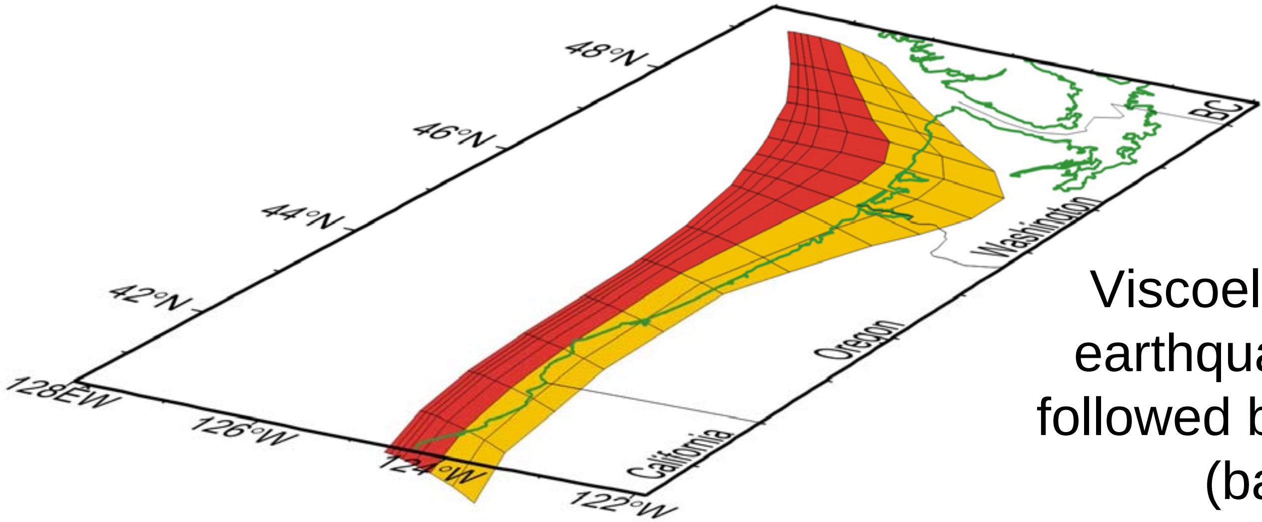

Rupture
After-slip



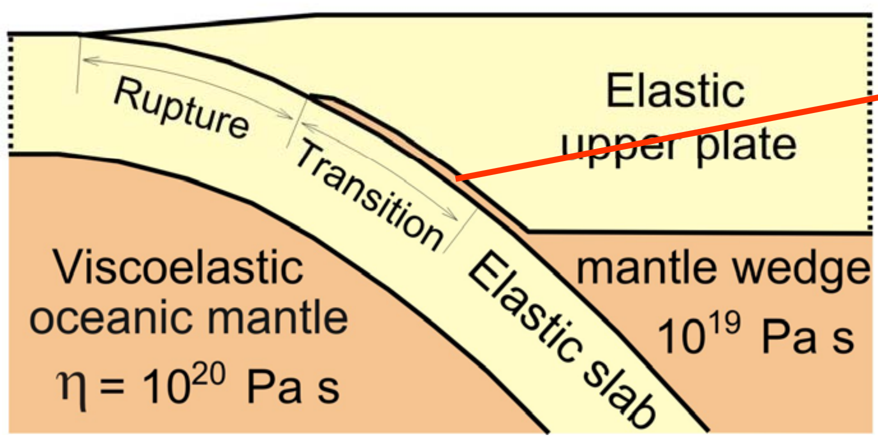
Afterslip: ~ 1 – 10 years?
Relaxation: ~ decades? Hopefully effects of transient and/or nonlinear rheology also become less pronounced

Backslip model for fault locking

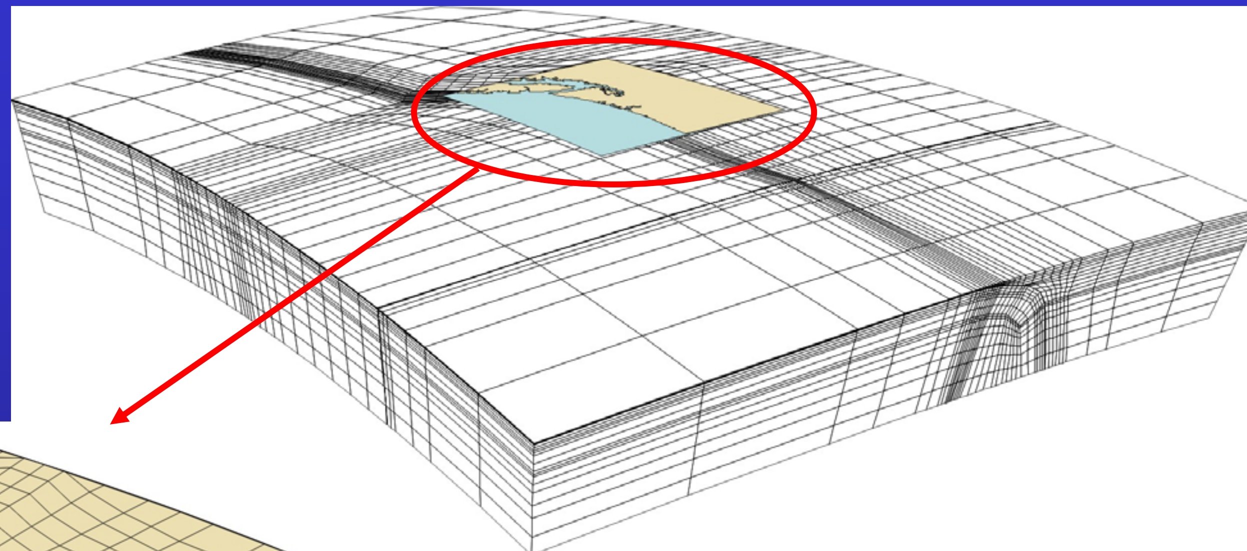

Locked
=
Backslip
+
Steady Subduction

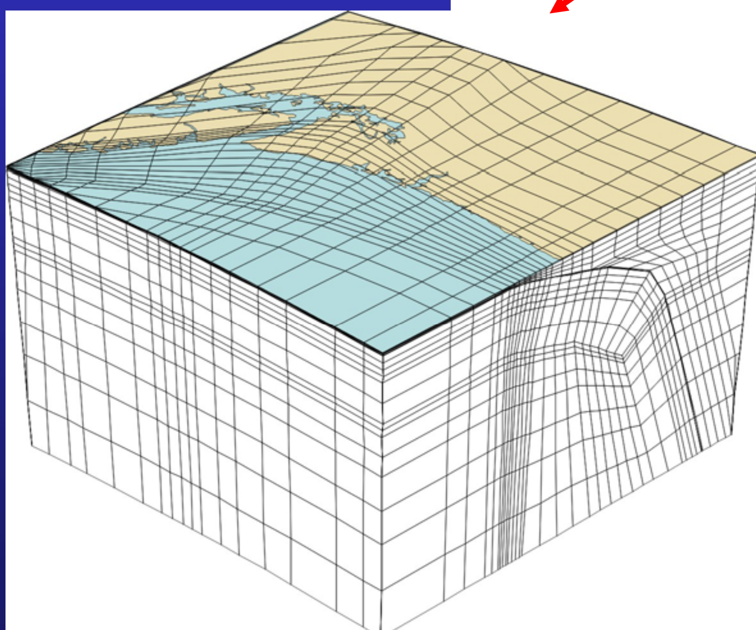


Viscoelastic model:
earthquake (foreslip)
followed by fault locking
(backslip)
Red: Locked (rupture)
Orange: transition



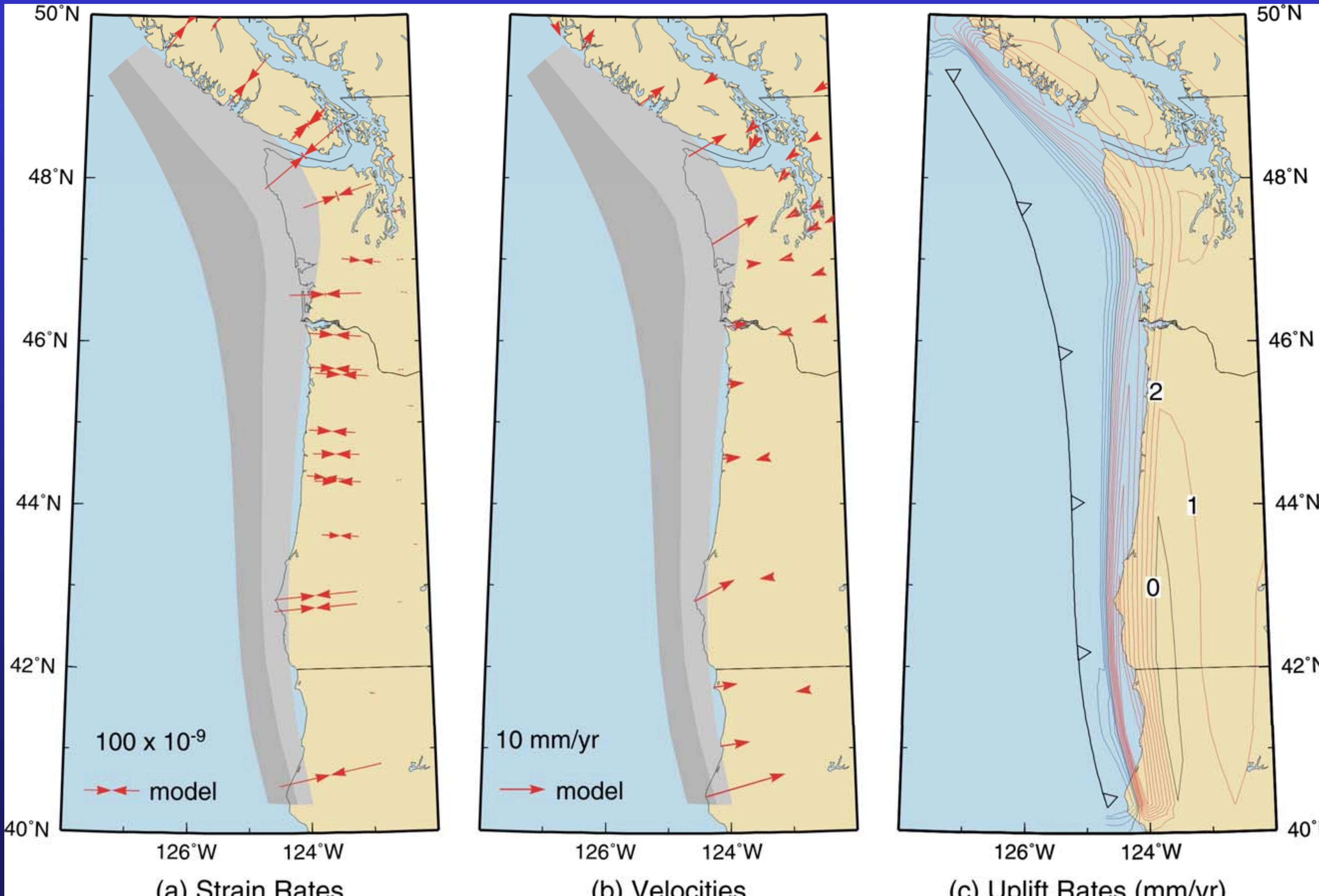
This accounts for some afterslip in a crude way



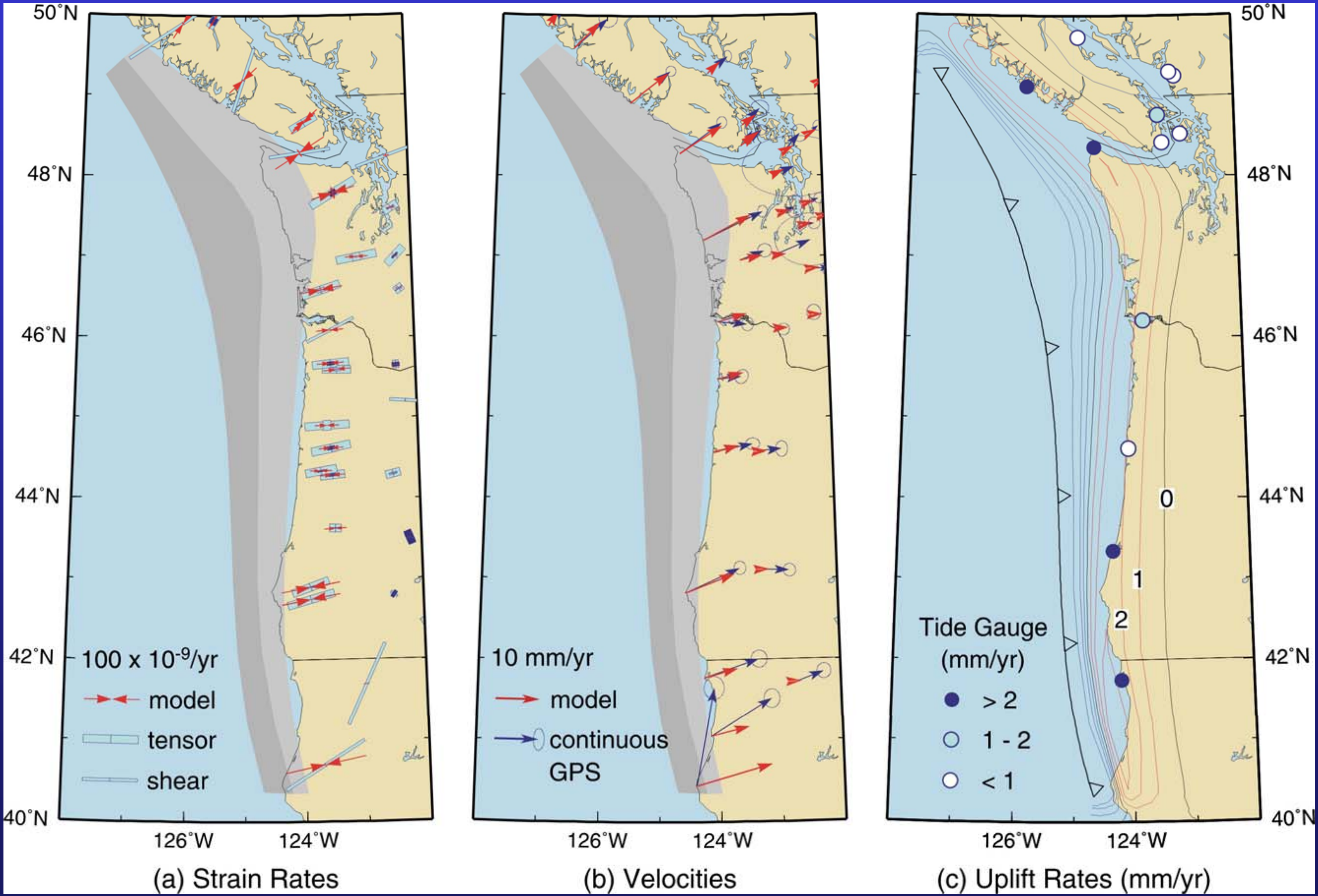


Finite element model;
27-node elements;
Maxwell viscoelastic

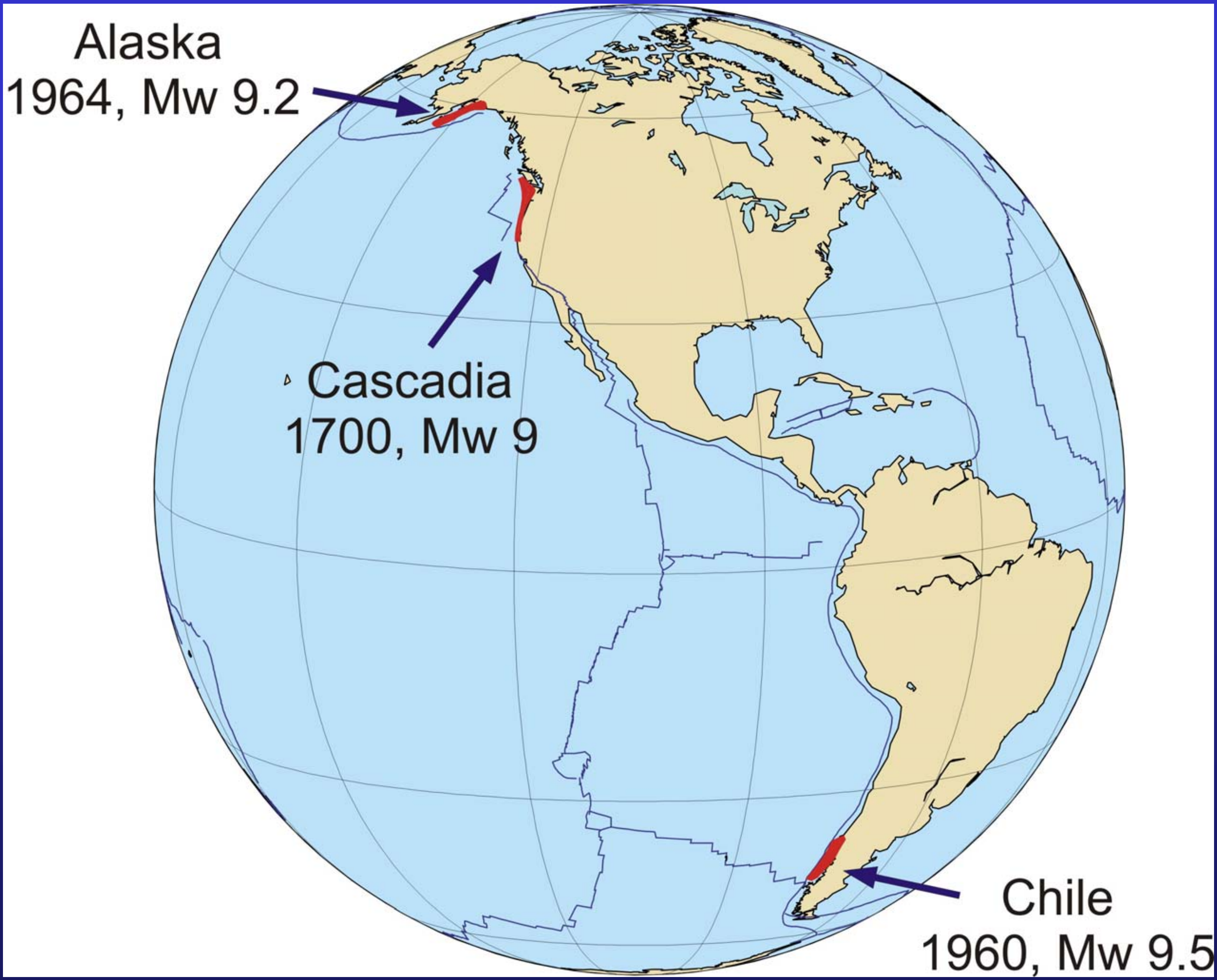
50 years after earthquake



300 years after earthquake (today)

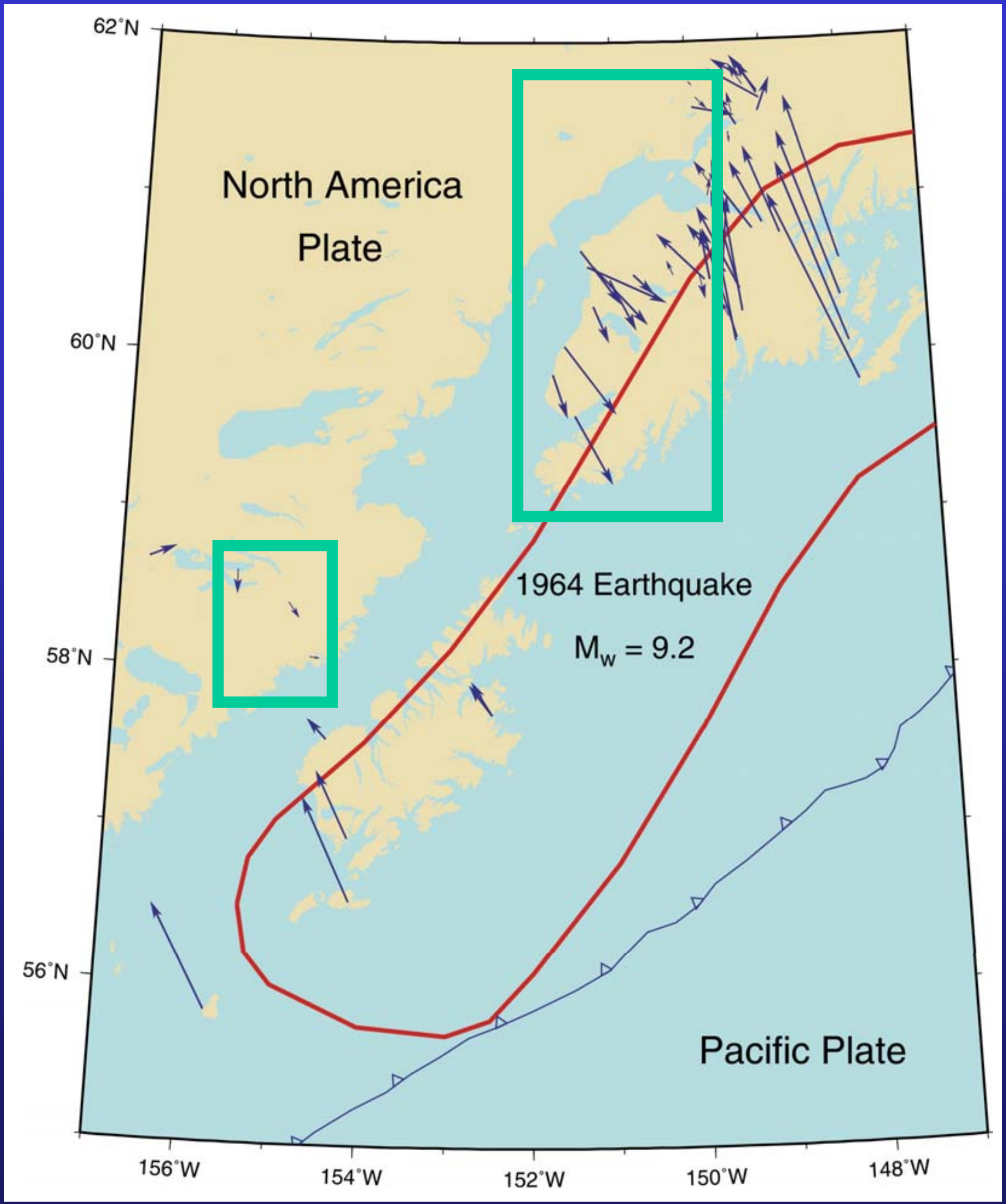


Prolonged post-seismic deformation and stress relaxation

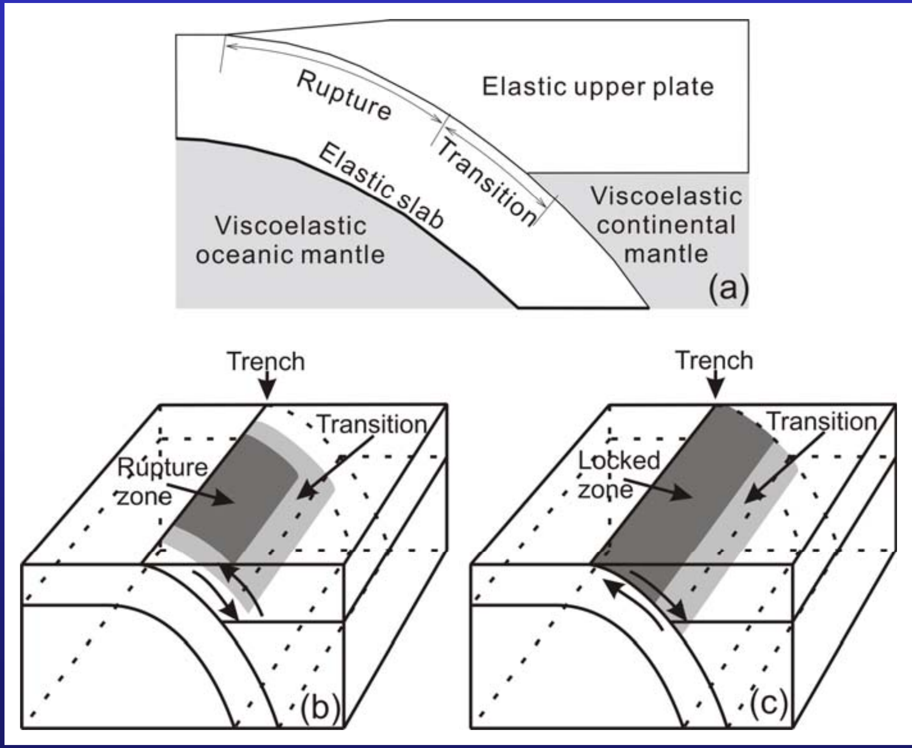

Alaska
1964, Mw 9.2
Cascadia
1700, Mw 9
Chile
1960, Mw 9.5

Alaska GPS campaigns
(1993-1997)

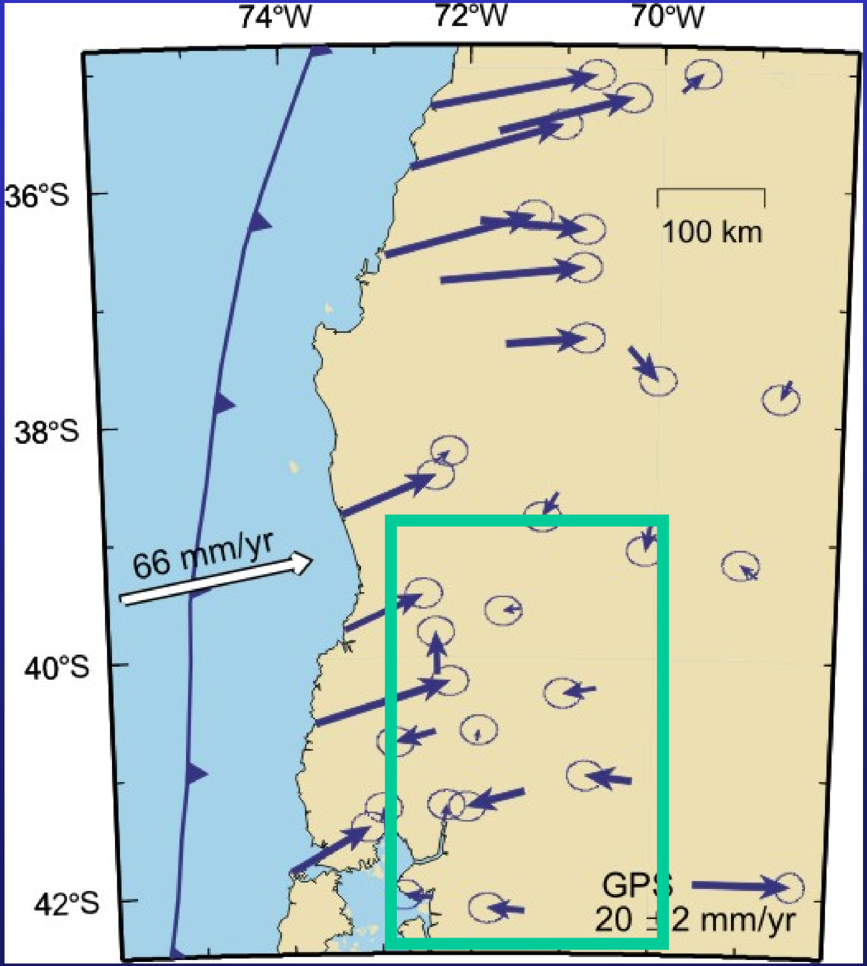
Freymueller et al. (2000, JGR)
Savage et al. (1999, GRL)



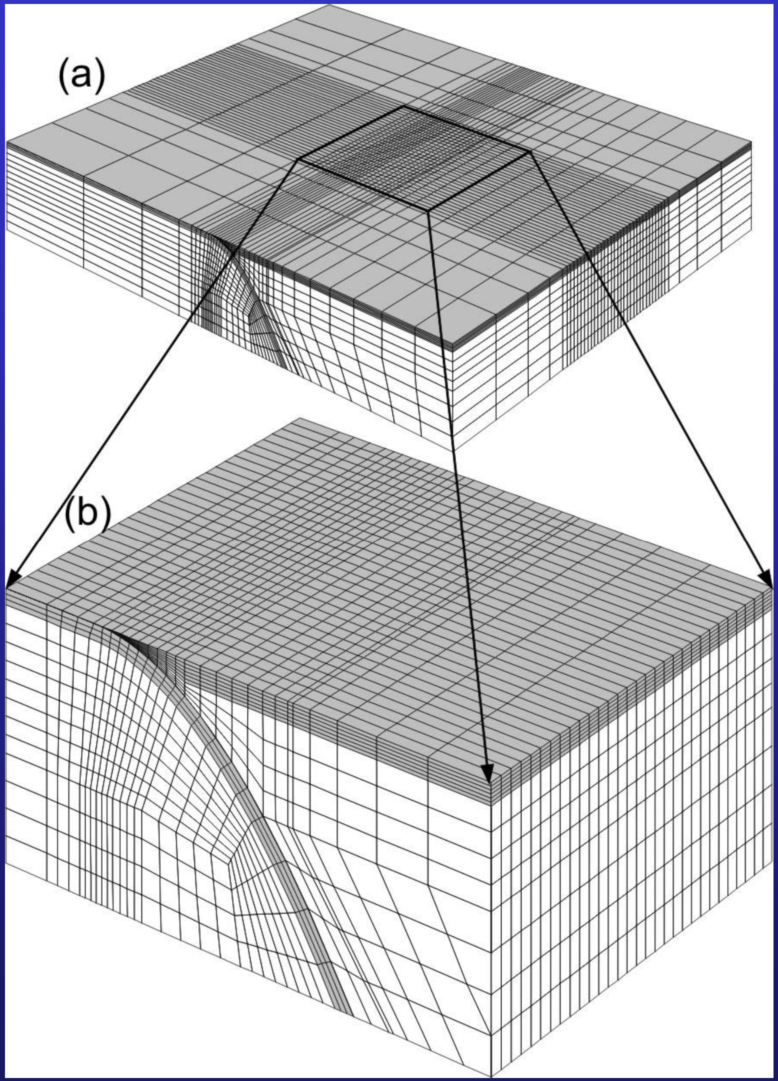
3D finite element model of mantle stress relaxation; an earthquake (foreslip) followed by fault locking (backslip)



GPS data at Chile margin ~ 35 years after the 1960 great earthquake (Mw 9.5) (Klotz et al., EPSL, 2001)



8-node finite elements;
Maxwell viscoelastic



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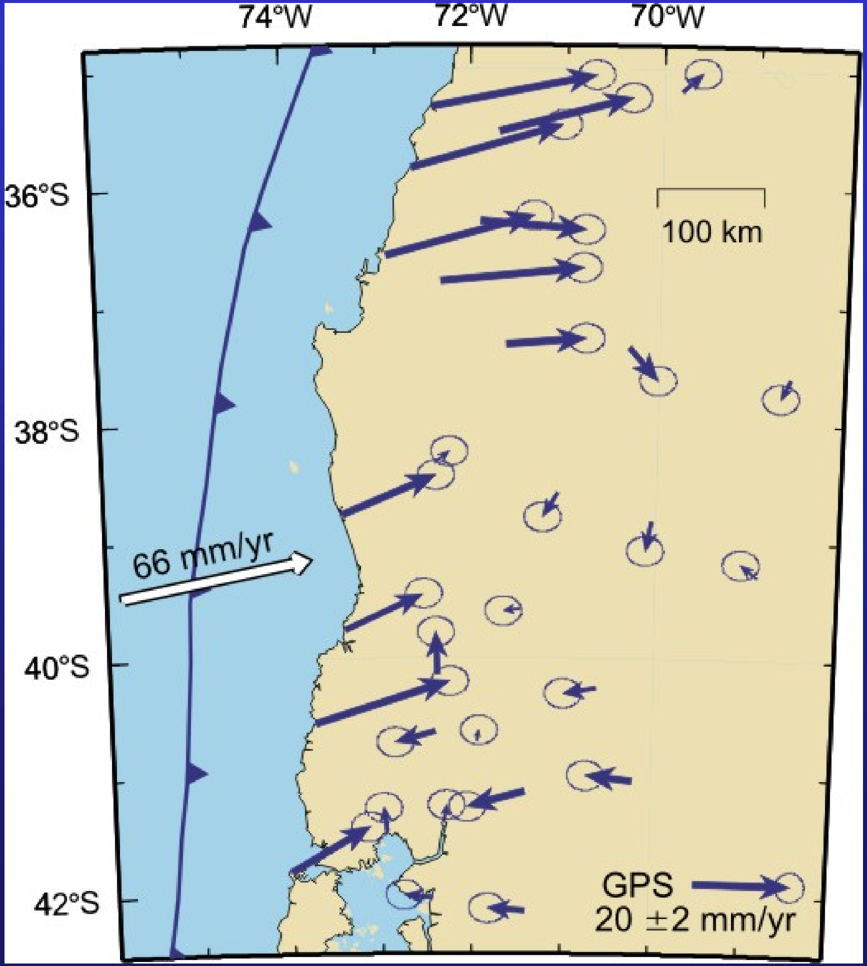
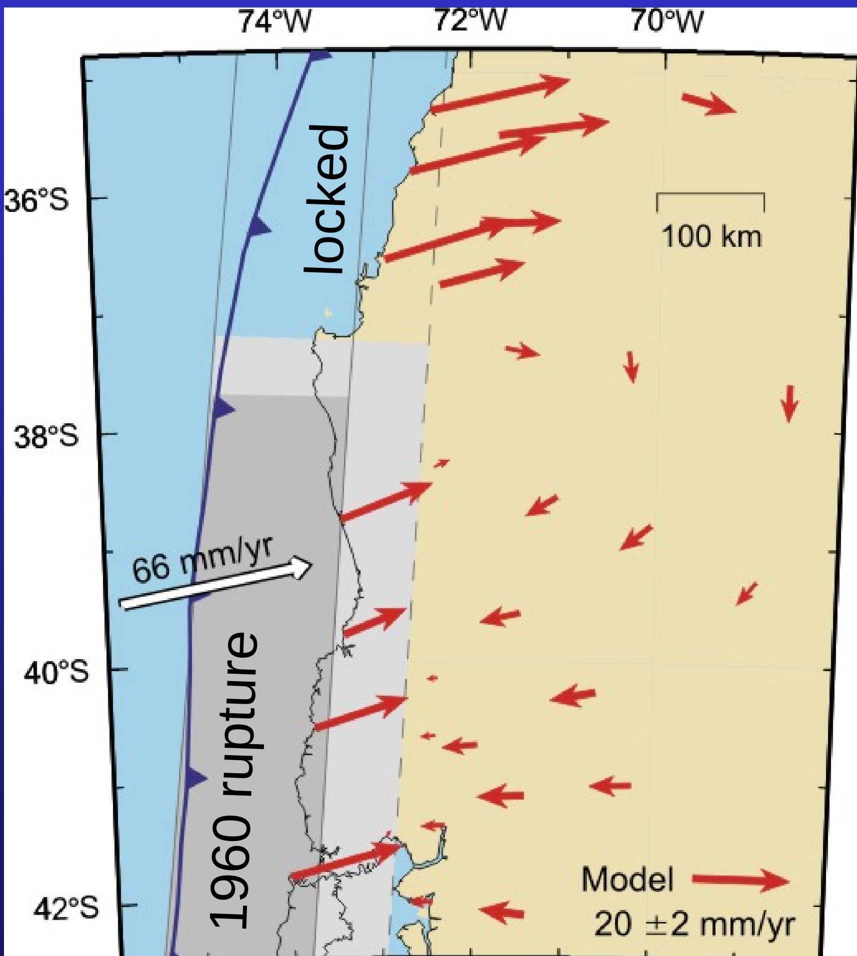
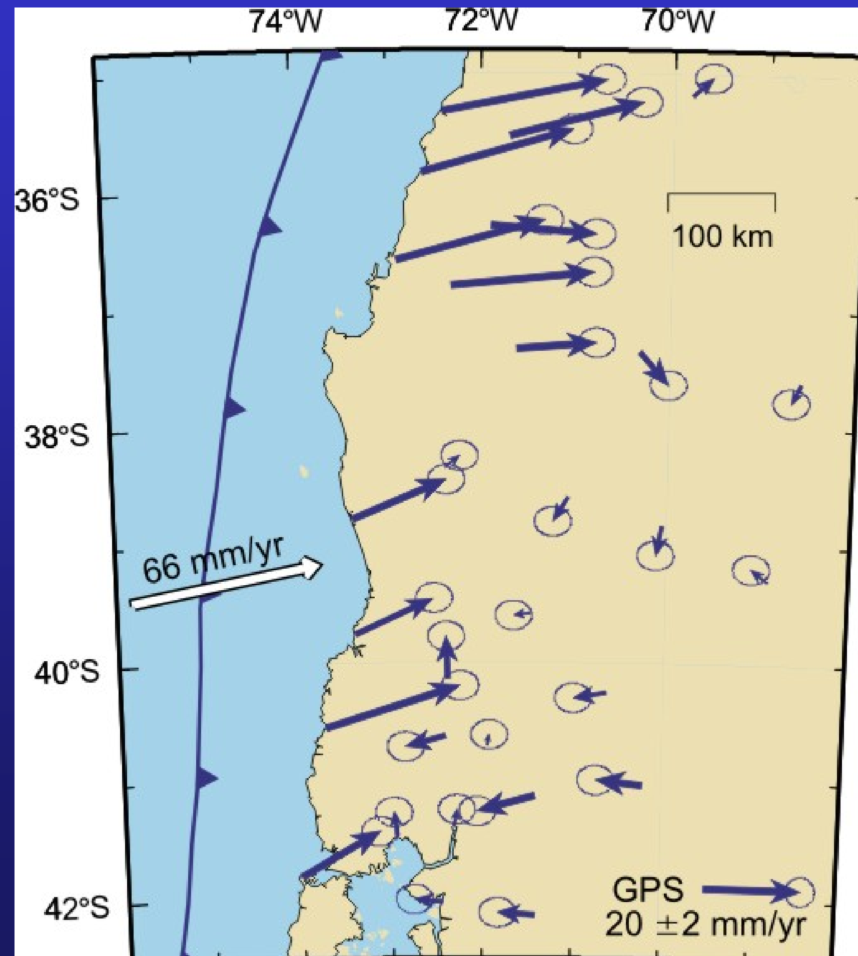


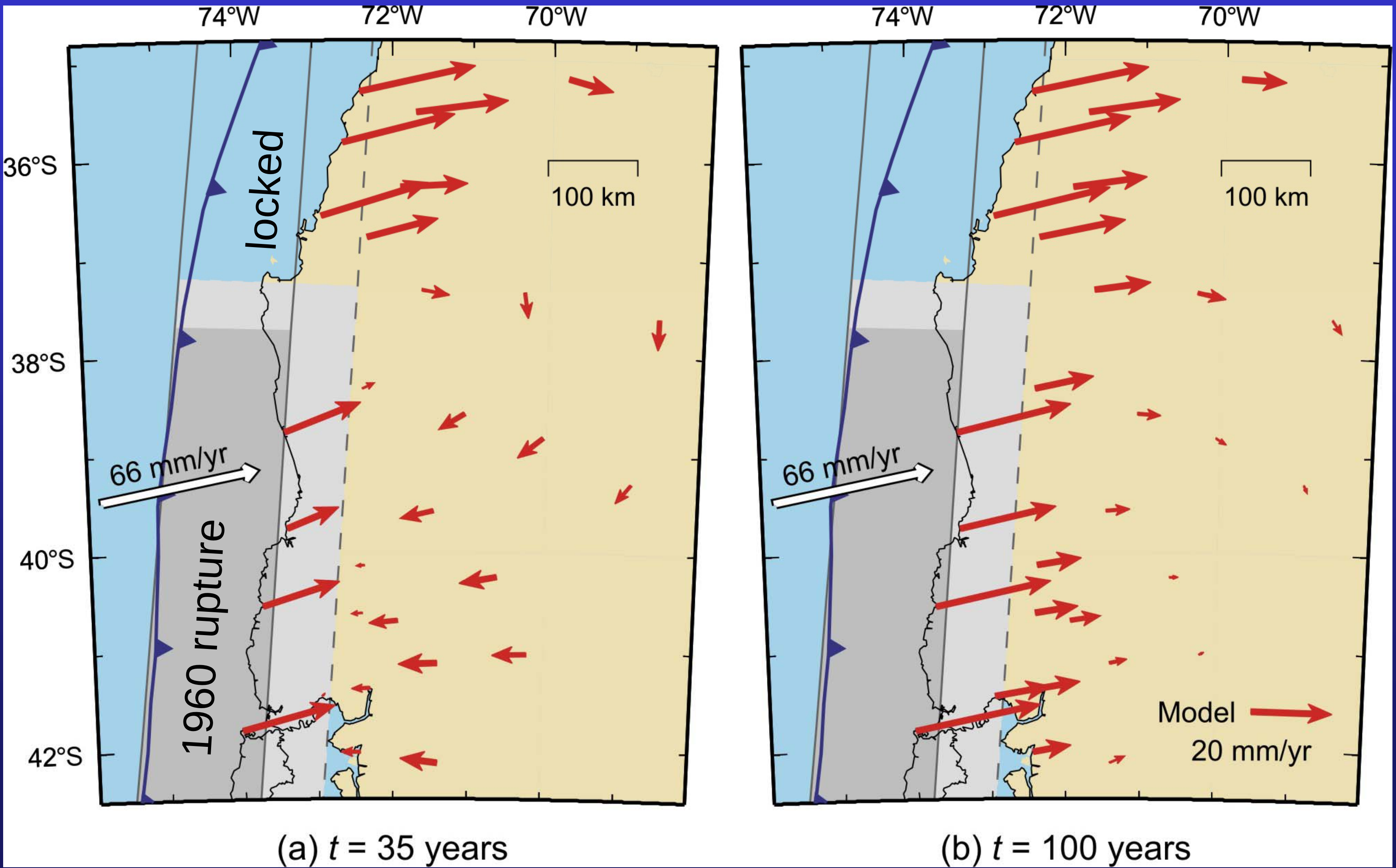
3D Viscoelastic model of post-seismic deformation (mantle viscosity 2.5 x 10^{19} Pa s) (Hu et al., JGR, 2004)



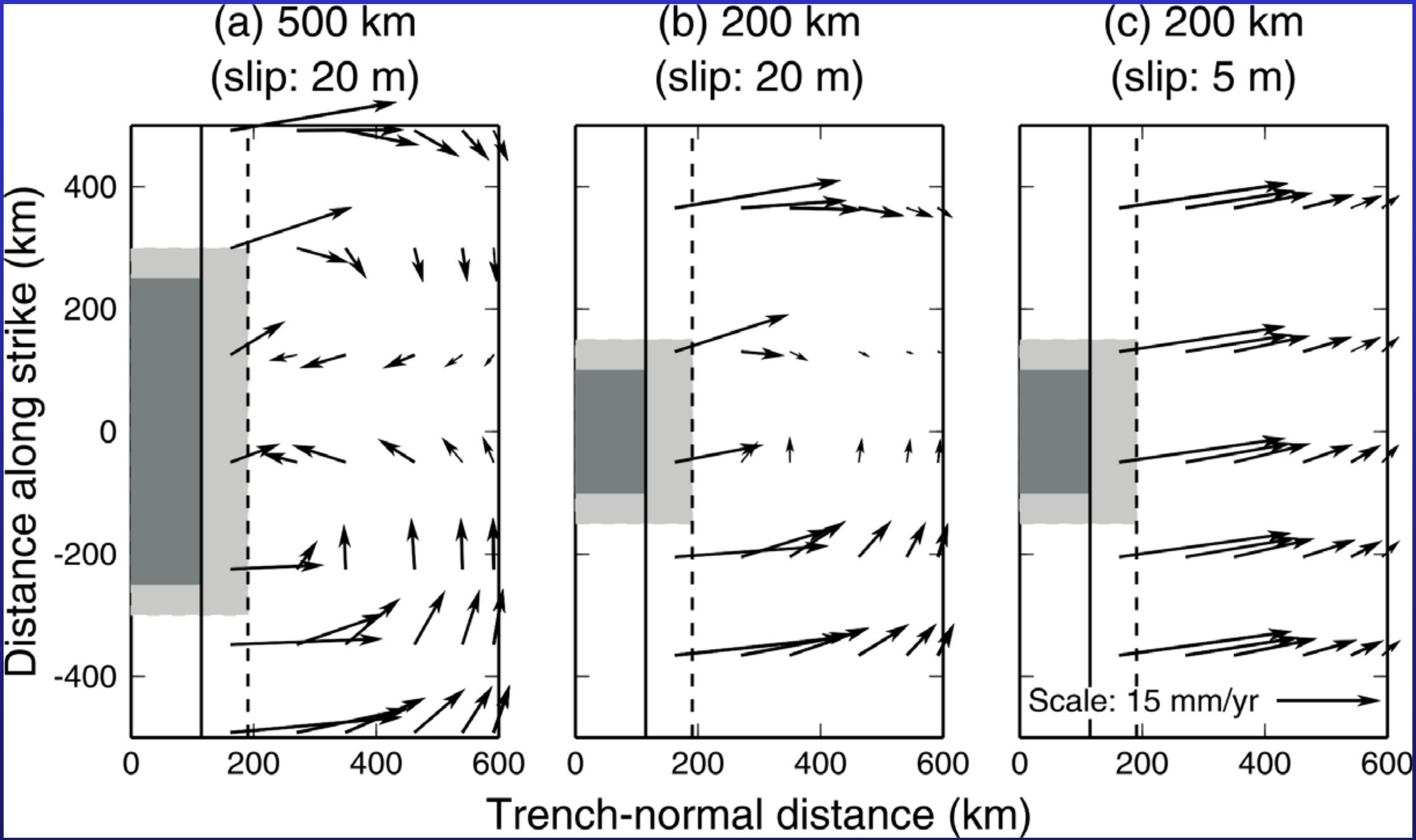
GPS data at Chile margin ~ 35 years after the 1960 great earthquake (Mw 9.5) (Klotz et al., EPSL, 2001)



3D Viscoelastic model of crustal deformation following 1960 (M 9.5) Chile earthquake (Hu et al., JGR, 2004)



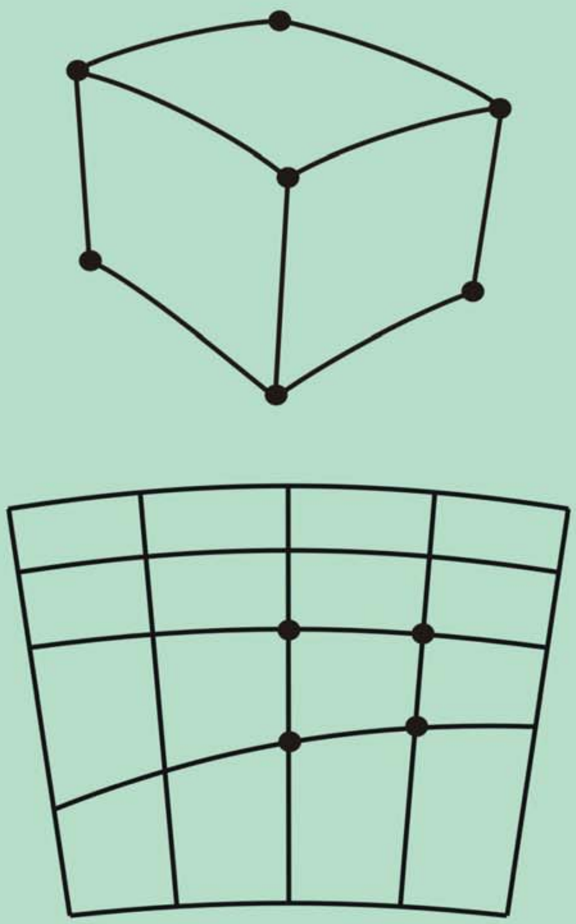
Importance of along-strike rupture length and slip magnitude
(35 years after earthquake; mantle viscosity 2.5 x 10^{19} Pa s)
(Hu et al., 2004)



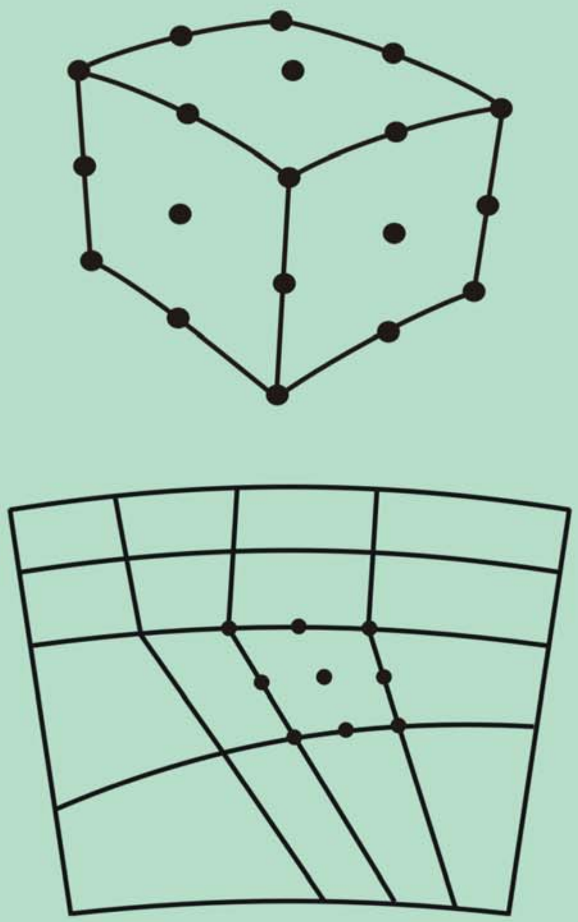
Summary

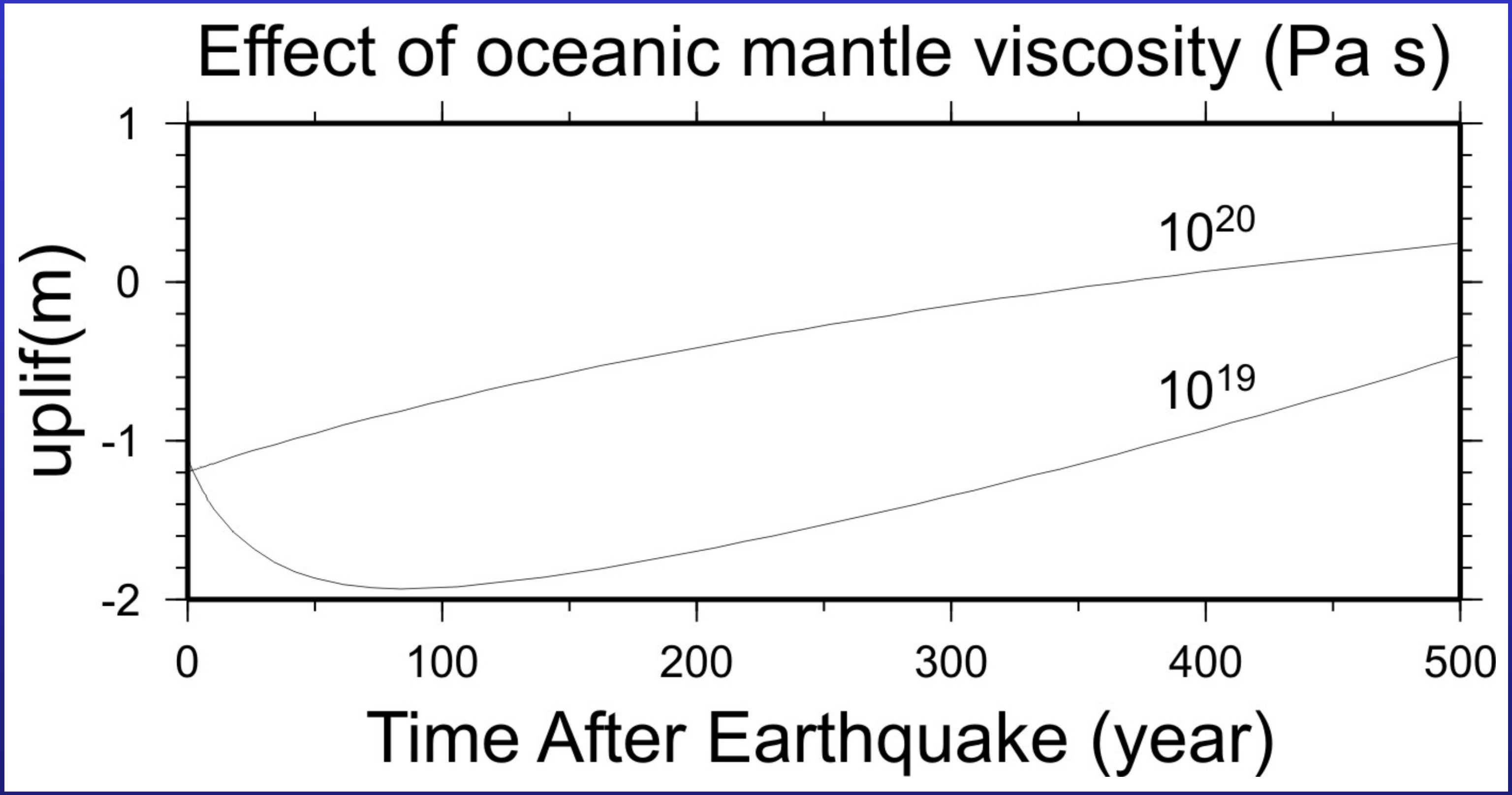
- A great subduction earthquake is the rupture of a weak plate boundary fault; earthquake cycles cause small stress changes but large strain rates
- Afterslip (or interseismic slip) and stress relaxation cannot always be distinguished (model-dependent)
- Mantle wedge viscosity required in stress relaxation models is ~ 10^{19} Pa s
- Prolonged seaward motion of inland GPS sites can be explained as post-seismic deformation following long-rupture great earthquakes

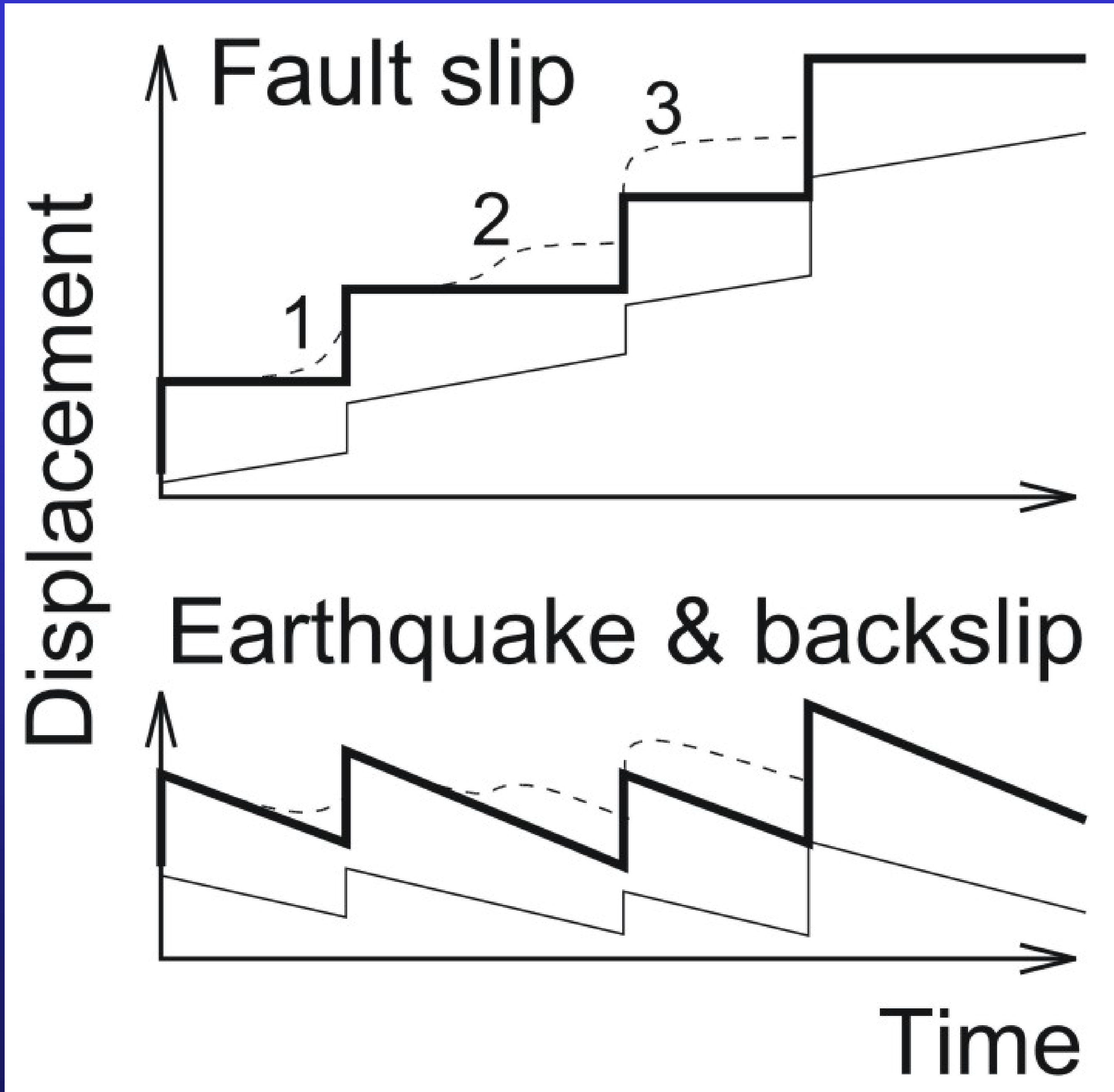
8-node elements

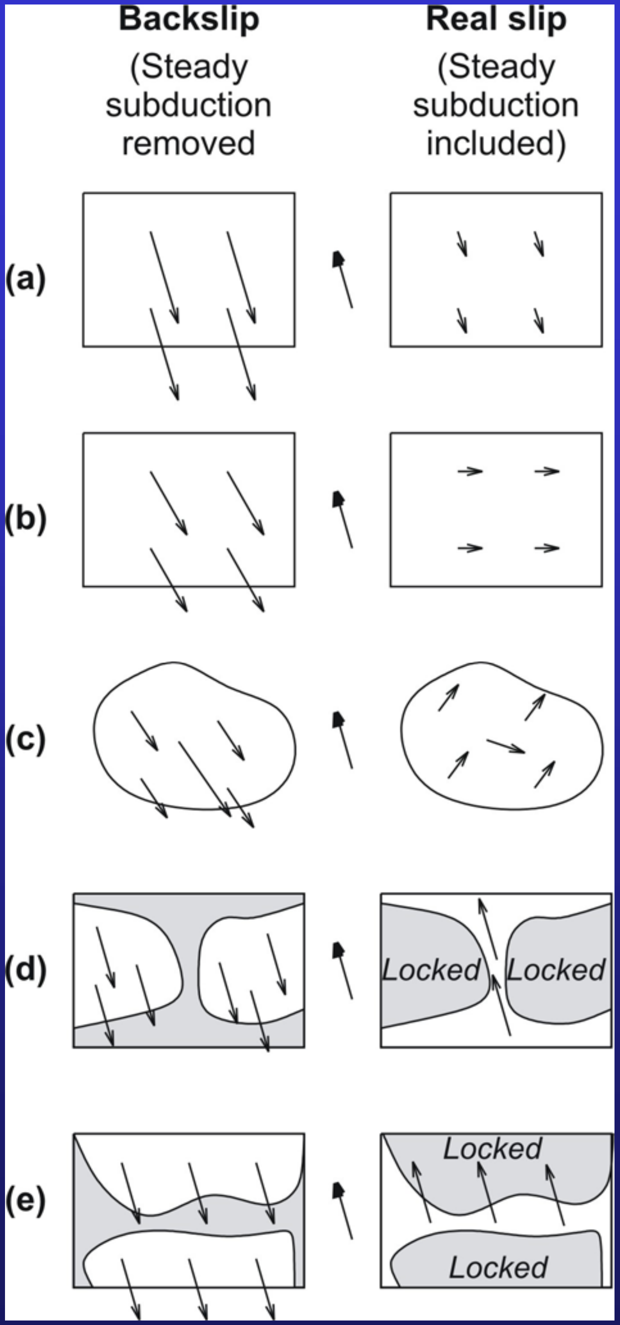


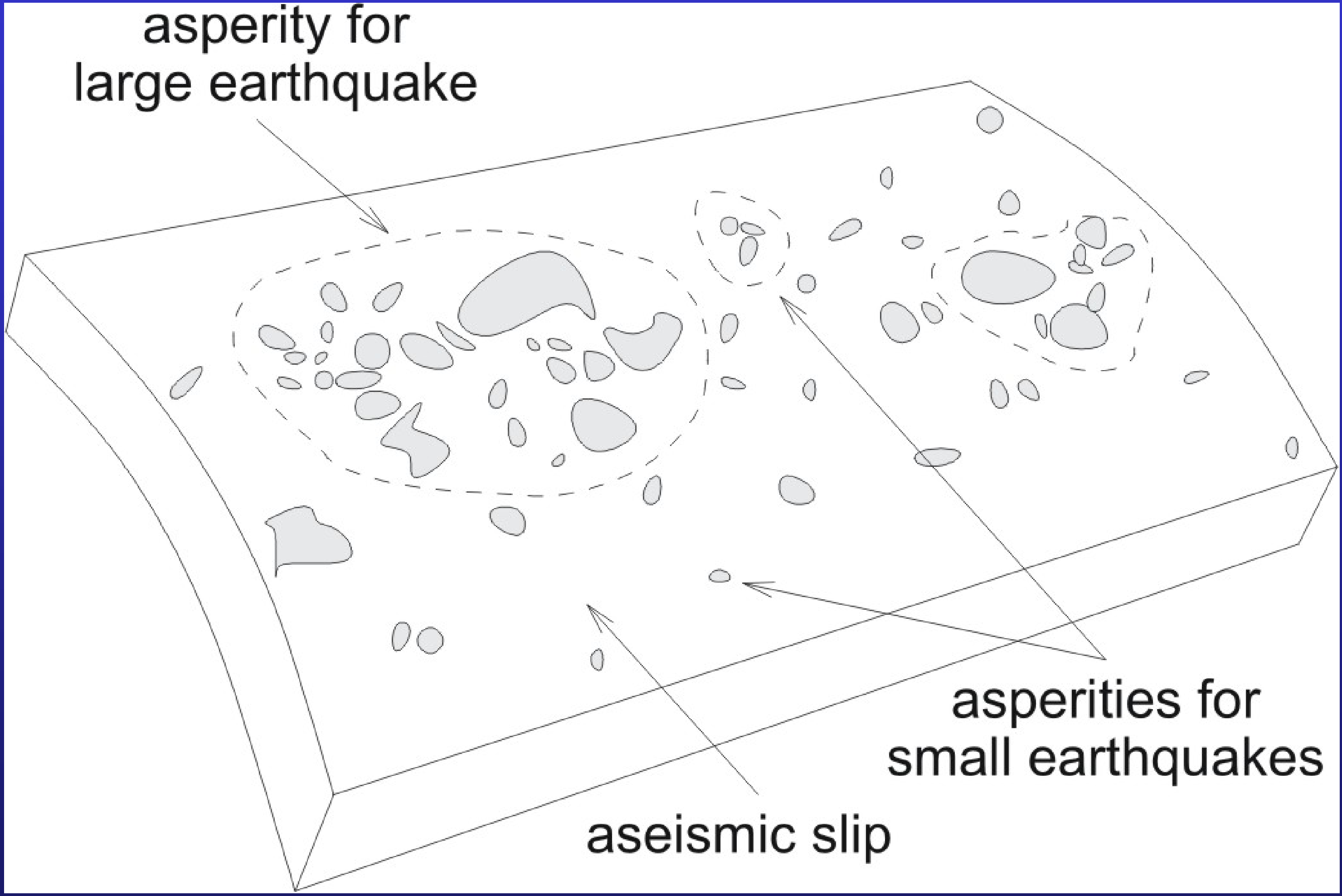
27-node elements




Effect of oceanic mantle viscosity (Pa s)
uplif(m)
1
0
-1
-2
10^{20}
10^{19}
0
100
200
300
400
500
Time After Earthquake (year)


Fault slip
Displacement
1
2
3
Earthquake & backslip
Time


Backslip
(Steady
subduction
removed
Real slip
(Steady
subduction
included)
(a)
(b)
(c)
(d)
Locked
Locked
(e)
Locked
Locked


asperity for
large earthquake
asperities for
small earthquakes
aseismic slip

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