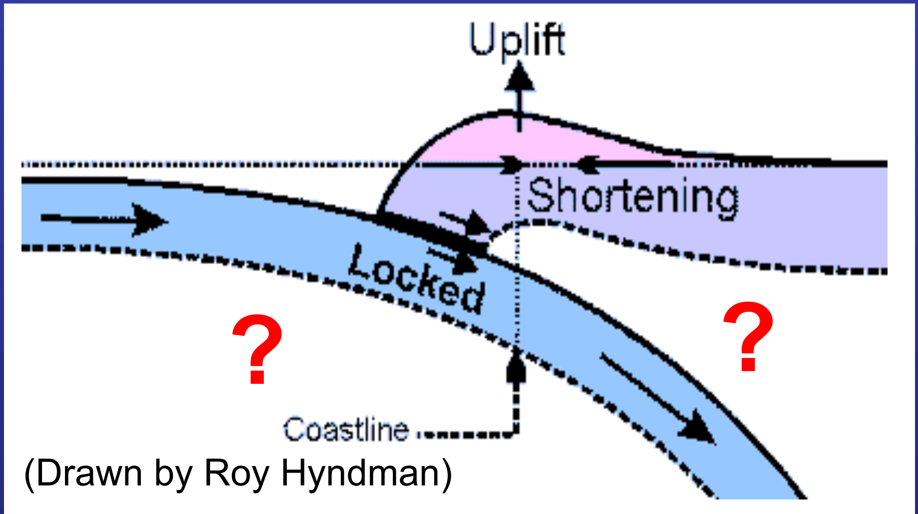
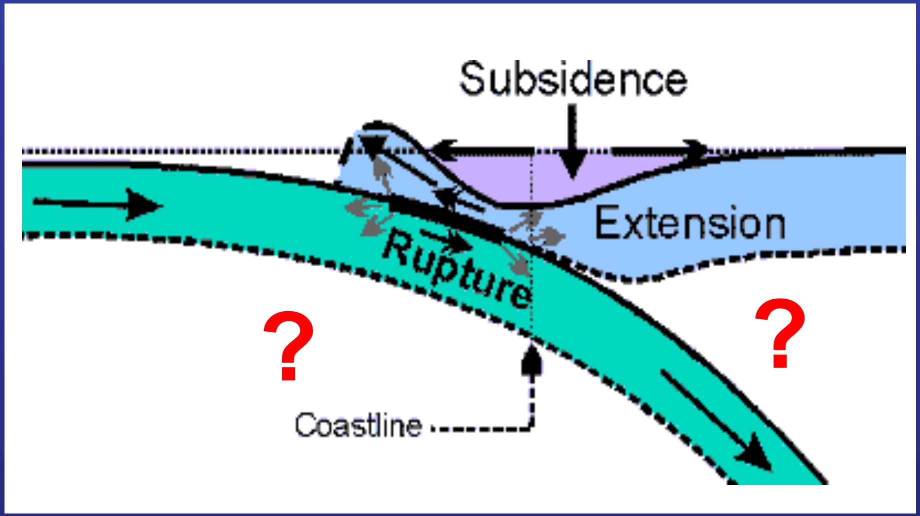
Deformation cycles of great subduction earthquakes in a viscoelastic Earth

Kelin Wang

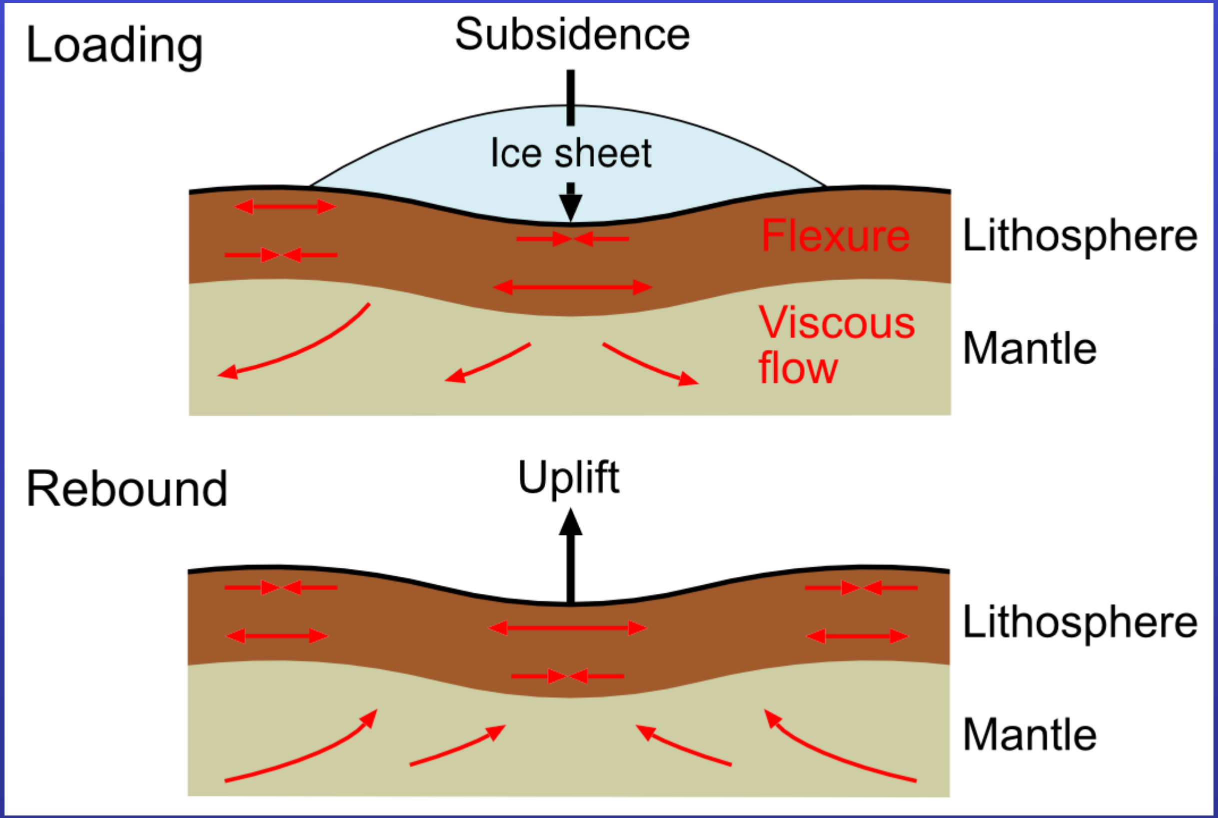
Pacific Geoscience Centre, Geological Survey of Canada
School of Earth and Ocean Science, University of Victoria



(Drawn by Roy Hyndman)



Global Isostatic Adjustment (GIA) (or Post-glacial rebound)



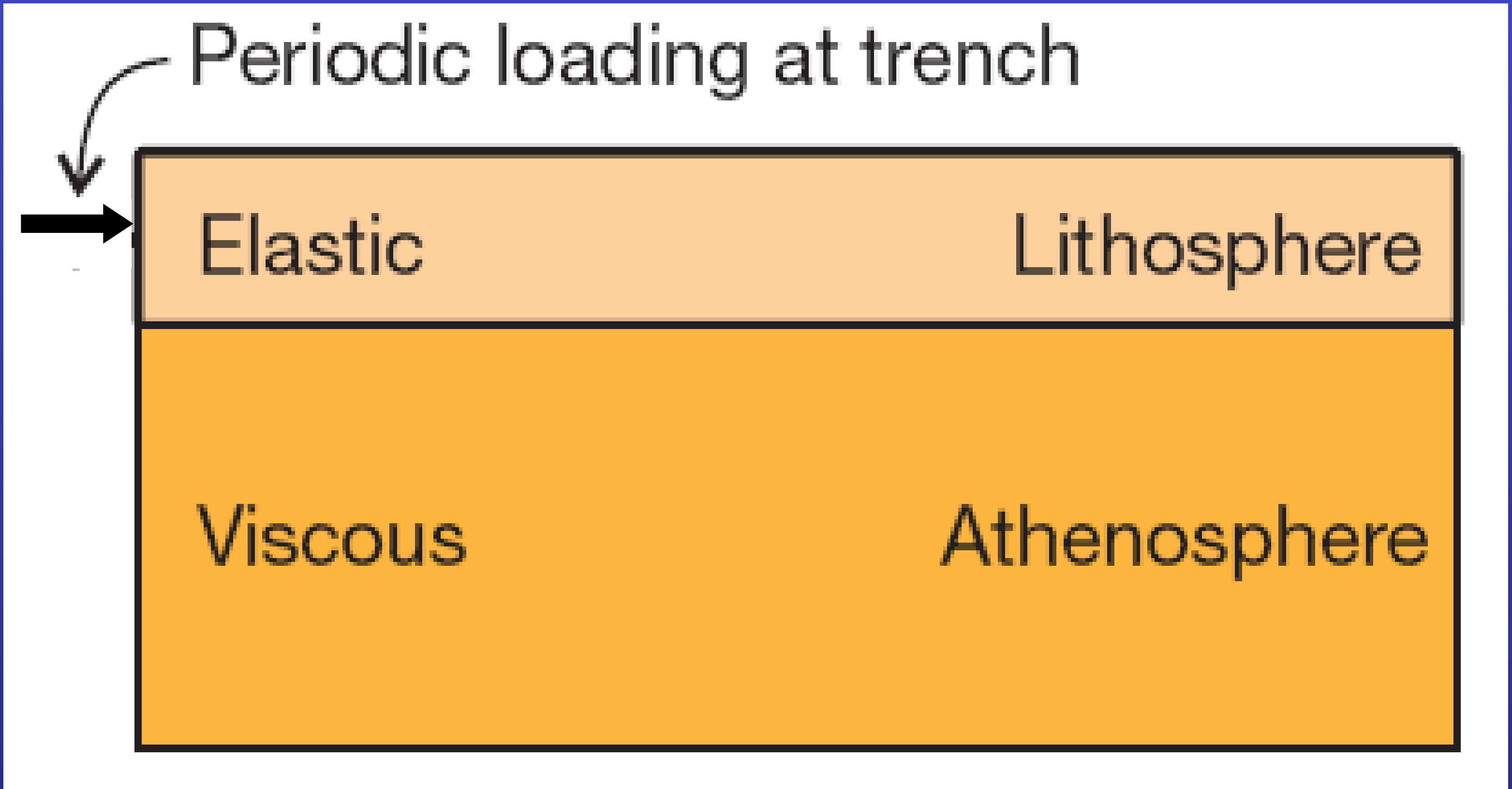
Nansen (1928) established Fennoscandian ice sheet history

Haskell (1935) determined a mantle viscosity of 10^{21} Pa s

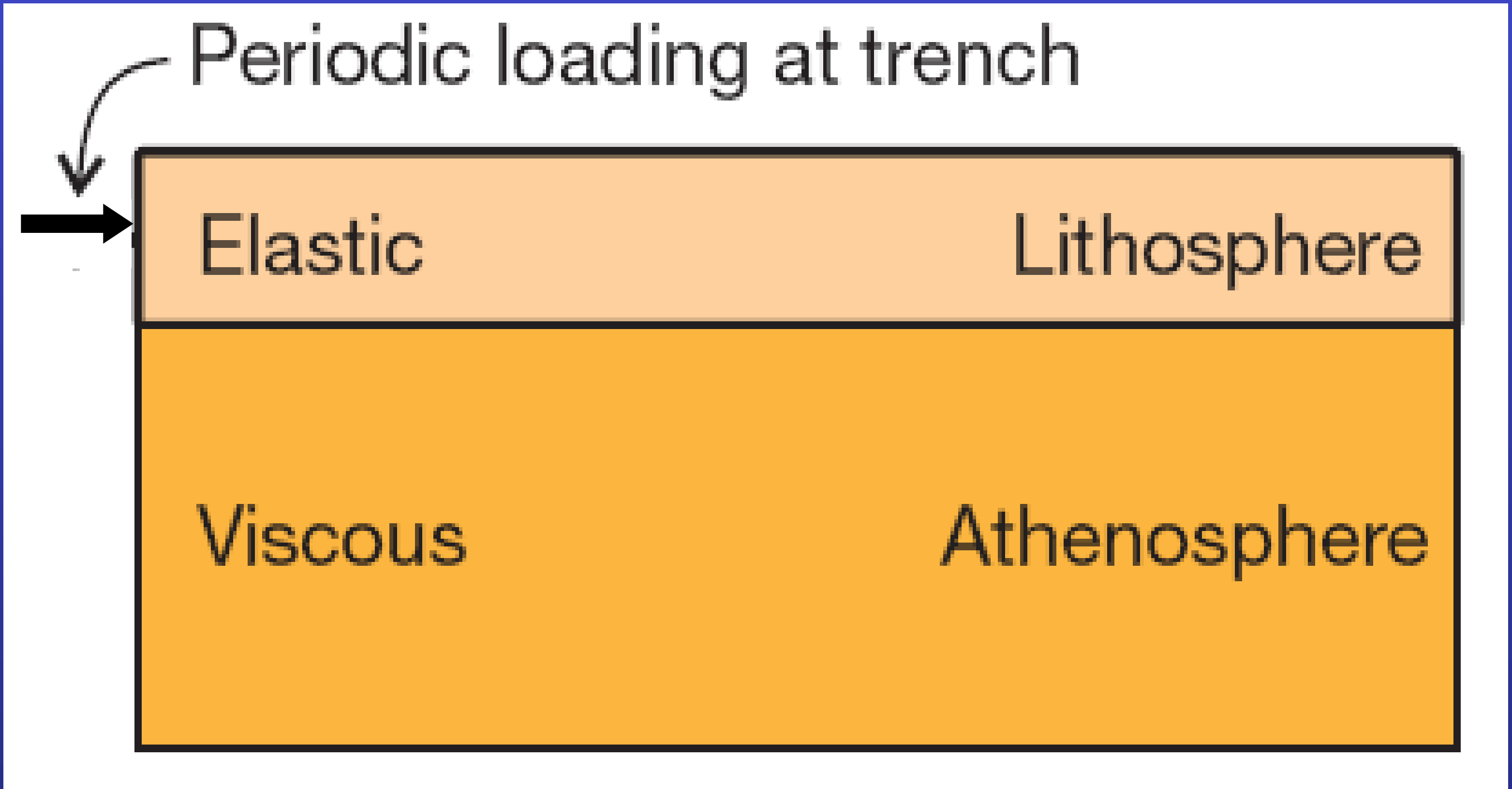
Commonly accepted global average today: 10^{20} - 10^{21} Pa s

Viscosity of honey at room temperature: about 1000 Pa s

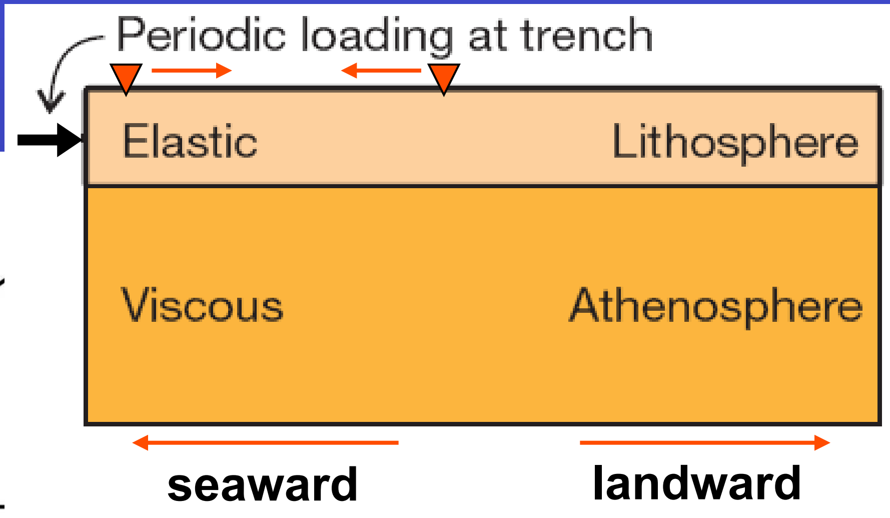
When plate tectonics just gained recognition:

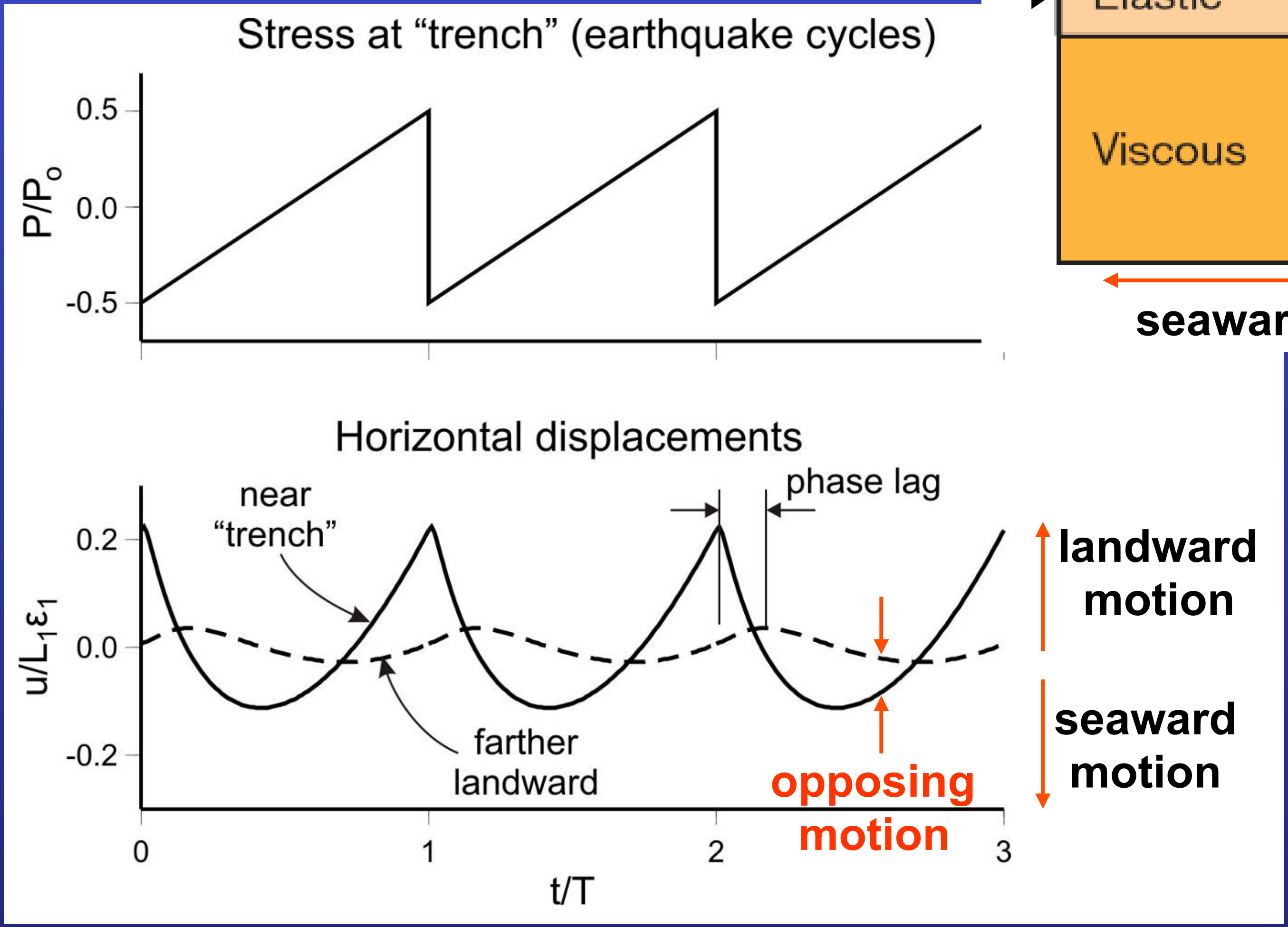


1-D stress diffusion model of Elssaser (1969), Bott and Dean (1973)


Periodic loading at trench
Elastic
Lithosphere
Viscous
Athenosphere

Based on 1-D stress diffusion model of Elssaser (1969), Bott and Dean (1973)





Saw-tooth solution by Wang (1995)

Earth rheology for different timescales

Viscous

Viscoelastic

Elastic

Time-independent plasticity (shallow depths)

Mantle convection

Post-glacial rebound

Earthquake cycle

Post-seismic deformation

Earthquake rupture

millions of years

millennia

centuries

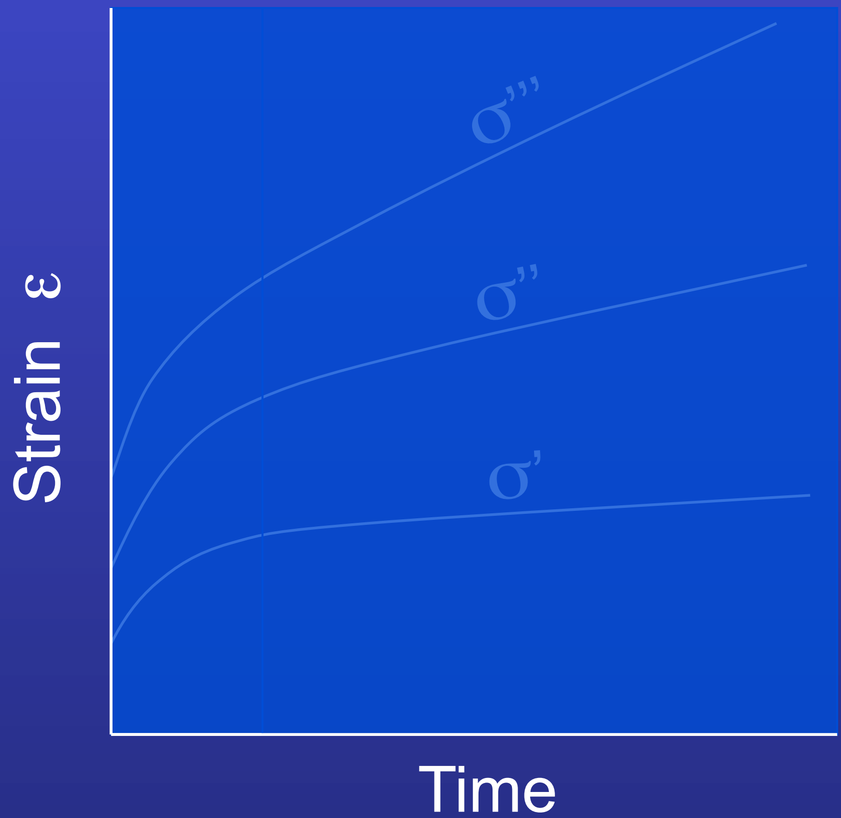
decades

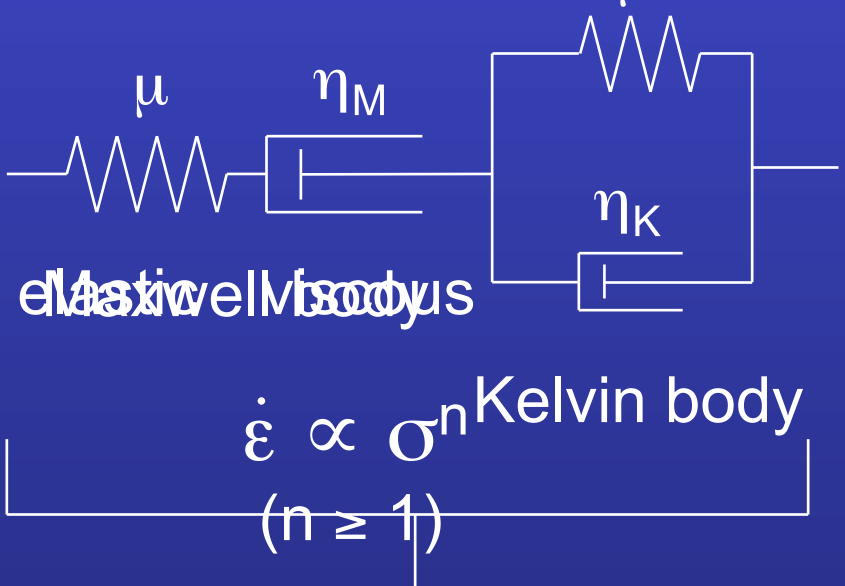
years

seconds

$$C = M_o / M_{o\_ref}$$

$$T_M = C\,\eta_M/\mu \qquad T_K = C\,\eta_K/\mu$$





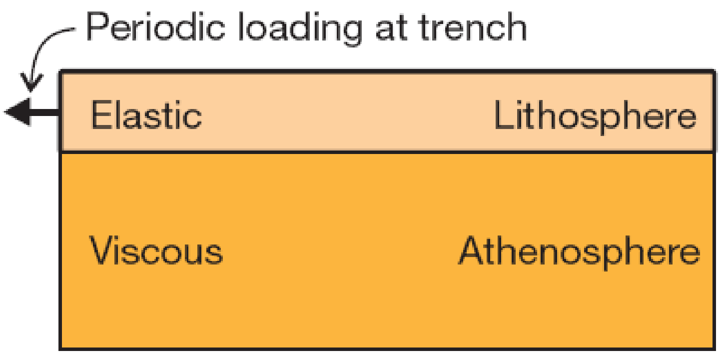
$$\dot{\varepsilon} \propto \sigma^n$$

$(n \geq 1)$

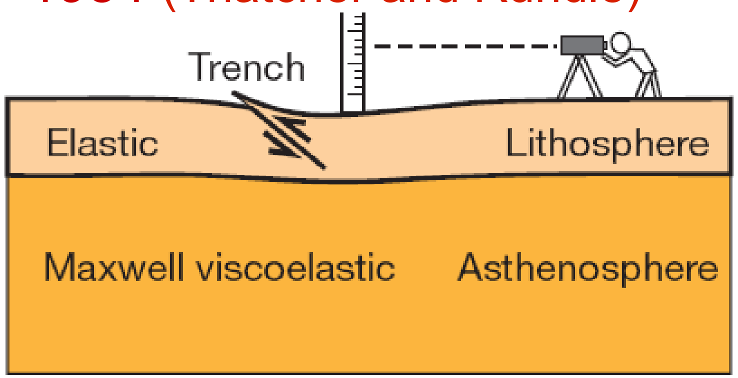
Bi-viscous Burgers body

We’ve come a long way in monitoring and modeling earthquake deformation

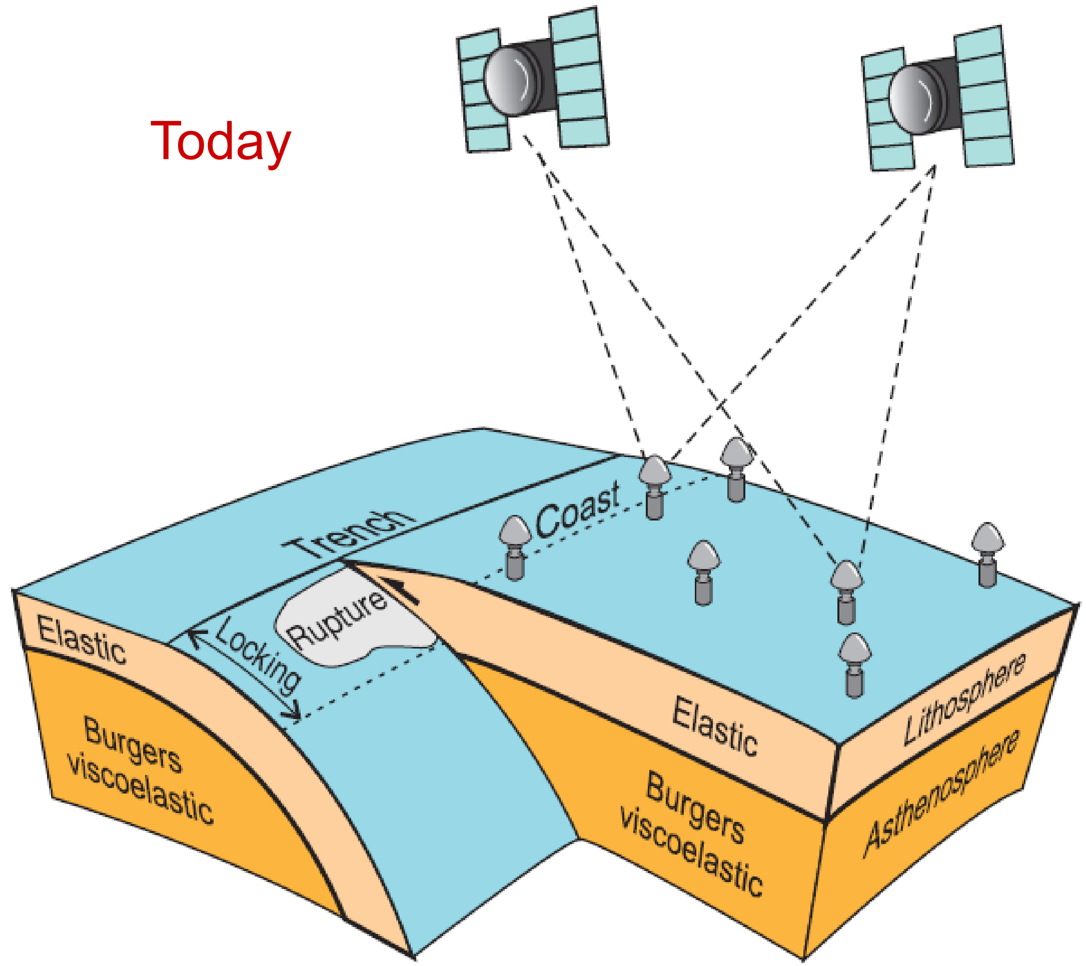
1973 (Bott and Dean)



1984 (Thatcher and Rundle)



Today



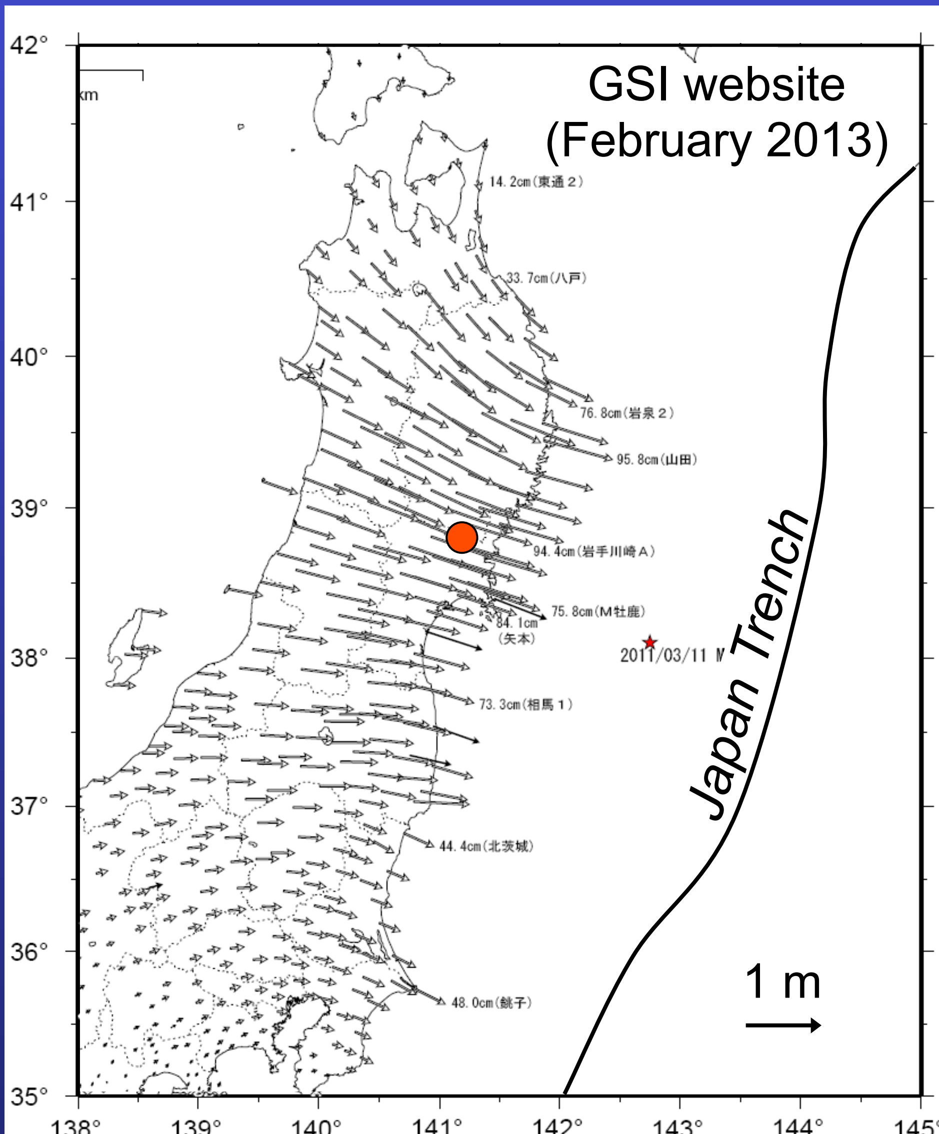
Wang, Hu, He (Nature, 2012)

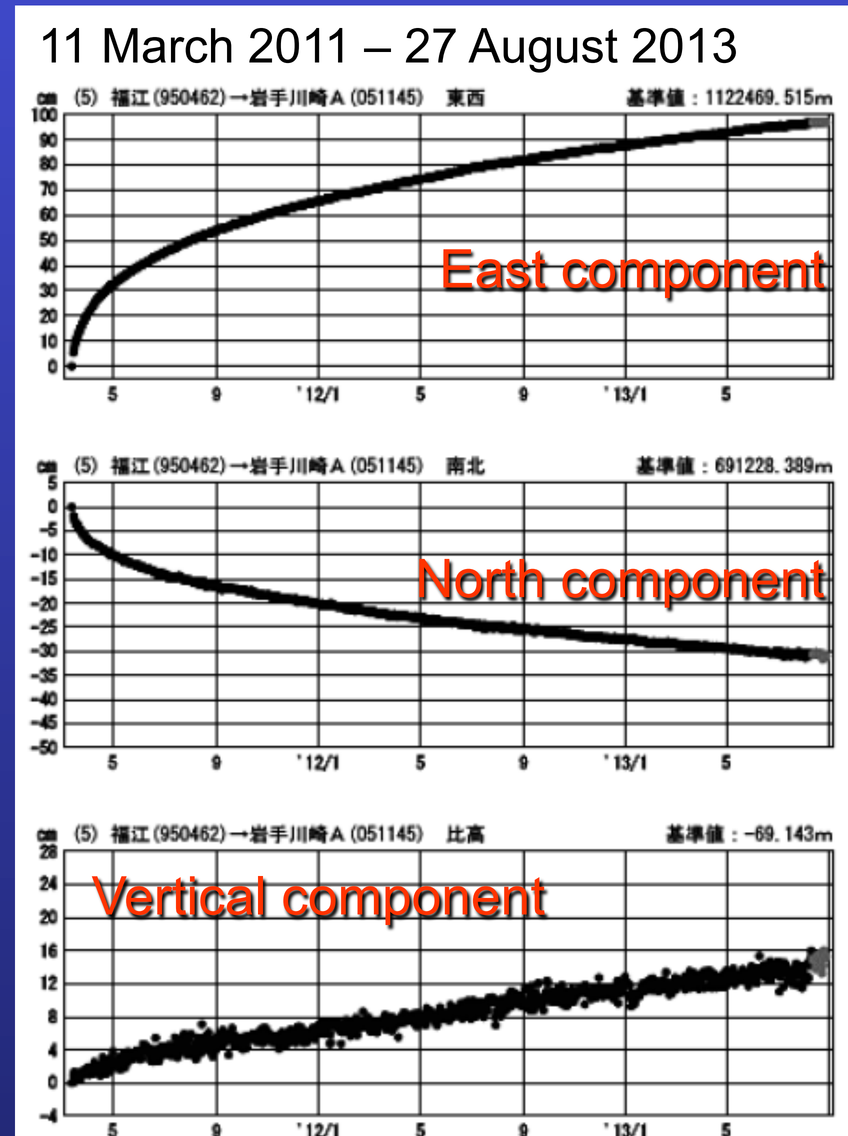
How do we observe a full earthquake cycle?

Subduction earthquake cycles – a few hundred years

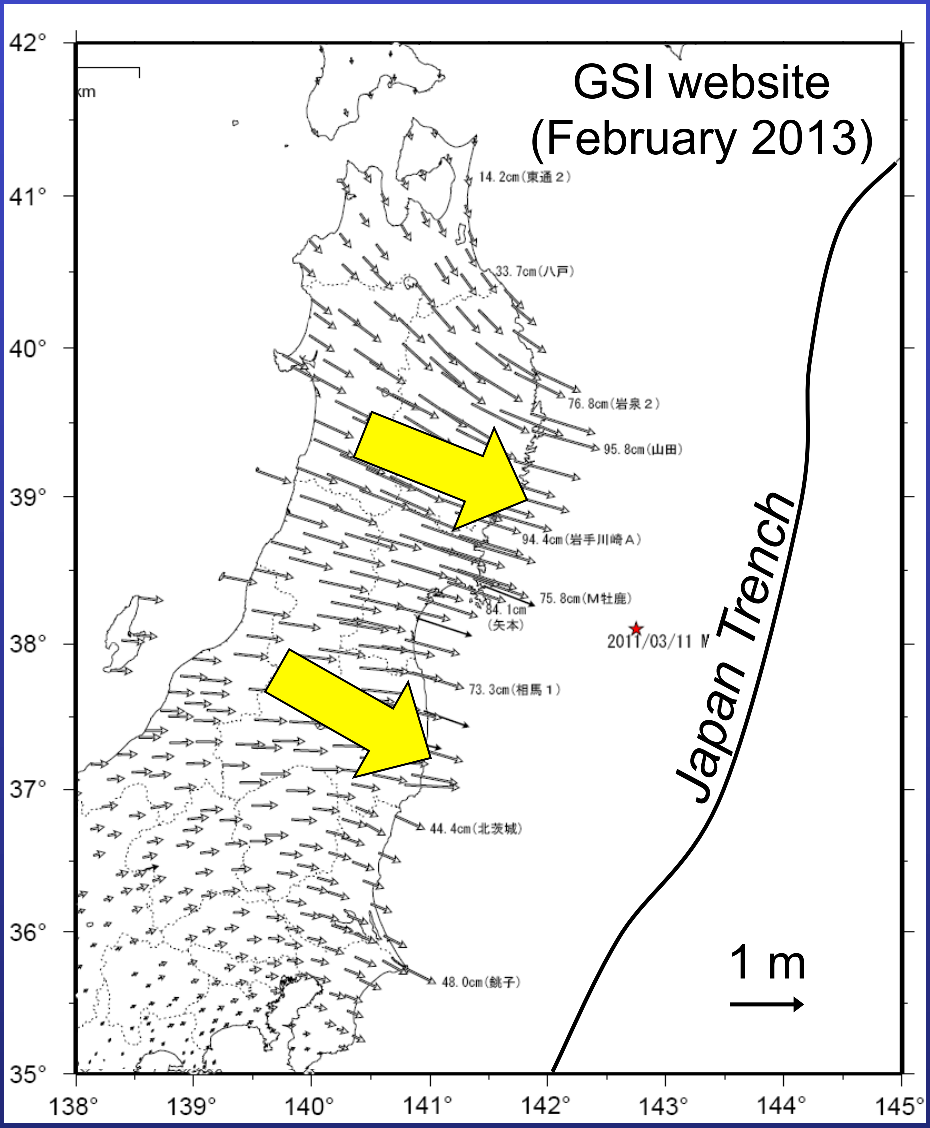
Modern geodesy (GPS) – less than two decades

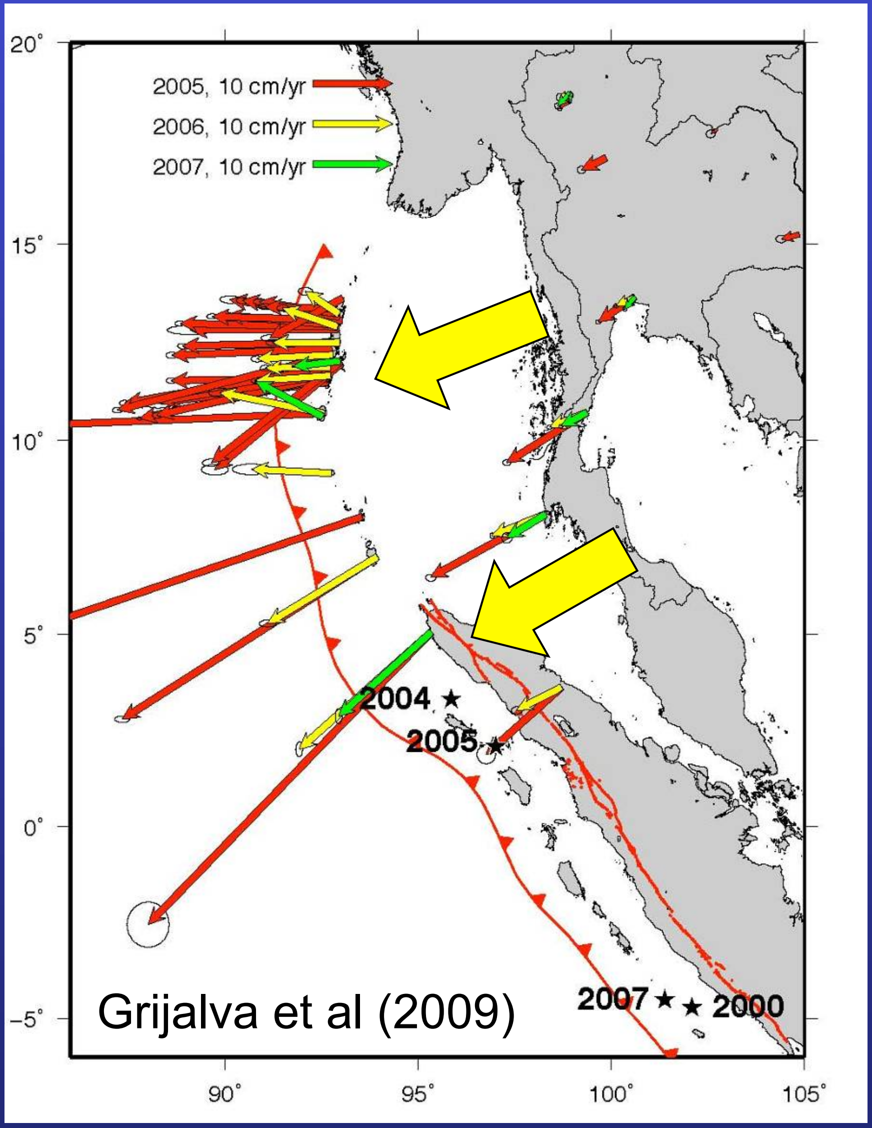
Japan: Two years after the M 9 Tohoku earthquake



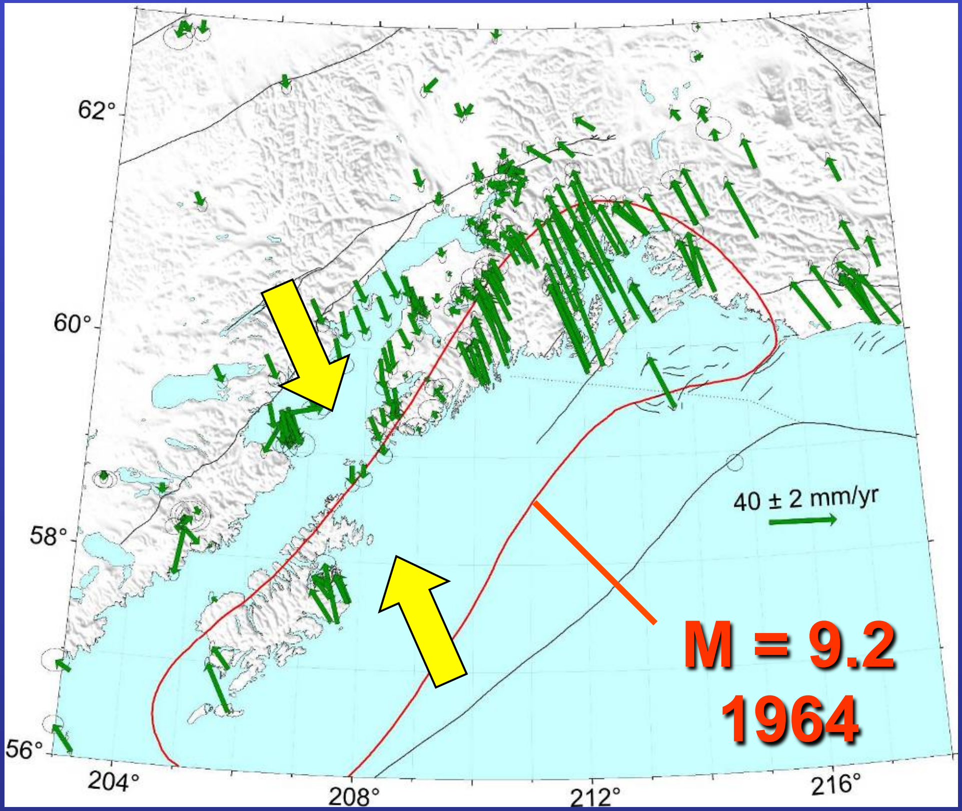


Japan and Sumatra: shortly after a great earthquake
All sites move seaward

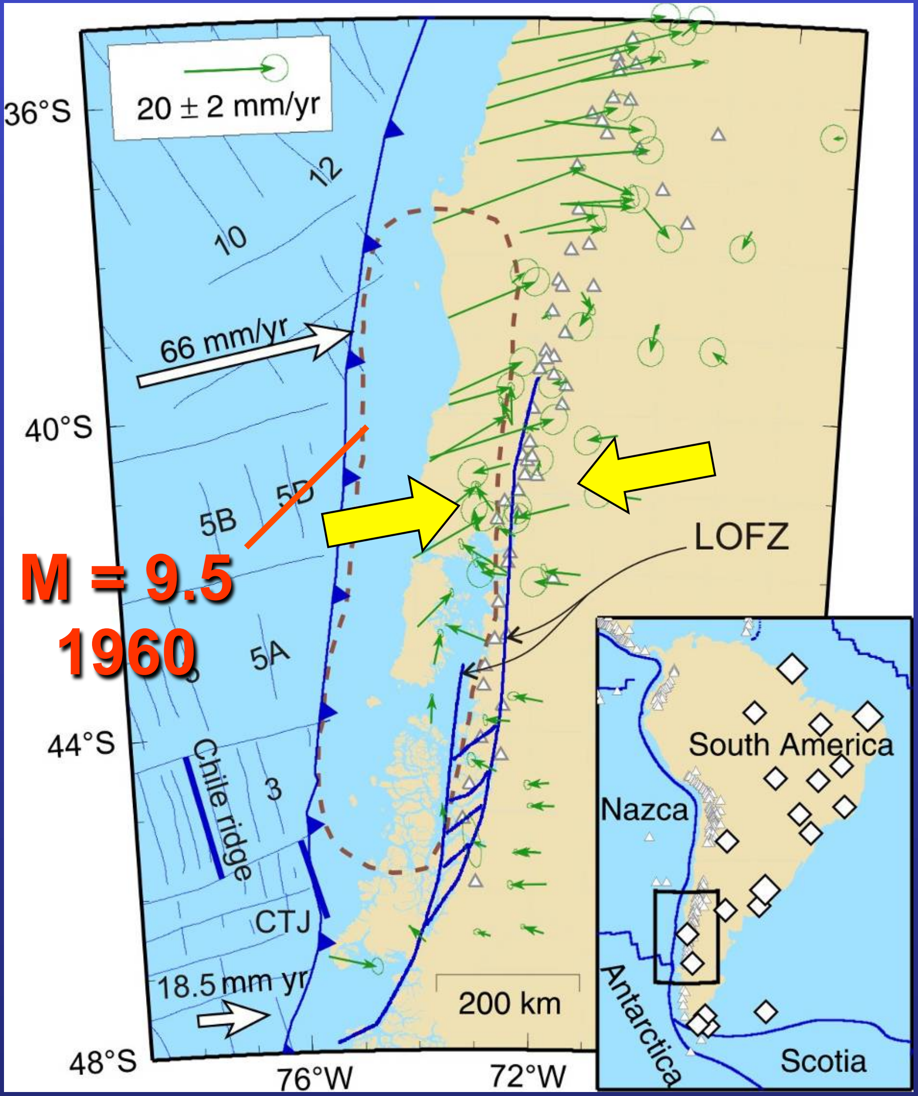




Alaska and Chile: ~ 40 years after a great earthquake: Opposing motion of coastal and inland sites

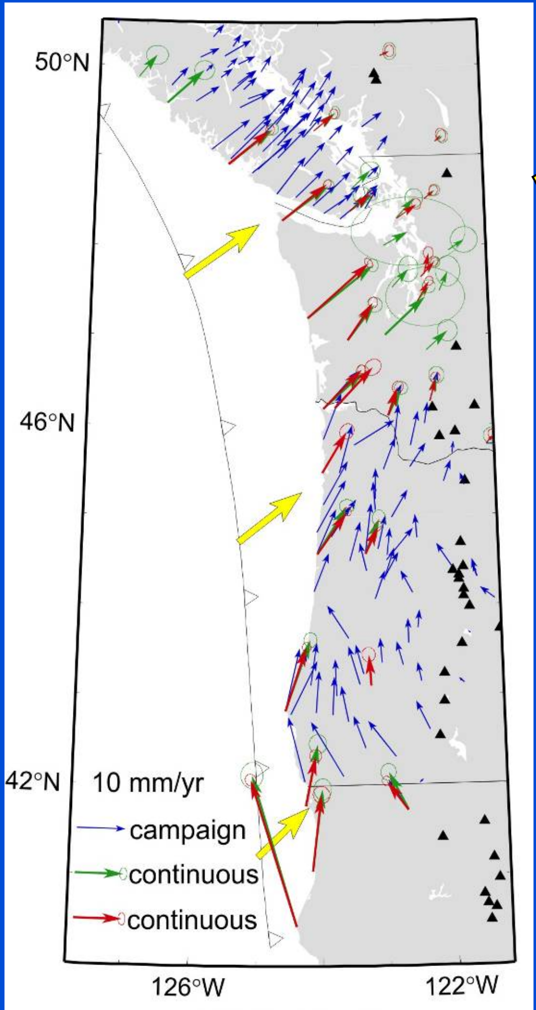


Freymueller et al. (2009)

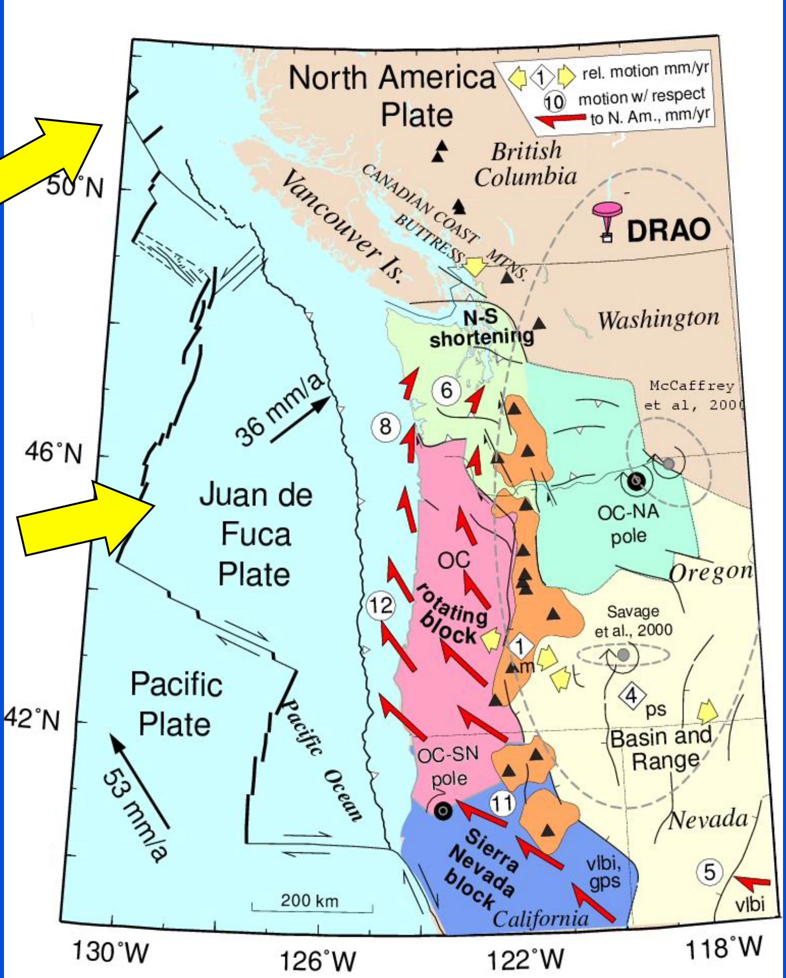


Wang et al. (2007)

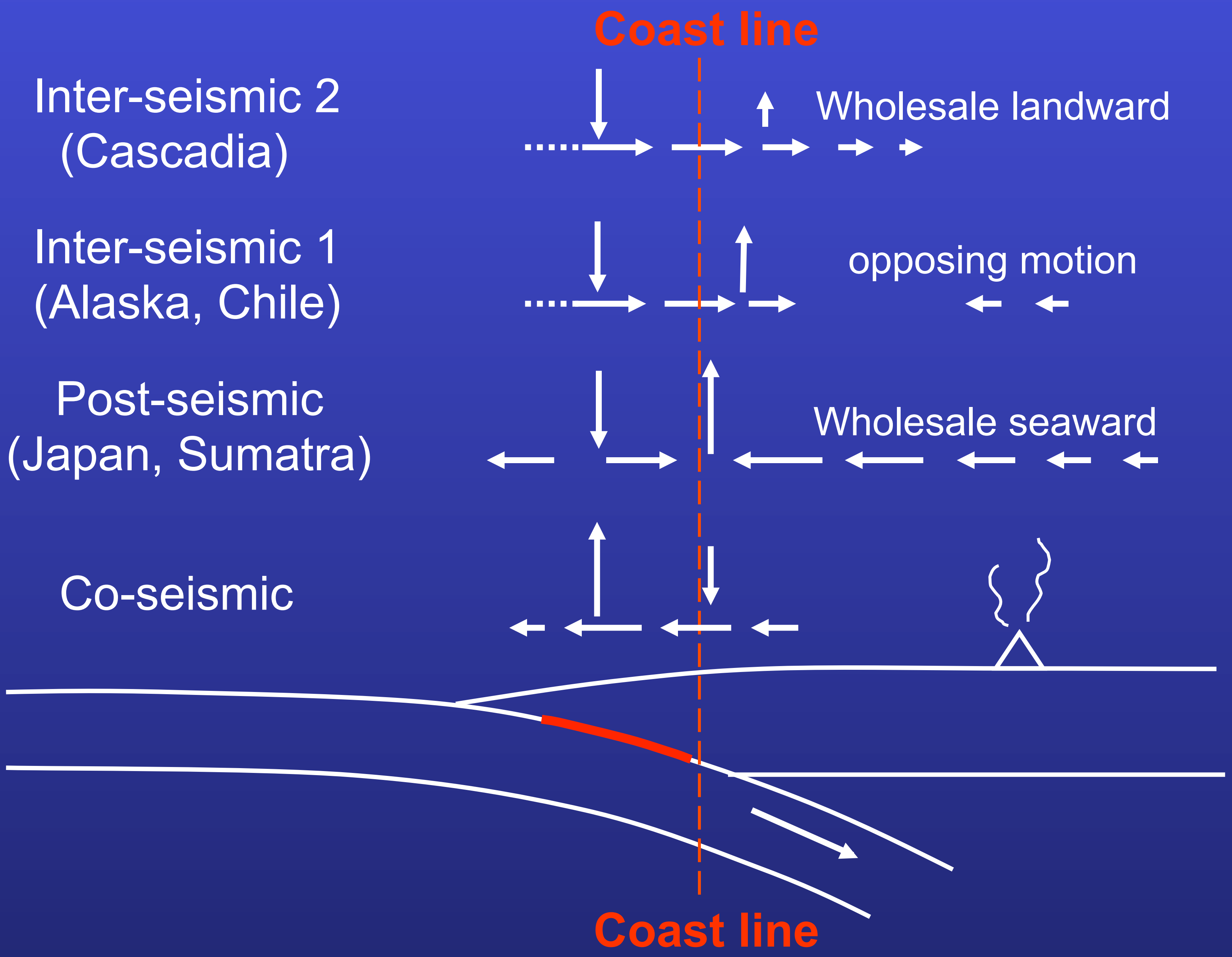
Cascadia: ~ 300 years after a M ~ 9 earthquake: All sites move landward

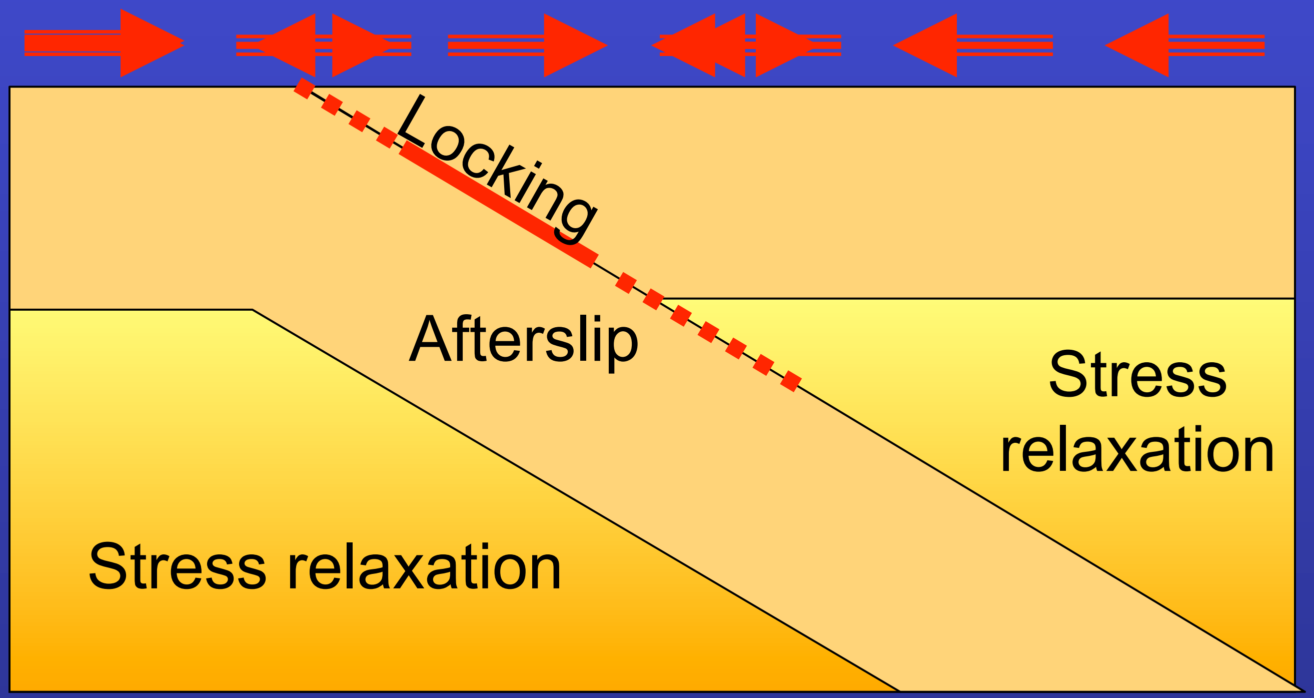


(a) GPS Velocities



Wells and Simpson (2001)


Coast line
Inter-seismic 2
(Cascadia)
Wholesale landward
Inter-seismic 1
(Alaska, Chile)
opposing motion
Post-seismic
(Japan, Sumatra)
Wholesale seaward
Co-seismic
Coast line



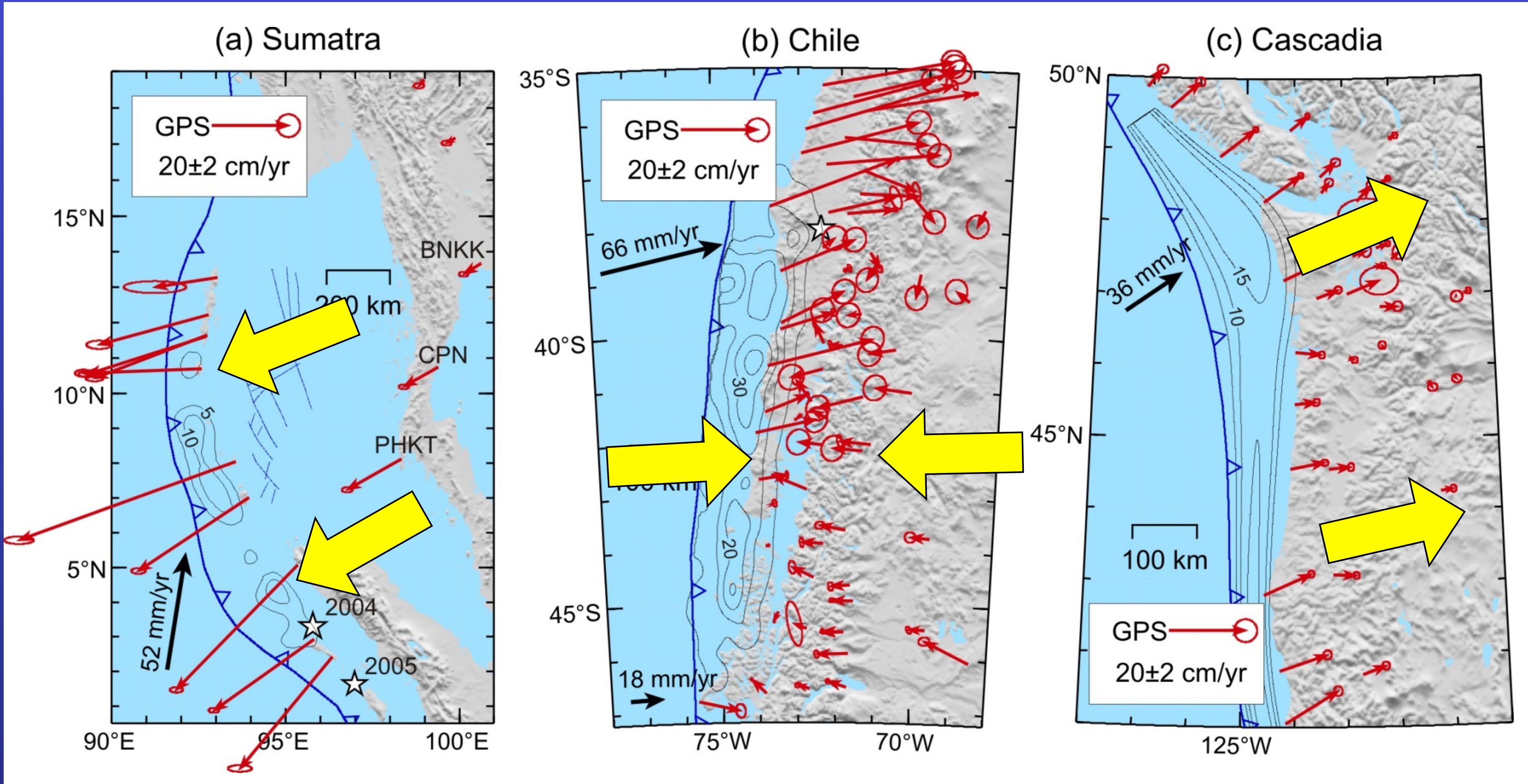
Characteristic timescales:

Afterslip – months to a few years

Viscoelastic relaxation (transient) – a few years

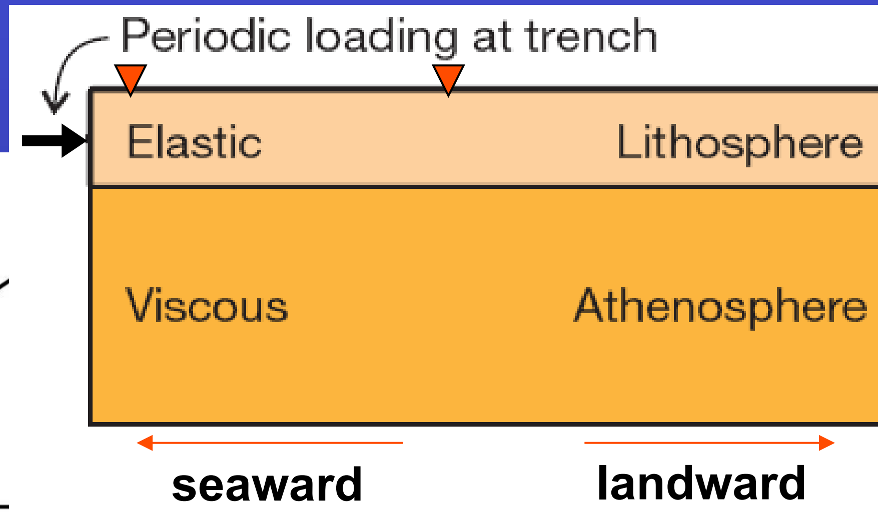
Viscoelastic relaxation (steady-state) – a few decades

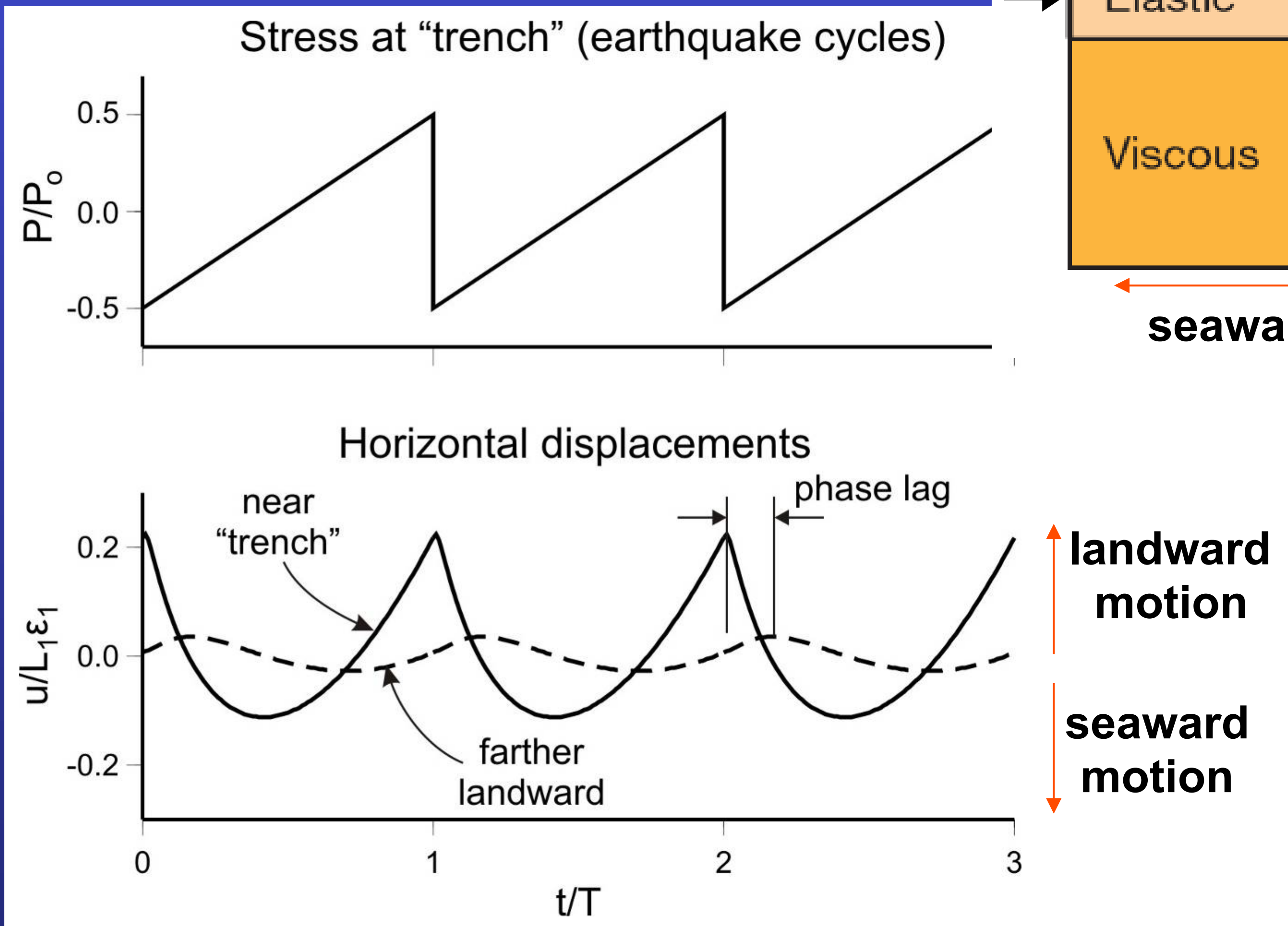
Locking – length of the earthquake cycle



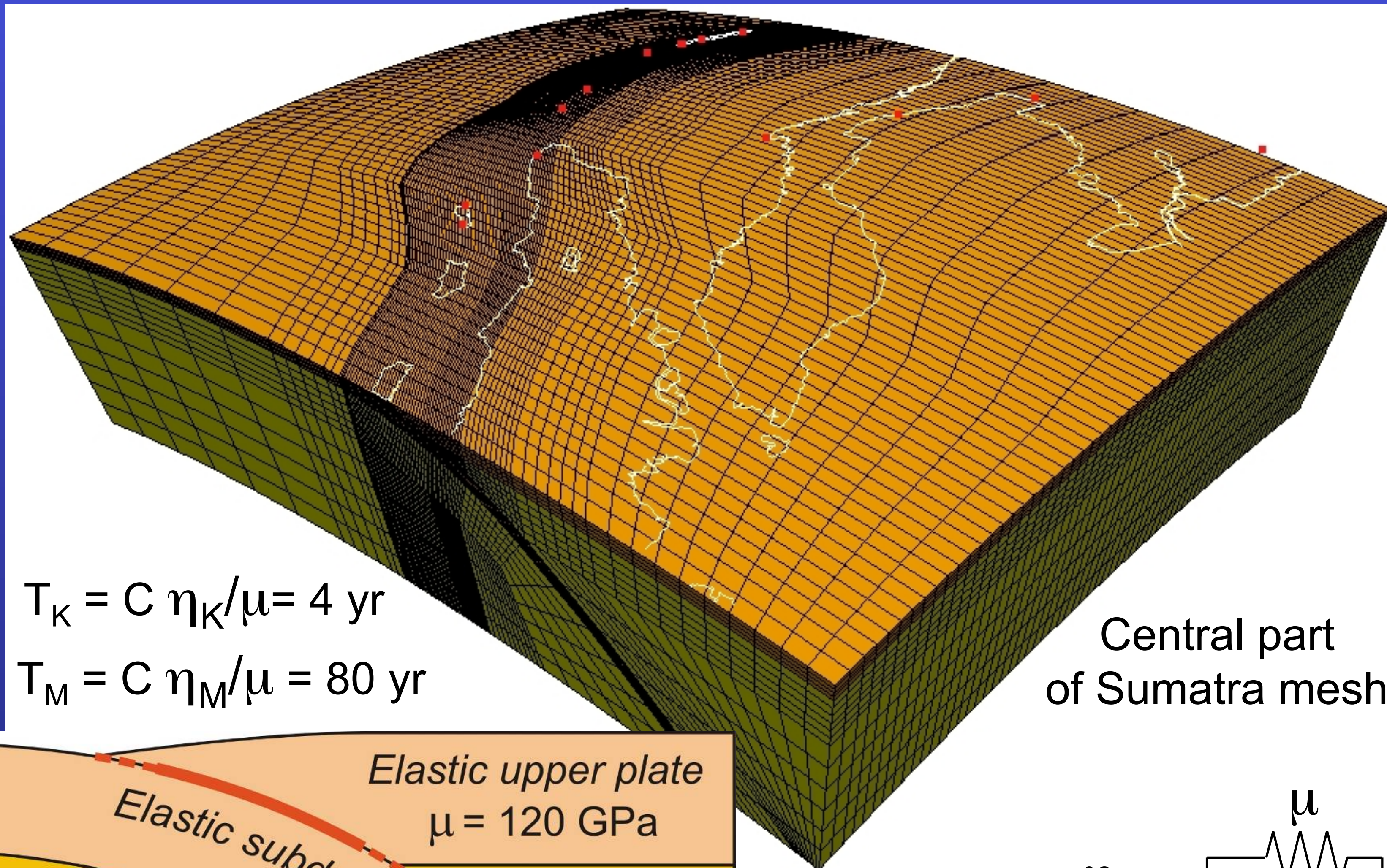
A couple of years | About four decades | Three centuries

Based on 1-D stress diffusion model of Elssaser (1969), Bott and Dean (1973)





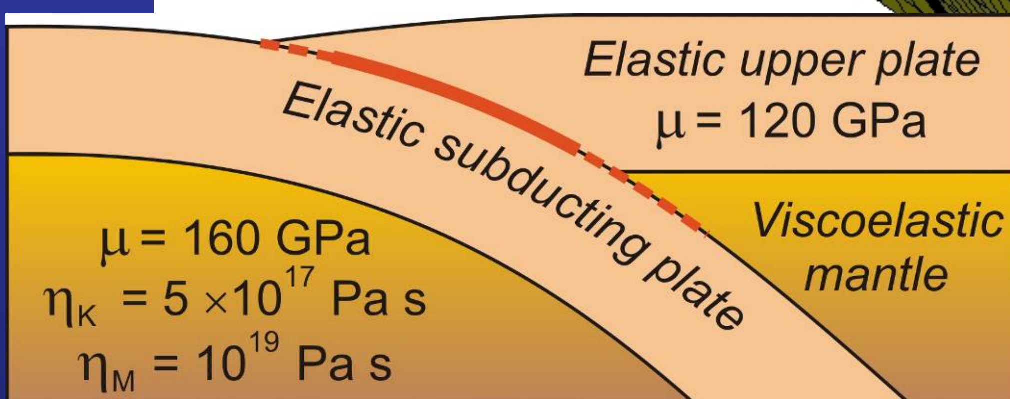
Saw-tooth solution by Wang (1995)

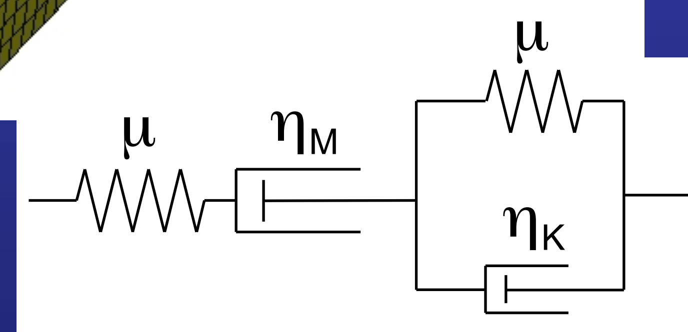


$$T_K = C\ \eta_K/\mu = 4\ \text{yr}$$

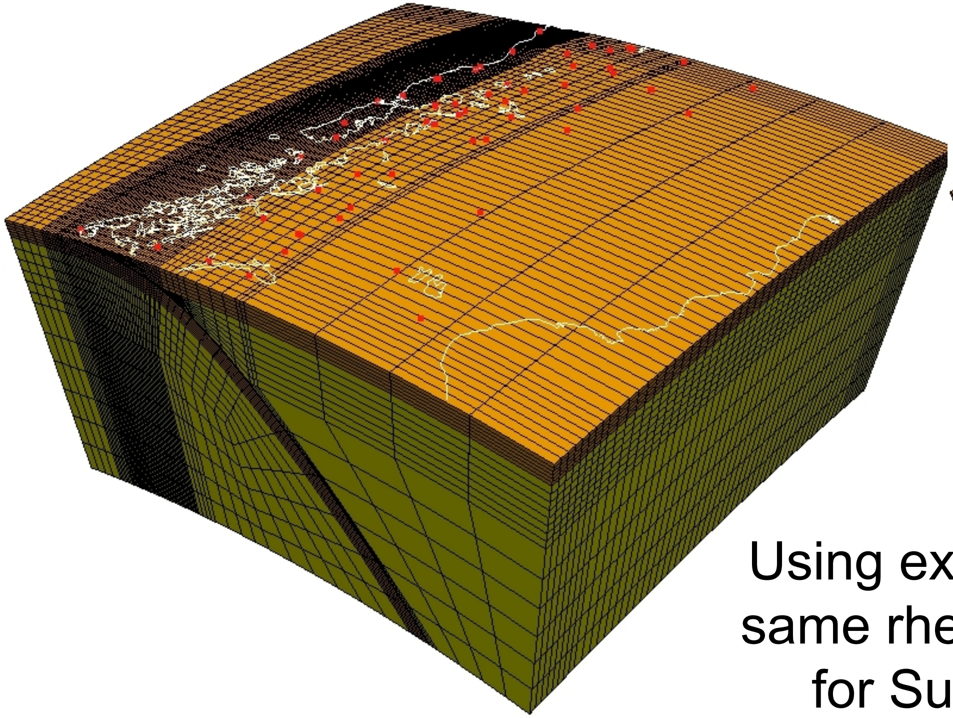
$$T_M = C\ \eta_M/\mu = 80\ \text{yr}$$

Central part
of Sumatra mesh

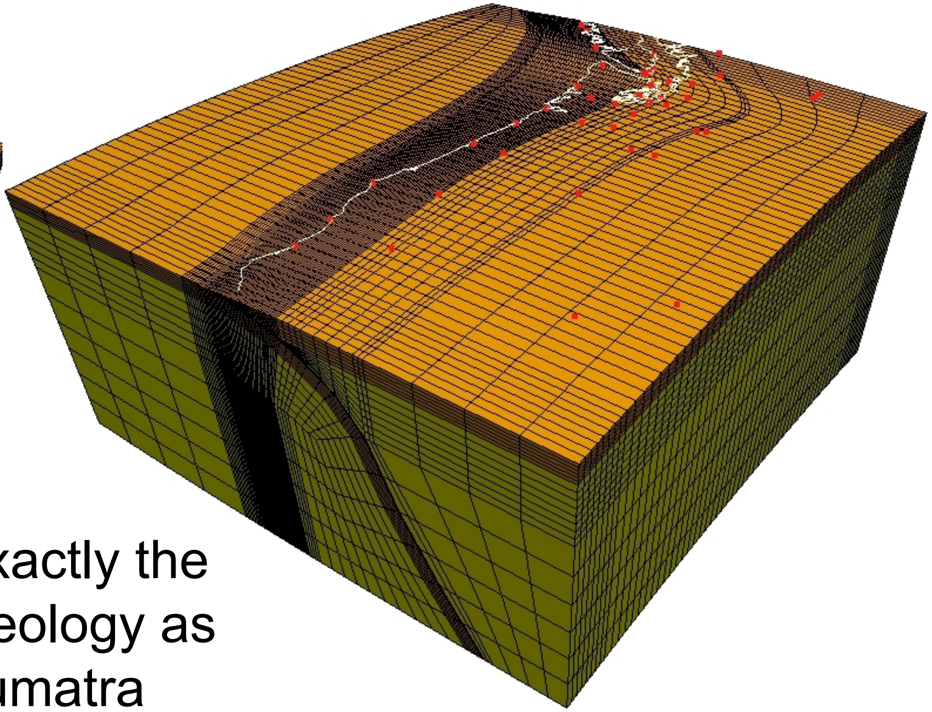




Central part of Chile mesh

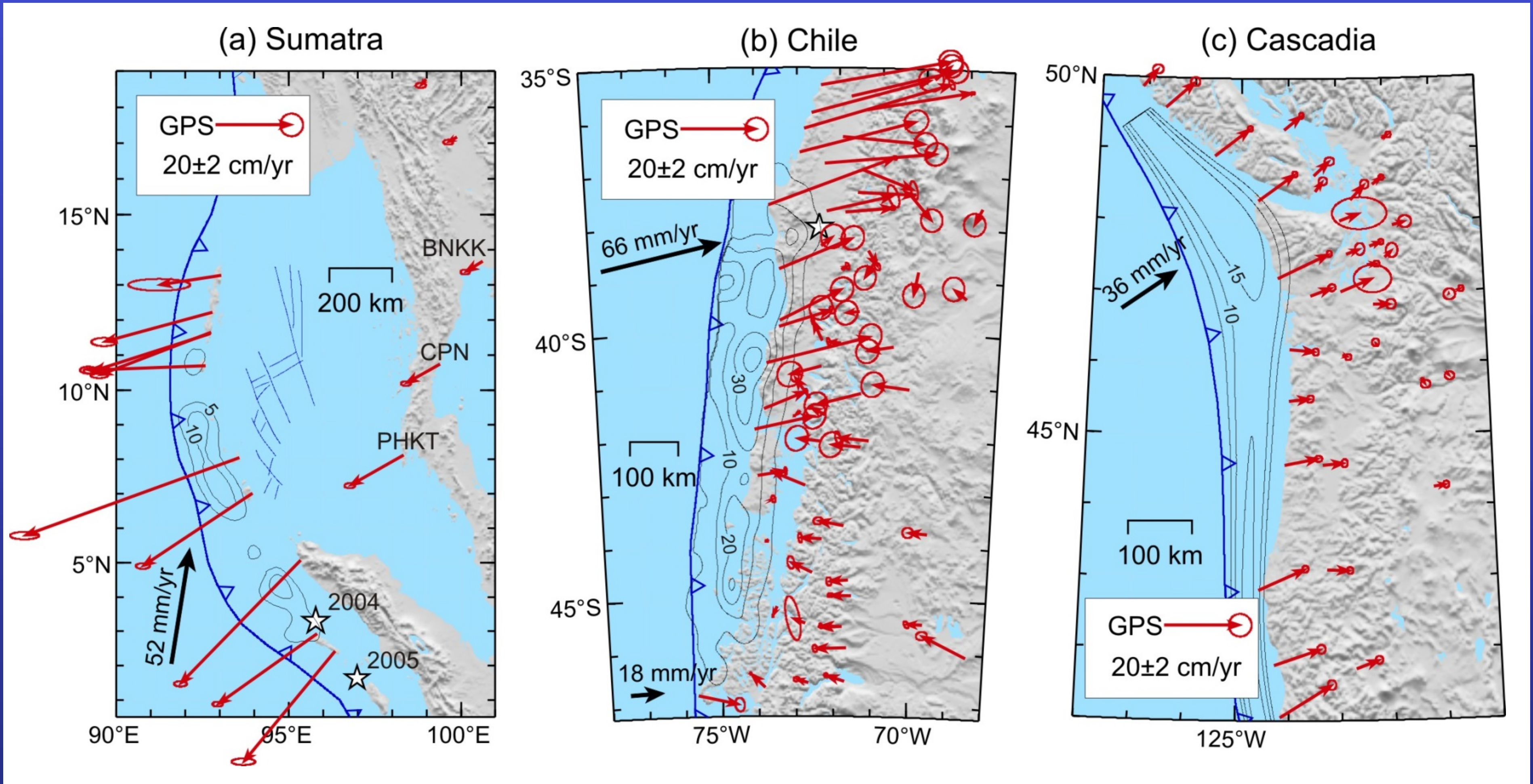


Central part of Cascadia mesh



Using exactly the same rheology as for Sumatra

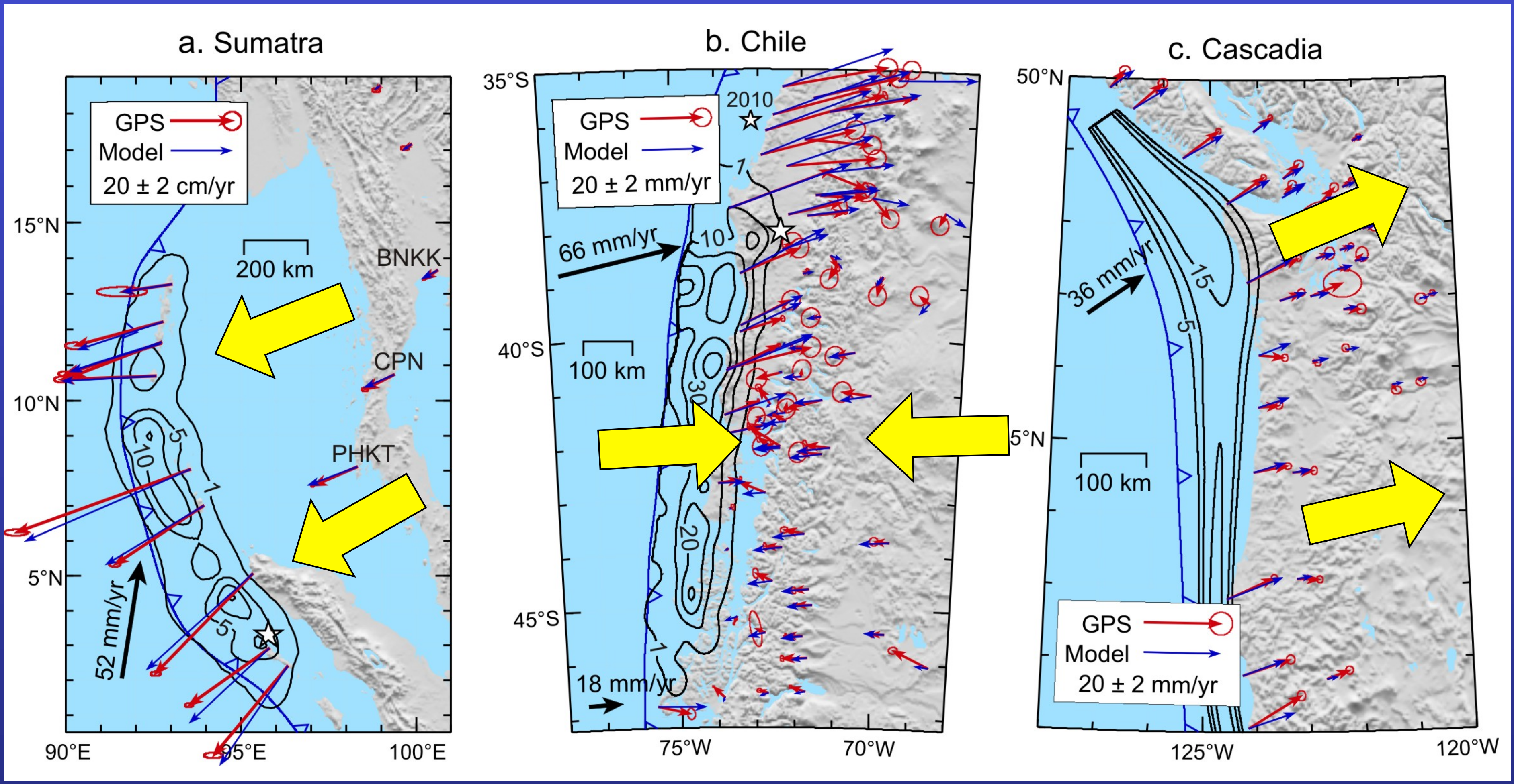
Assigning coseismic slip and afterslip distributions …



Chlieh et al. (2007) — Details important

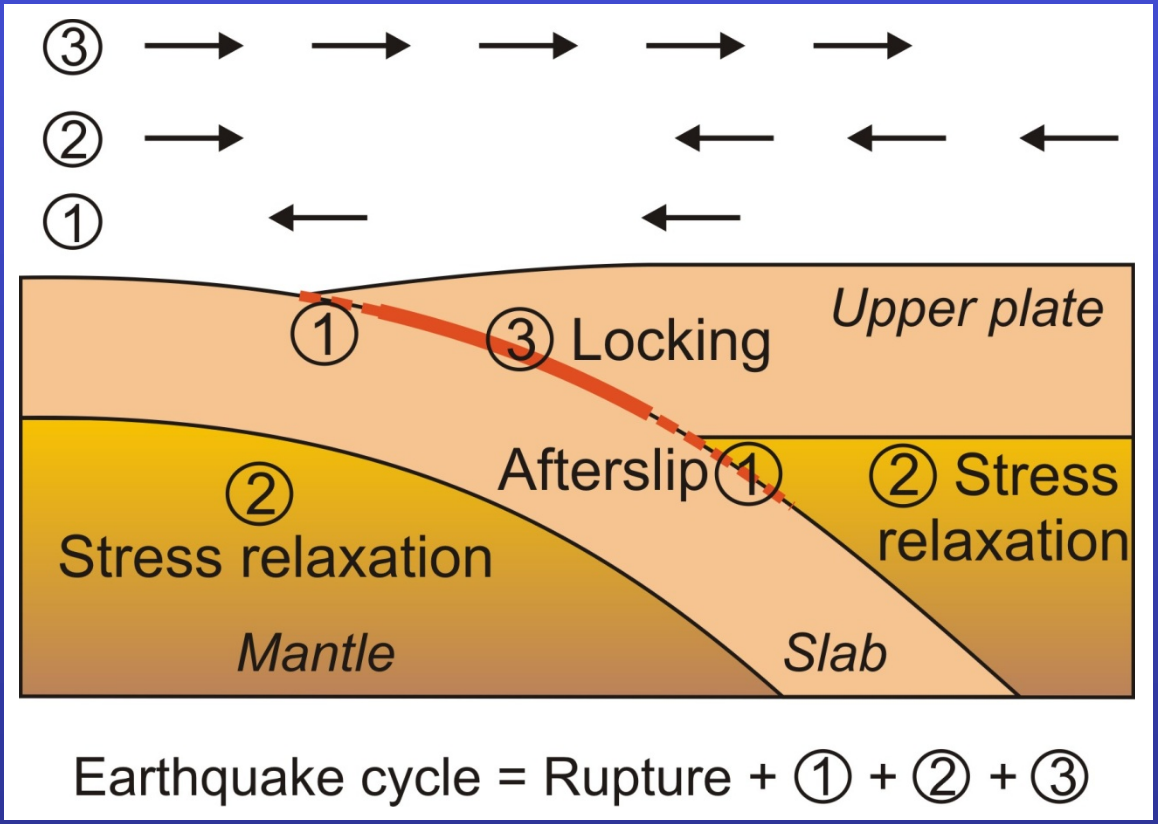
Moreno et al. (2009) — Details less important

Priest et al. (2009) — Details unimportant



A couple of years About four decades Three centuries

Wang, Hu, He (Nature, 2012)



Characteristic timescales used in the model:

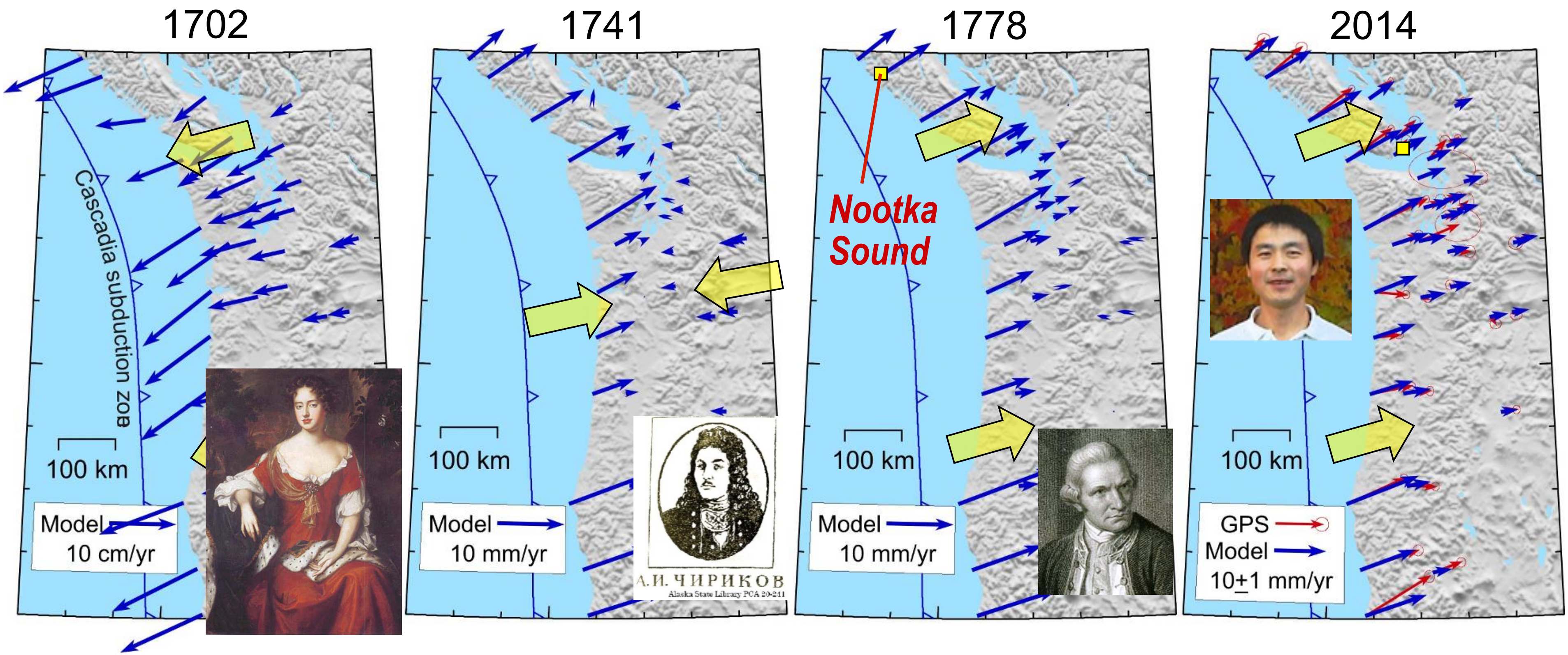
Afterslip – 1.25 yrs

Viscoelastic relaxation (transient) – 4 years

Viccoelastic relaxation (steady-state) – 80 years

Locking – length of the earthquake cycle

Cascadia since the 1700 earthquake



England and France began to fight in eastern North America (Queen Anne's War).

Captain Chirikov (Russia) landed on northwest coast of North America (Prince of Wales Island).

Captain Cook sailed along west coast of North America and traded with native people at Nootka Sound.

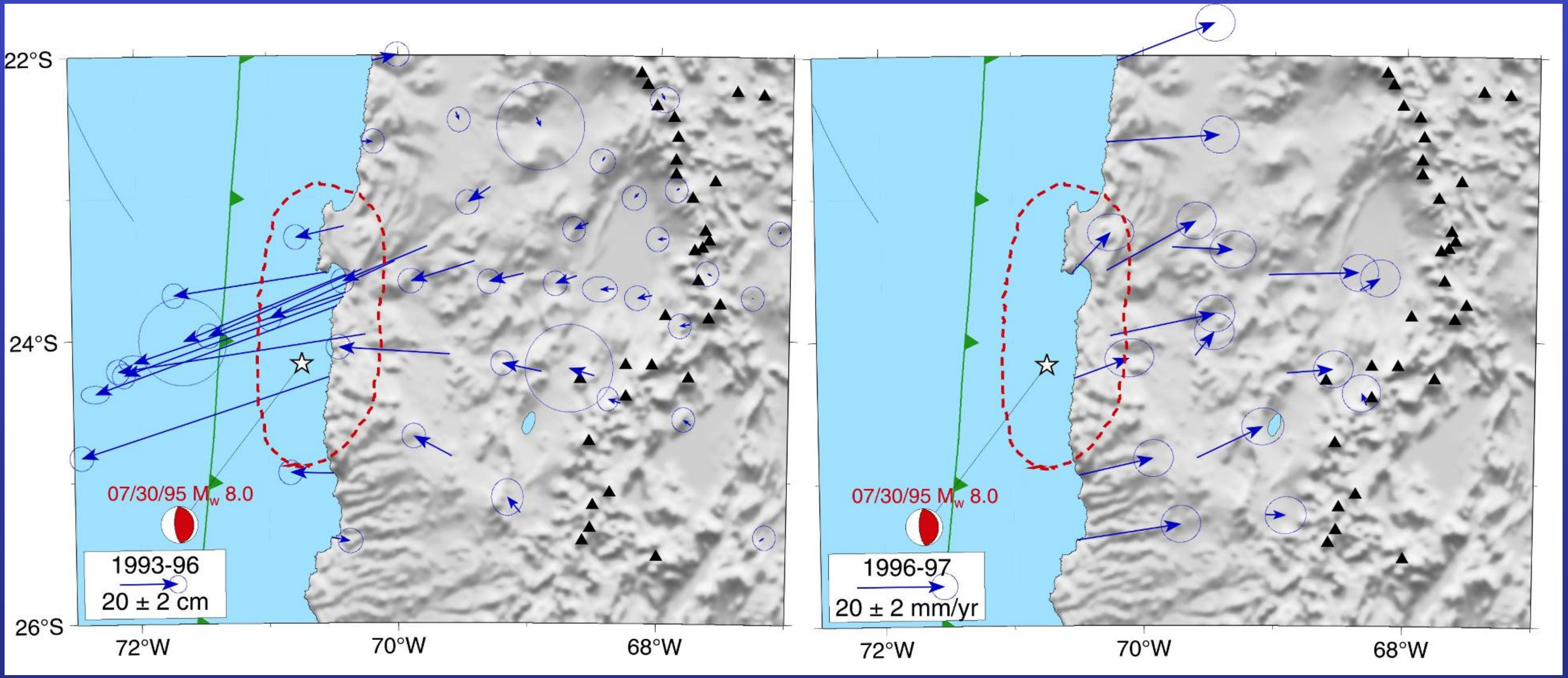
Dr. Wang lectures at ICTP Workshop on Megathrust earthquakes and Tsunamis

Model by Hu, 2011, PhD thesis

1995 Antofagasta earthquake, N. Chile (M_w = 8.0)

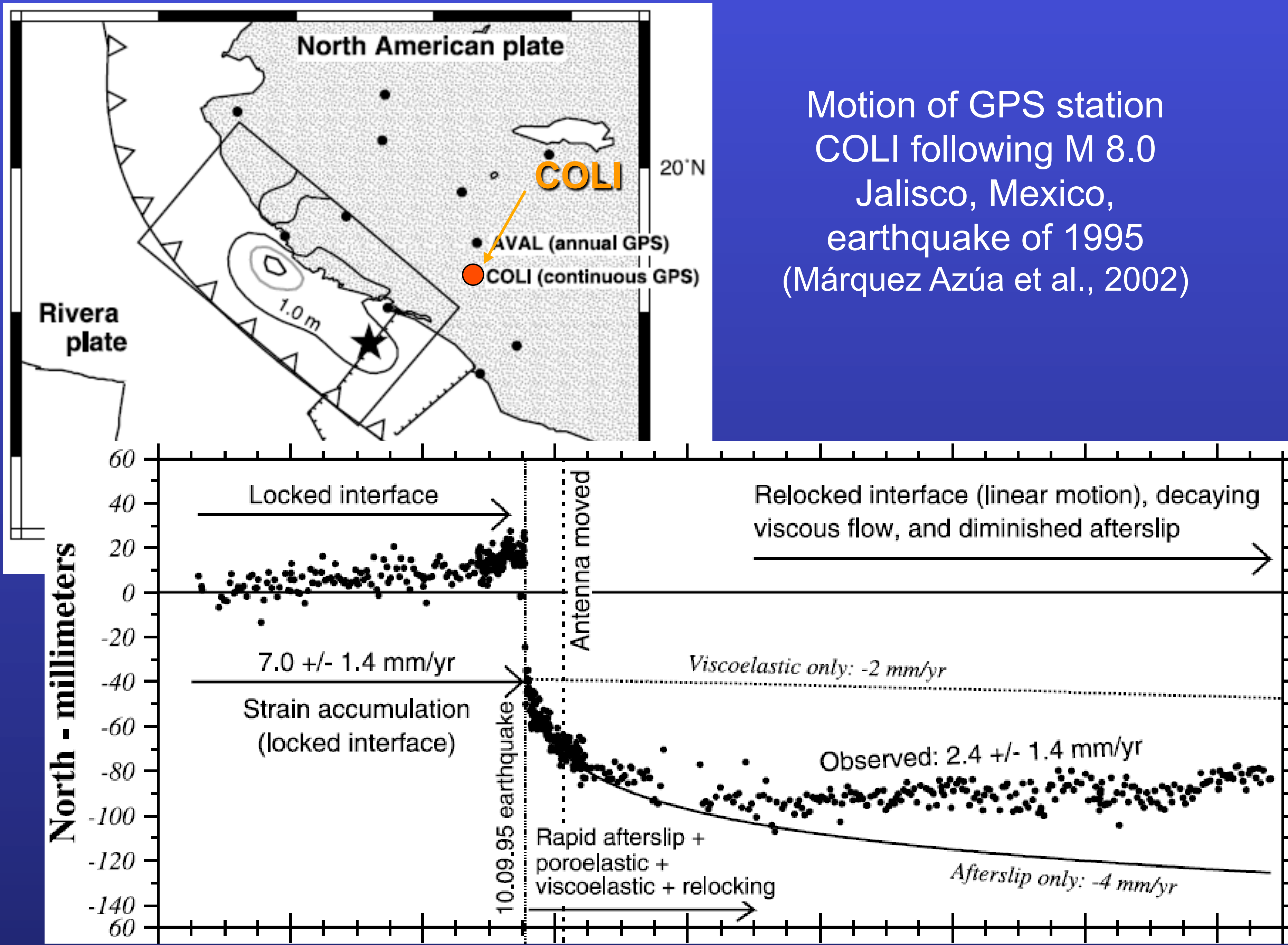
1993-95 Displacements
(dominated by co-seismic)

1996-97 Velocities
(2 years after earthquake)

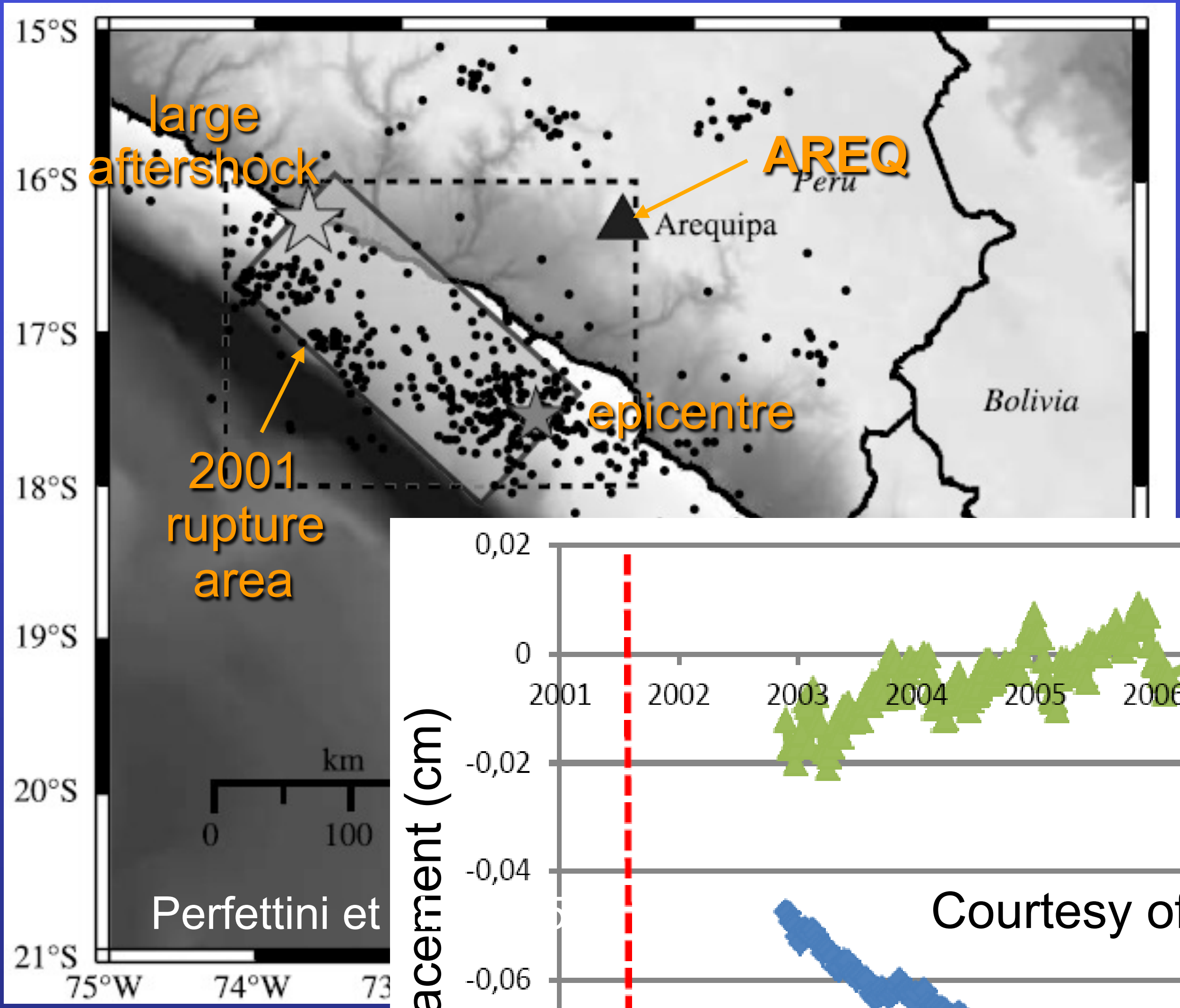


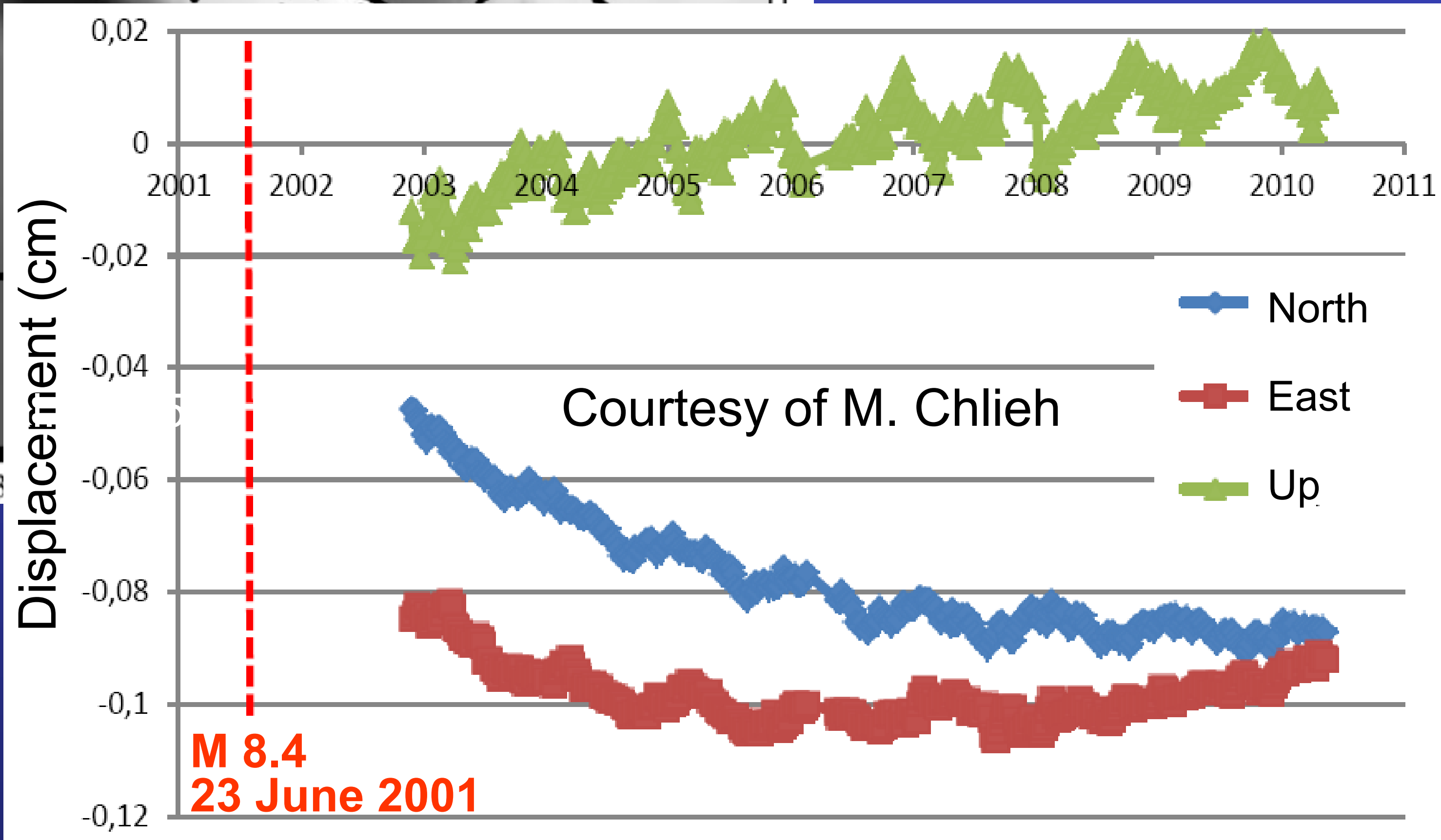
Data from Klotz et al. (1999) and Khazaradze and Klotz (2003)

Motion of GPS station COLI following M 8.0 Jalisco, Mexico, earthquake of 1995 (Márquez Azúa et al., 2002)



Motion of GPS station AREQ following M 8.4 Peru earthquake of June 2001

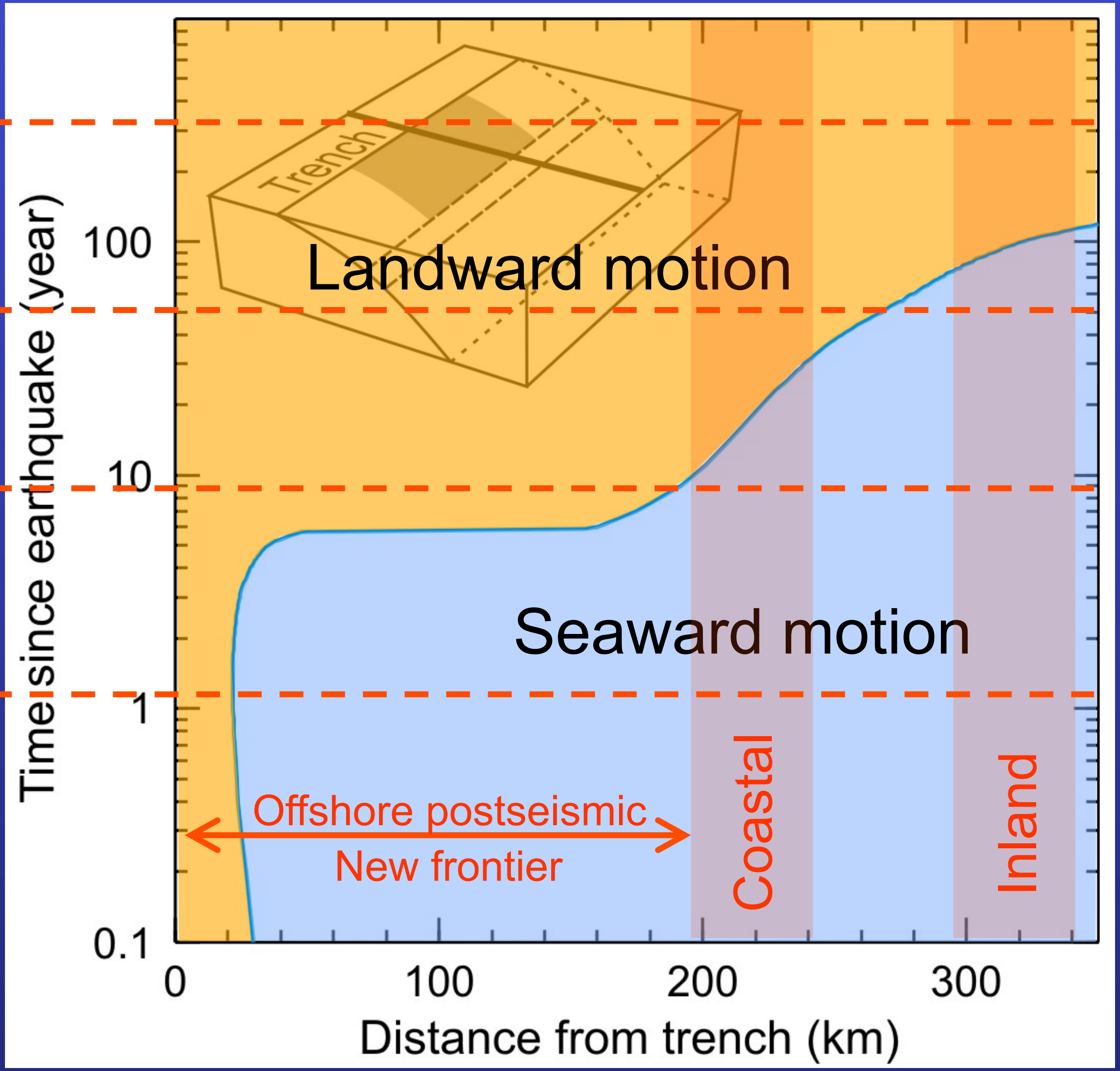




Cascadia

Chile
Alaska

Sumatra
Japan



$$T_M = C\ \eta_M / \mu$$

$$C = M_o / M_{o\_ref}$$

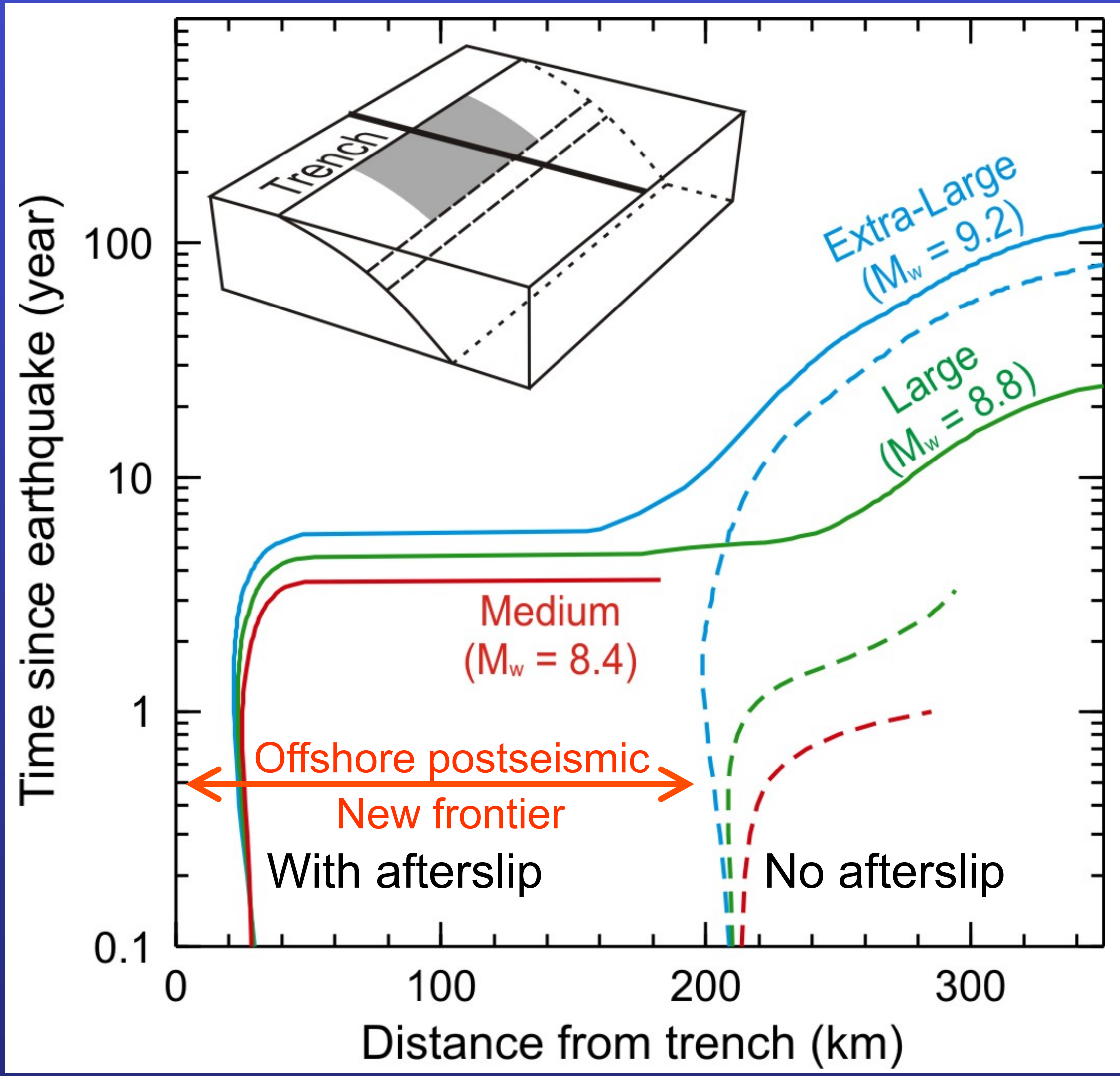
Wang, Hu, He (Nature, 2012)

Location of seaward-landward motion transition for different earthquake sizes

Cascadia

Chile
Alaska

Sumatra
Japan

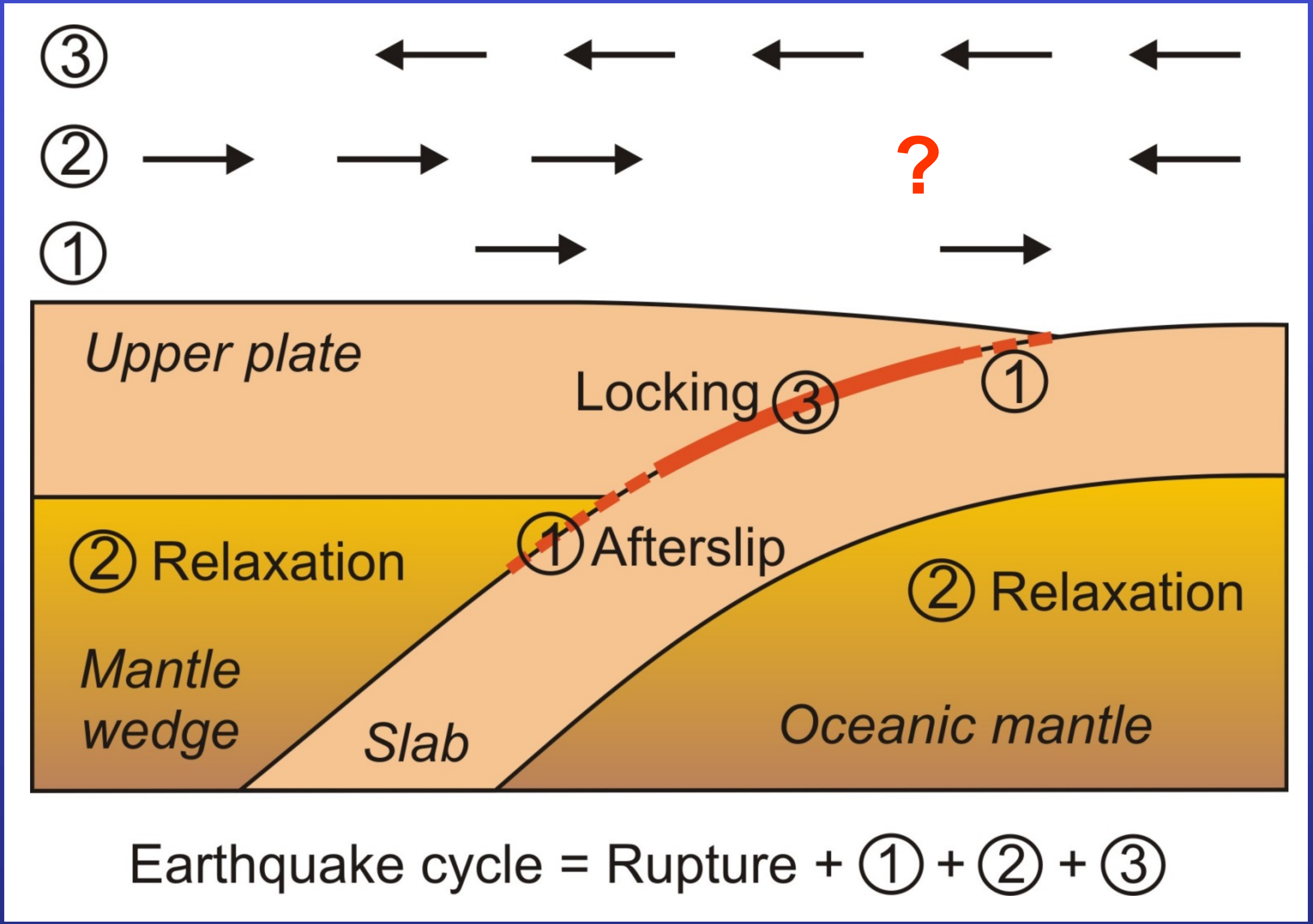


$T_M = C\ \eta_M/\mu$

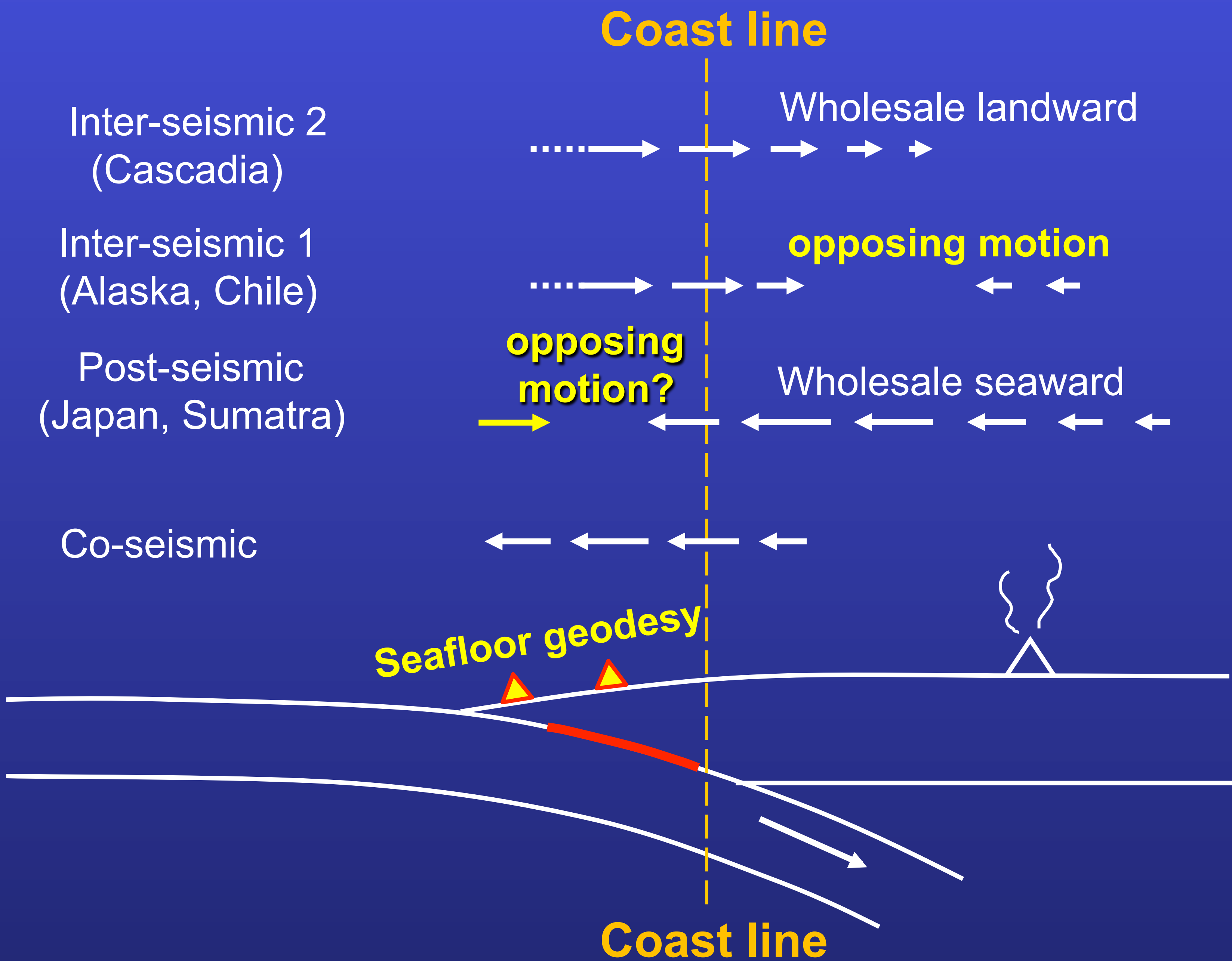
$C = M_o/M_{o\_ref}$

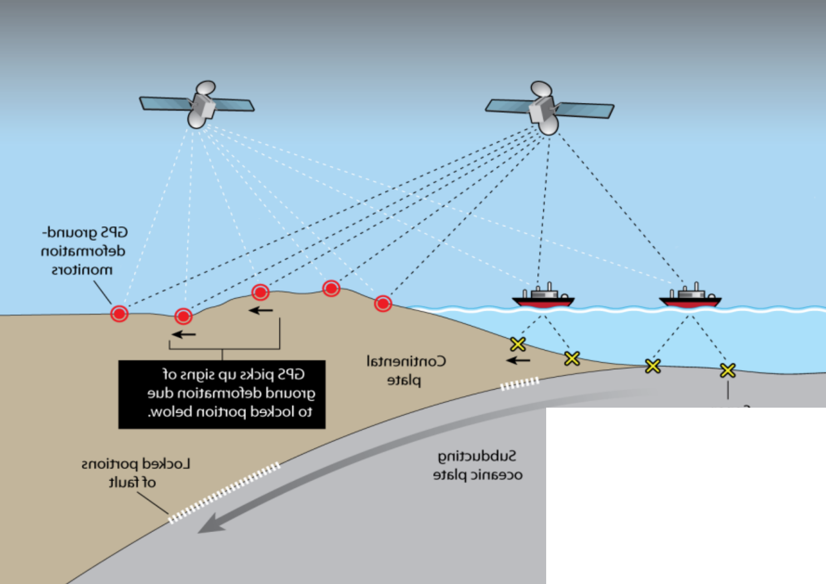
Wang, Hu, He (Nature, 2012)

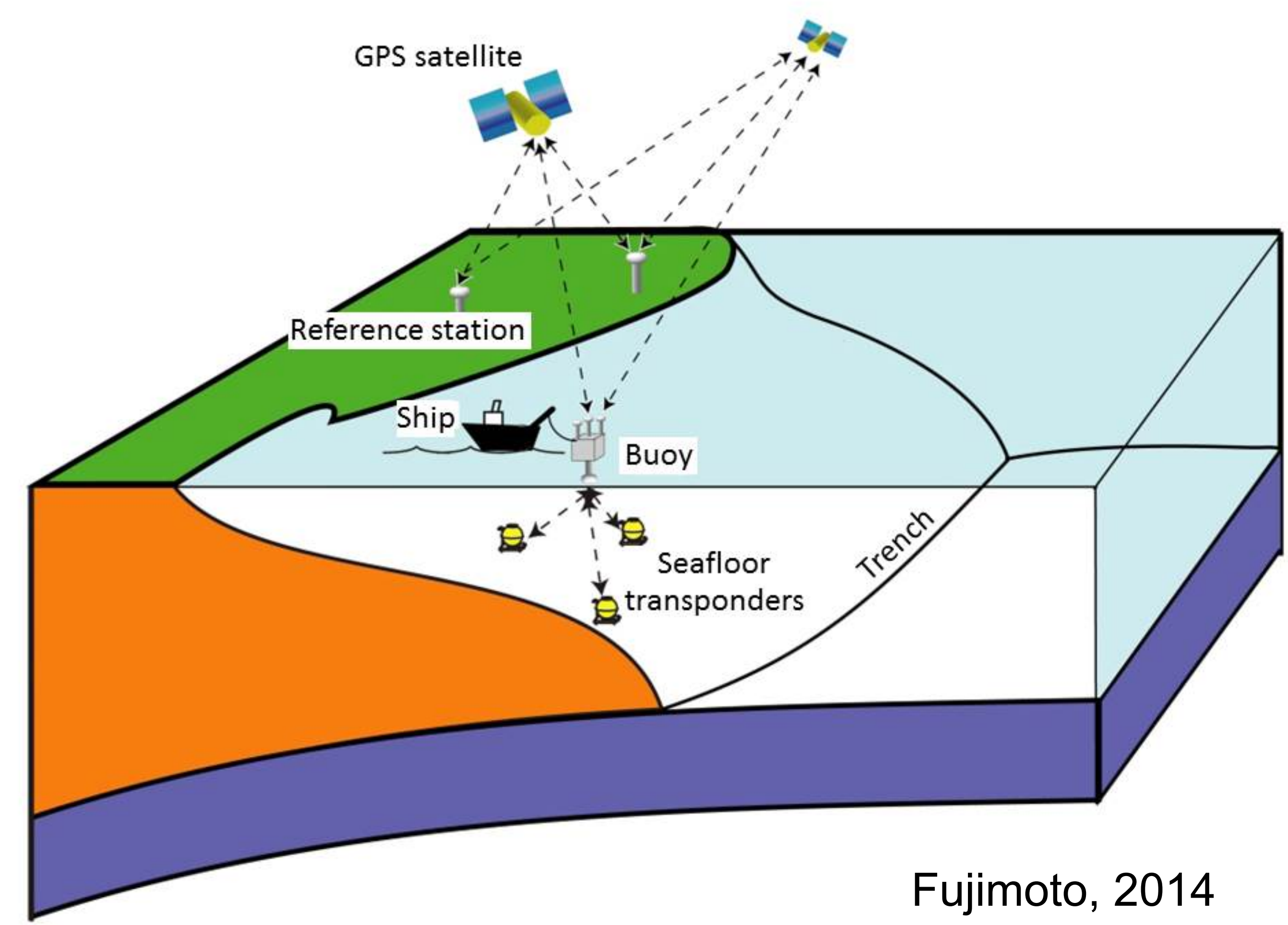
Wang, Hu, and He (2012, Nature)



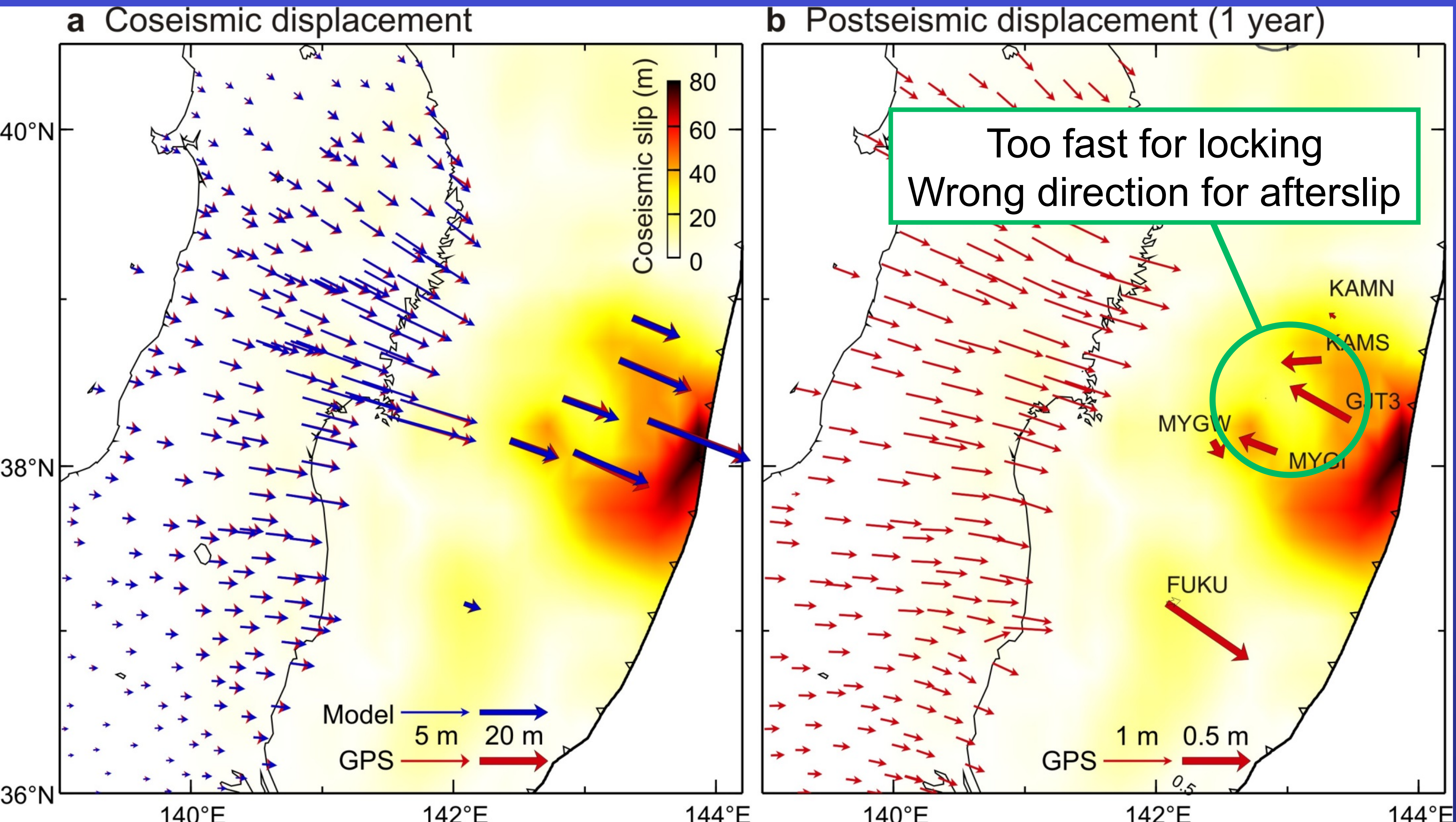
Related question: Can viscoelastic relaxation be ignored in short-term postseismic deformation?


Coast line
Inter-seismic 2
(Cascadia)
Wholesale landward
Inter-seismic 1
(Alaska, Chile)
opposing motion
Post-seismic
(Japan, Sumatra)
opposing
motion?
Wholesale seaward
Co-seismic
Seafloor geodesy
Coast line



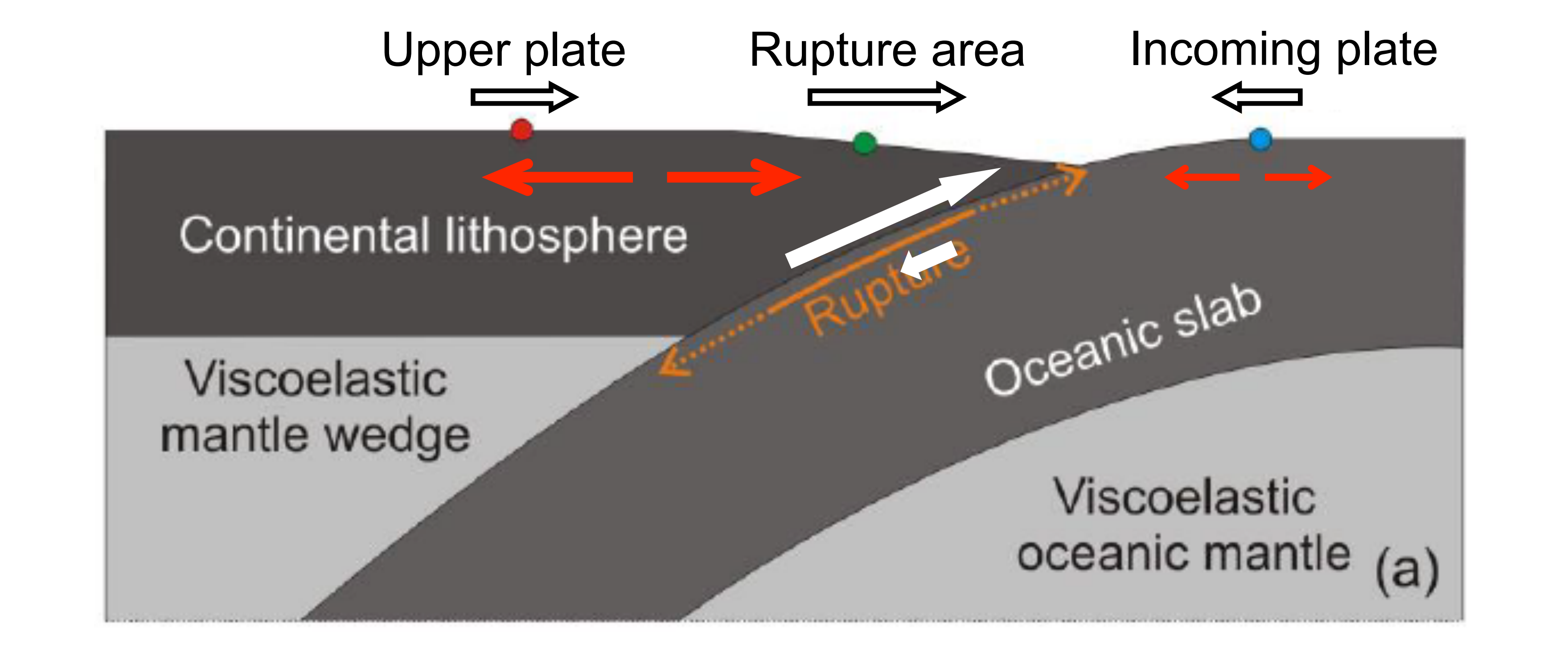


Fujimoto, 2014

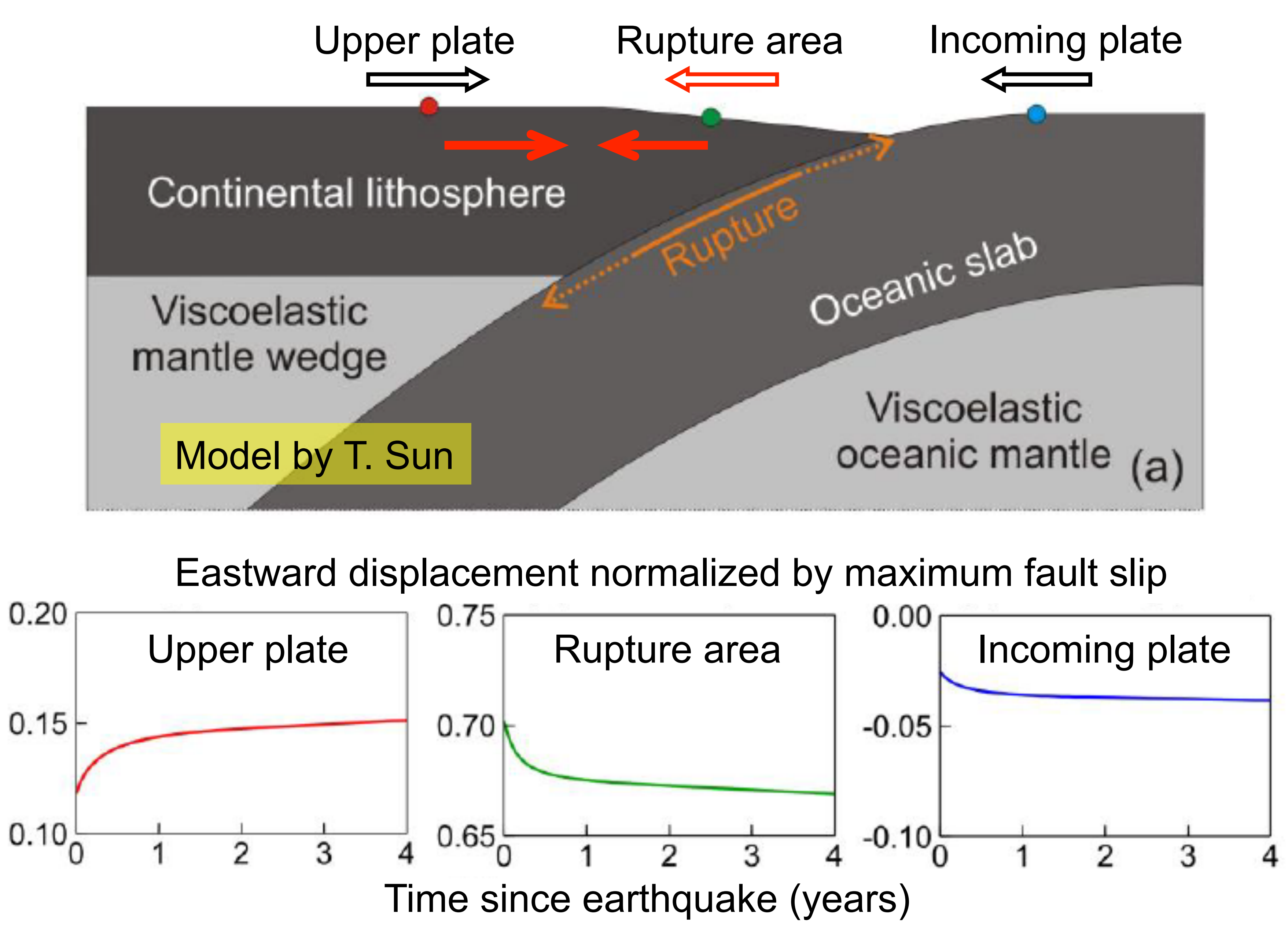


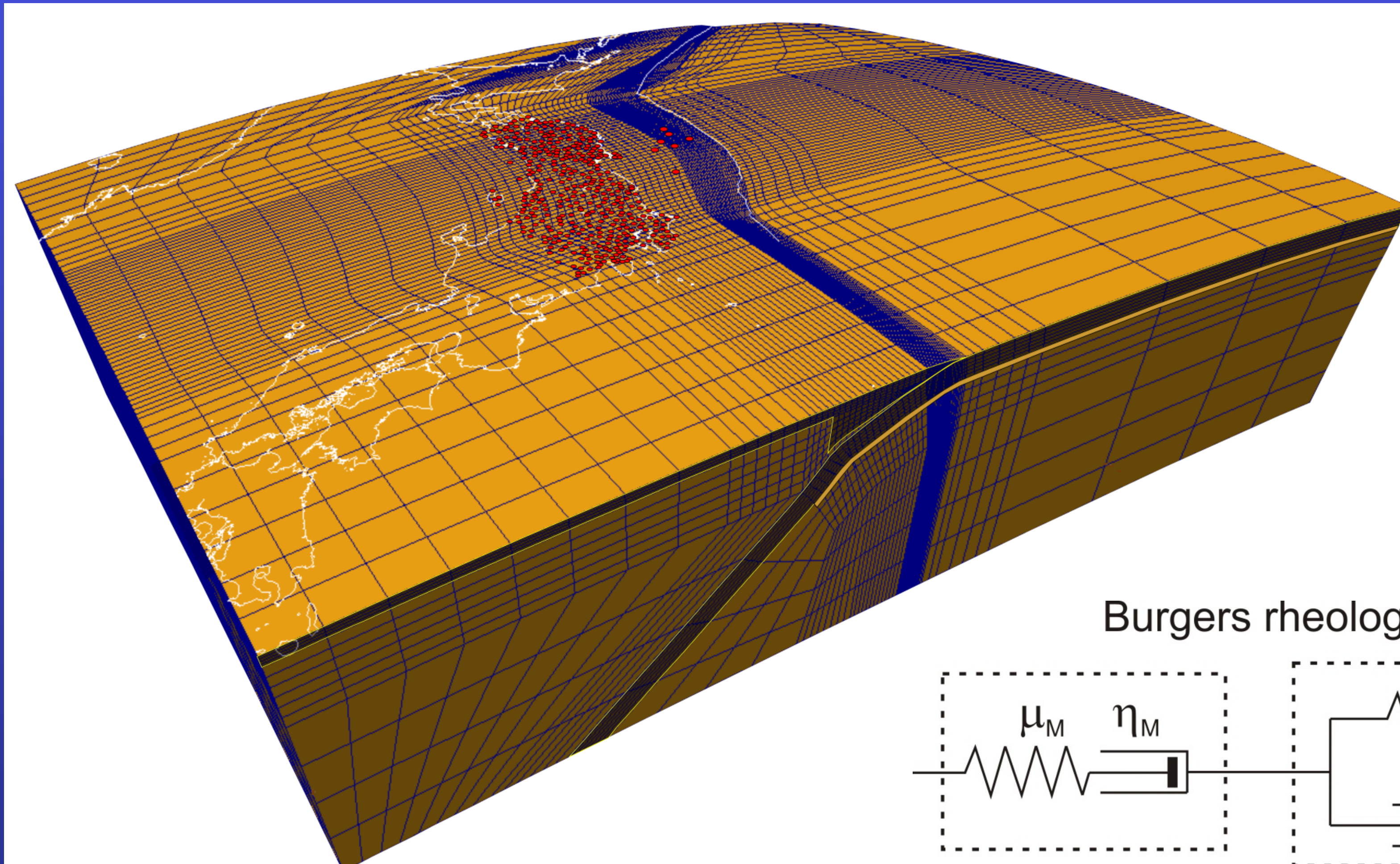
Rupture model: Iinuma et al. (2012)
Land GPS: Ozawa et al. (2011)
Seafloor GPS: Sato et al.; Kido et al. (2011)

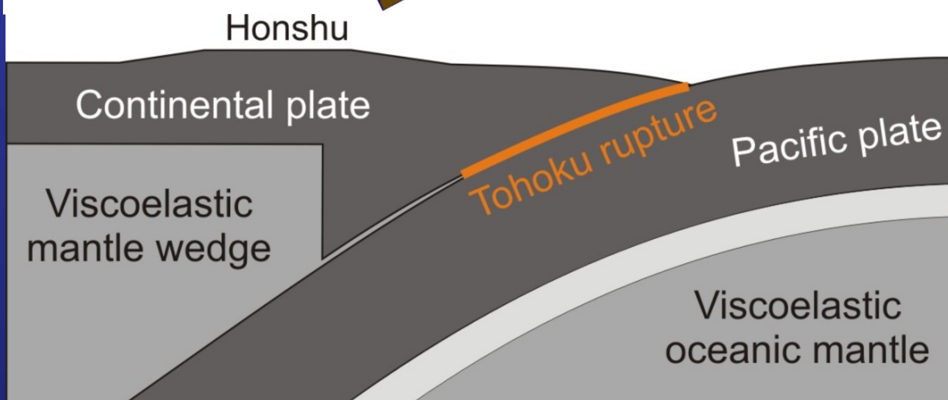
Land GPS: Ozawa et al. (2012)
Seafloor GPS: Watanabe et al. (submitted)
and this work

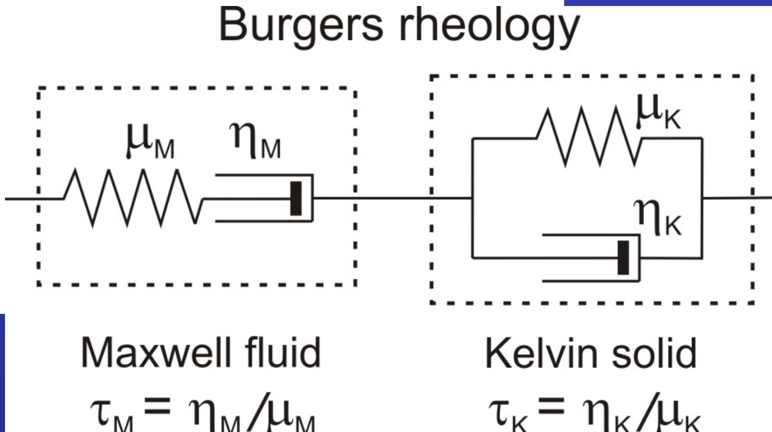


Asymmetric rupture


Upper plate
Rupture area
Incoming plate
Continental lithosphere
Rupture
Oceanic slab
Viscoelastic mantle wedge
Viscoelastic oceanic mantle
(a)
Model by T. Sun
Eastward displacement normalized by maximum fault slip
Upper plate
Rupture area
Incoming plate
0.20
0.15
0.10
0.75
0.70
0.65
0.00
-0.05
-0.10
0
1
2
3
4
Time since earthquake (years)



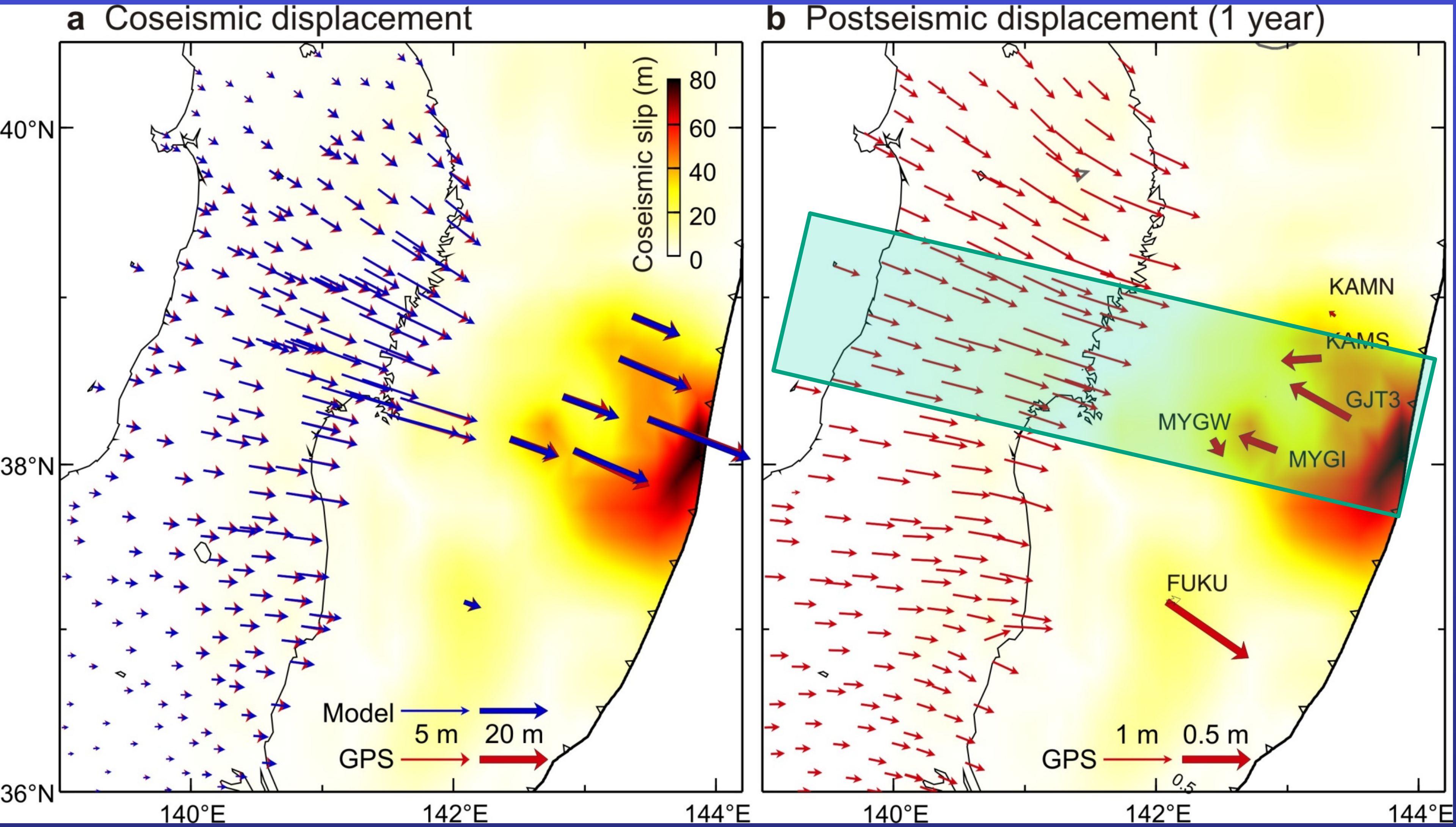


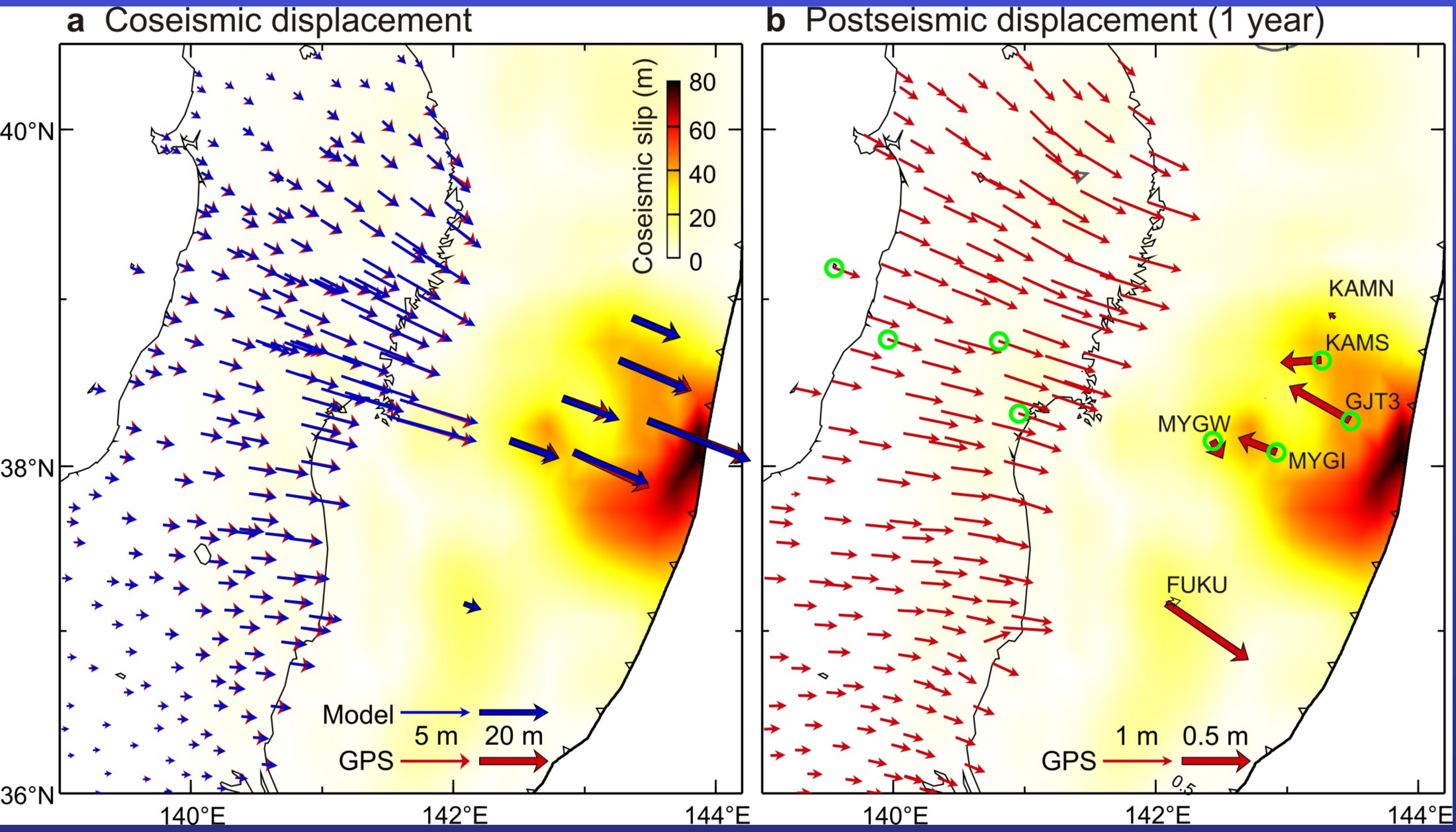


Mantle wedge viscosity:

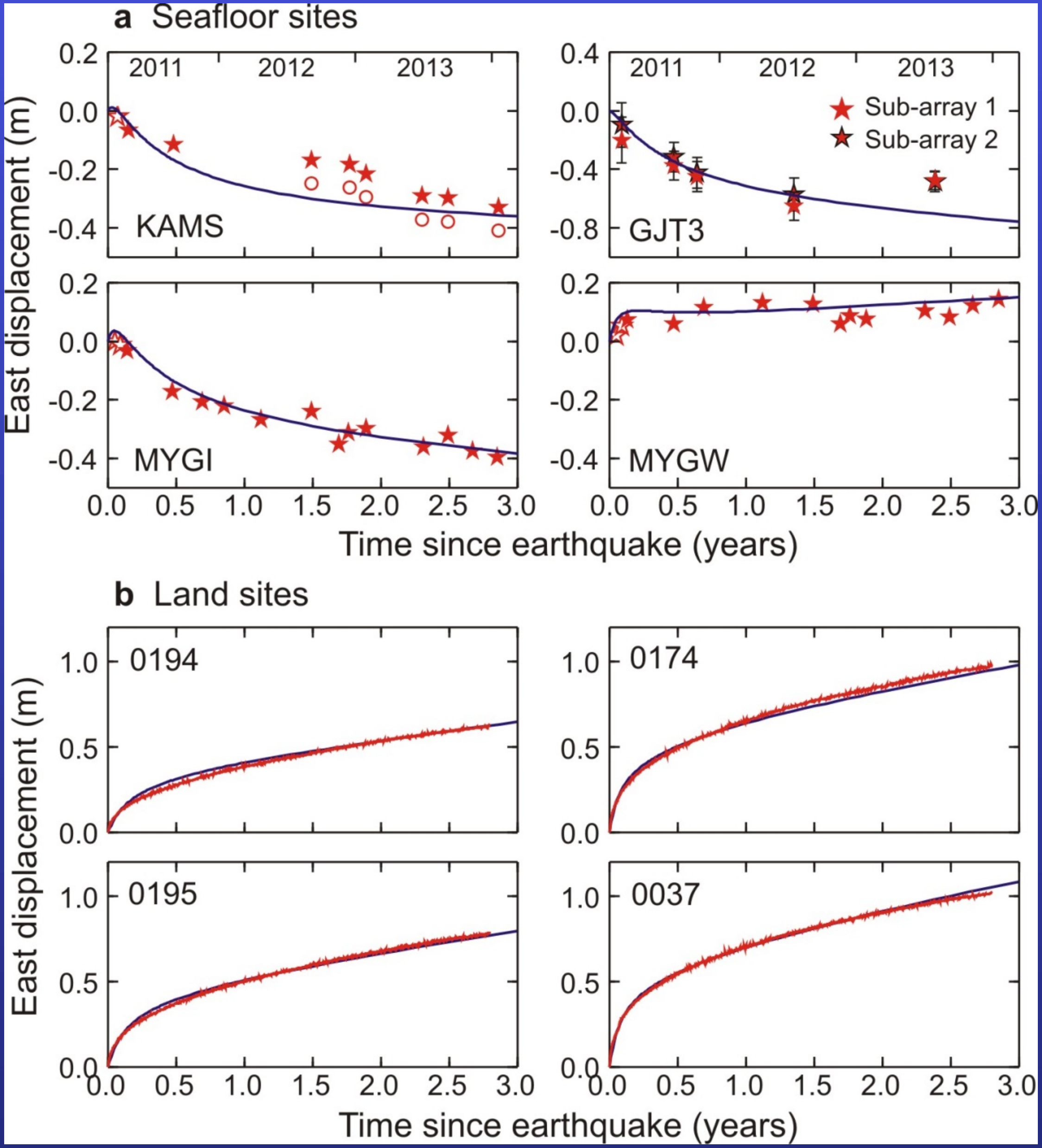
$\eta_M = 1.9 \times 10^{18}$ Pa s

$\eta_K = 2.5 \times 10^{17}$ Pa s

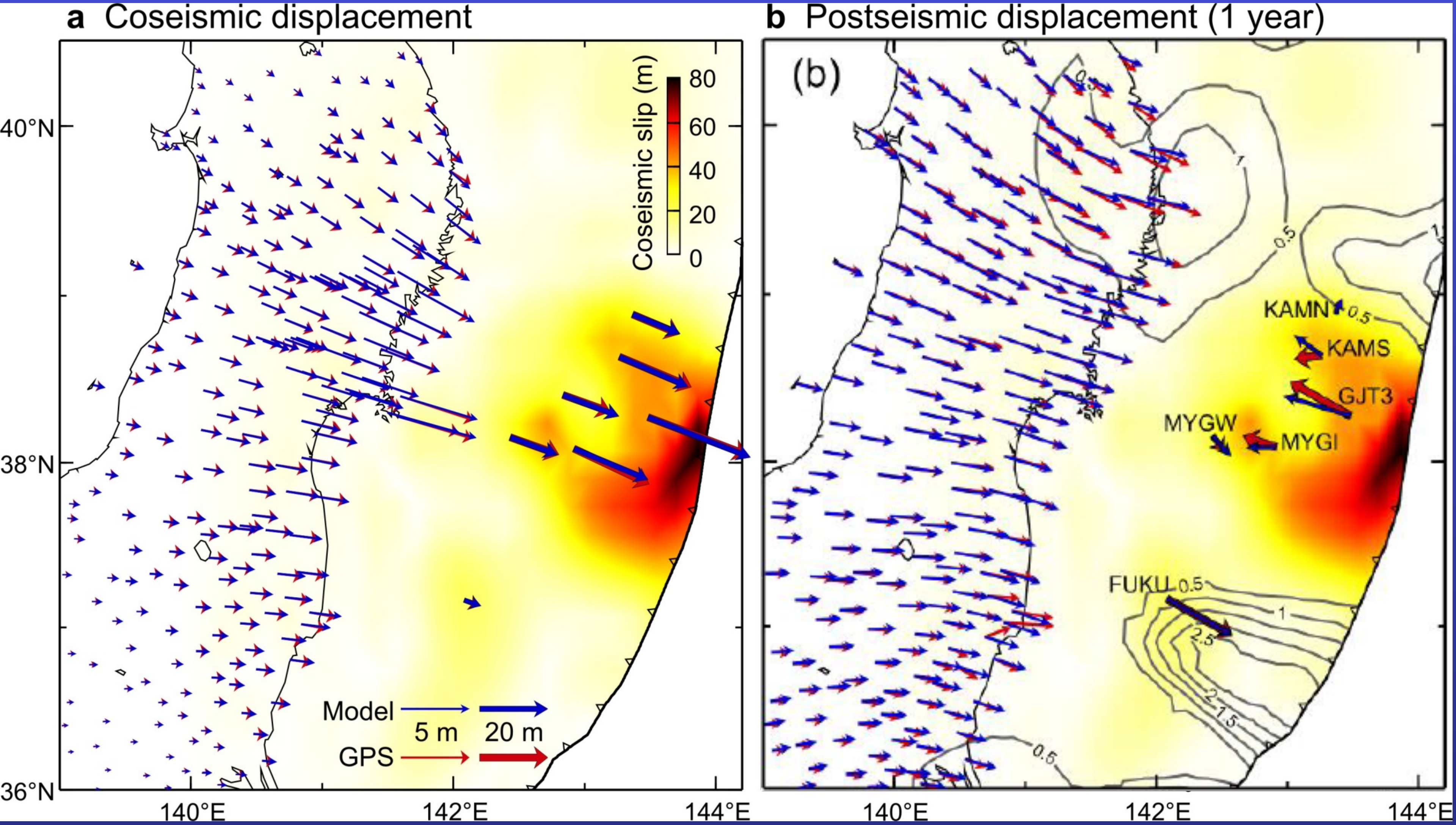

a Coseismic displacement
b Postseismic displacement (1 year)
Coseismic slip (m)
80
60
40
20
0
40°N
38°N
36°N
140°E
142°E
144°E
Model
5 m
20 m
GPS
KAMN
KAMS
GJT3
MYGW
MYGI
FUKU
1 m
0.5 m
GPS



Sun et al., 2014 Nature

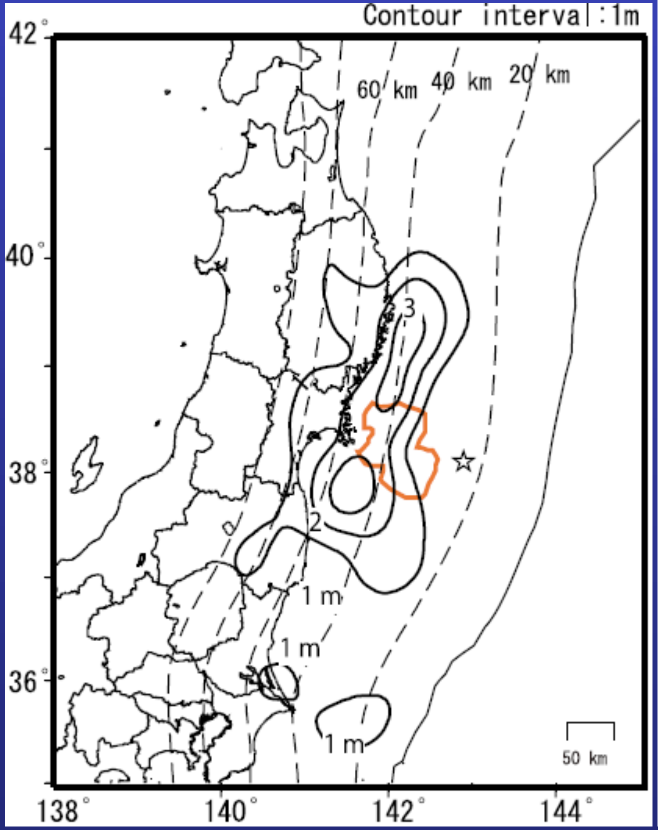


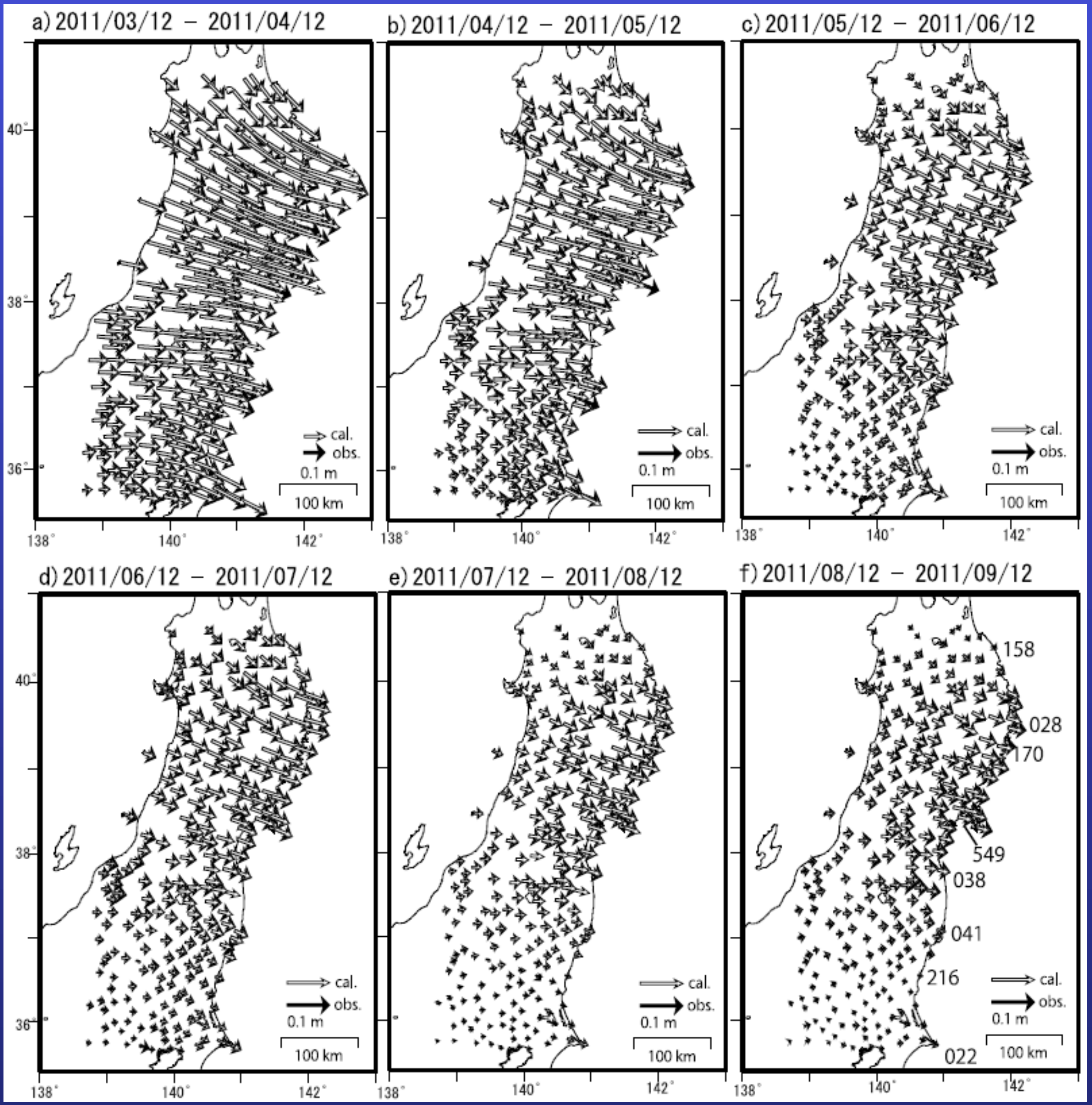
Sun et al., 2014 Nature



Contours lines: afterslip

Ozawa et al. (2012): Afterslip in elastic Earth fully explains 8-month postseismic motion of land GPS sites





Summary

- Interseismic deformation is not a mirror image of coseismic deformation
- Elastic model only provides an “equivalent” kinematic description (all elastic models of interseismic locking need revision)
- (Steady-state) mantle wedge viscosity ~ 10^{19} Pa s (very low!)
- Timescale of postseismic reversal of motion direction depends on earthquake size (longer for larger earthquakes)
- Transient rheology and afterslip are both responsible for short-term post-seismic deformation
- Rupture asymmetry leads to immediate motion reversal in the rupture area (important for constraining afterslip)
- All elastic models over-estimate afterslip downdip of rupture zone and under-estimate shallow afterslip
- Seafloor geodesy will soon bring more breakthrough discoveries