Reminder/Motivations for Why We Need CFEM

Mark Simons, Caltech

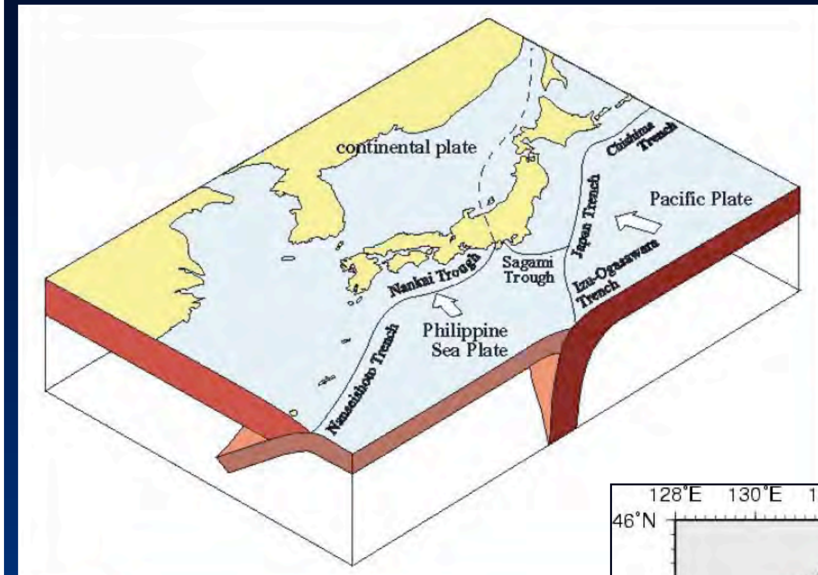
What is driving CFEM development?

Why Now?

Data, data, data, data, data
1. Geodetic (InSAR, GPS, …)
2. Structural (Geology, seismic)
3. Seismicity
4. Laboratory

Why FEM?

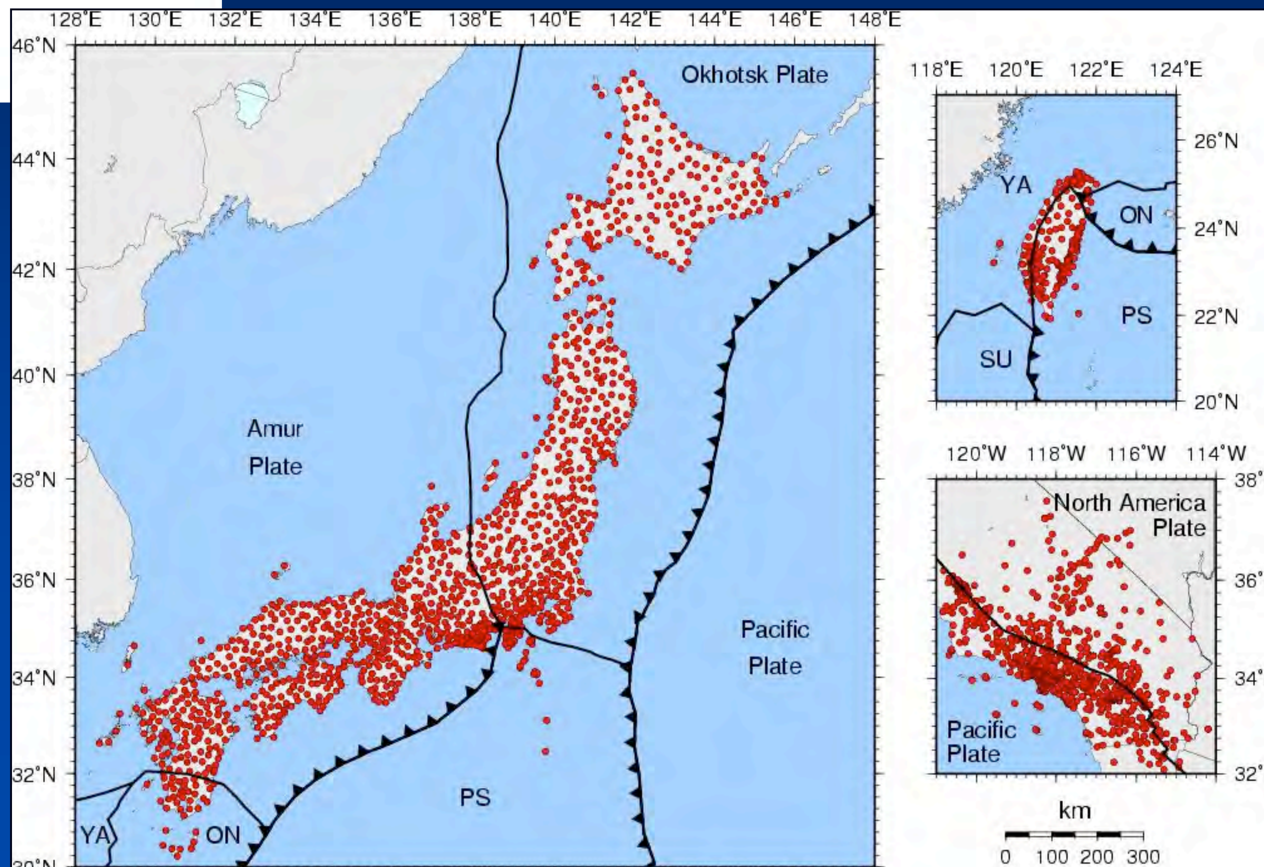
1. Geometric complexity
2. Rheologic complexity



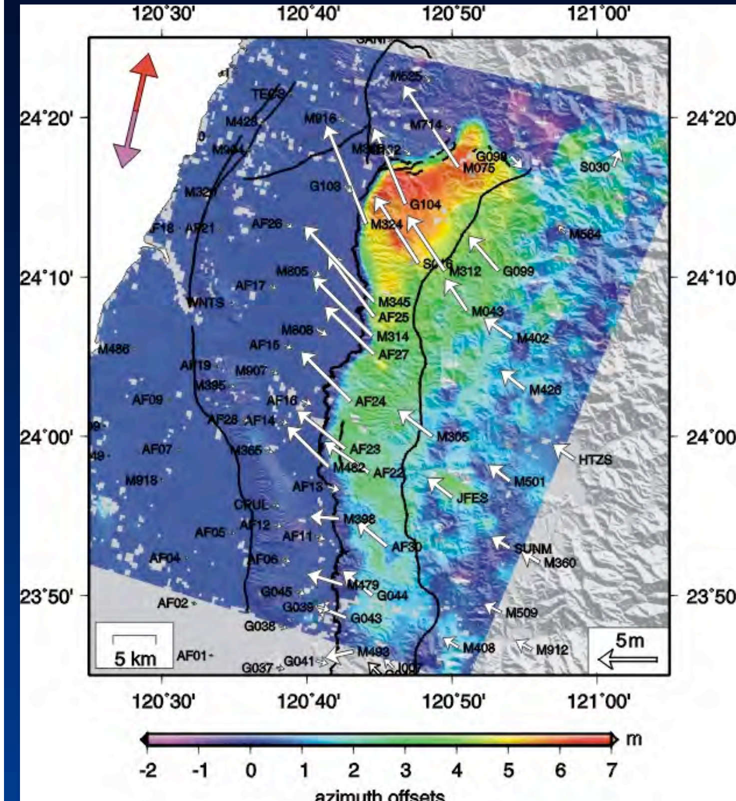
Modern Geodesy- The impetus

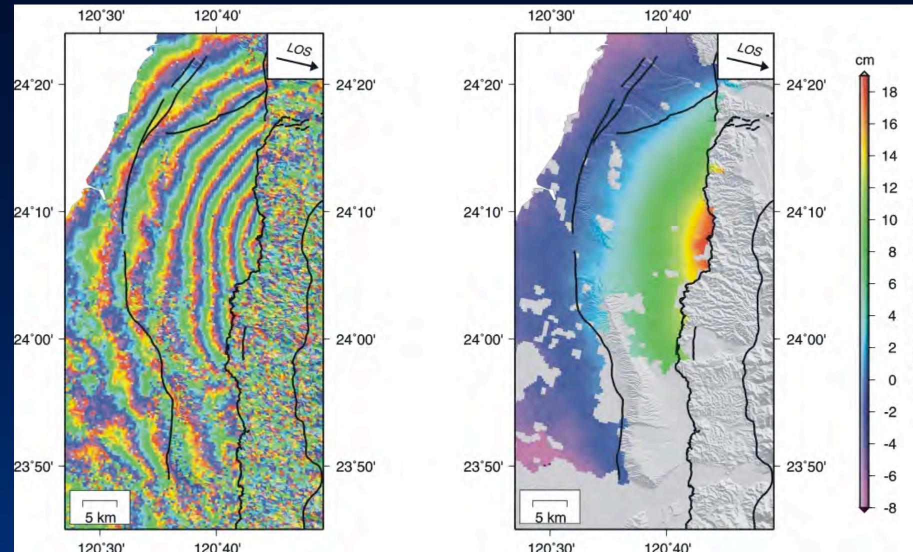
Temporal and spatial resolution

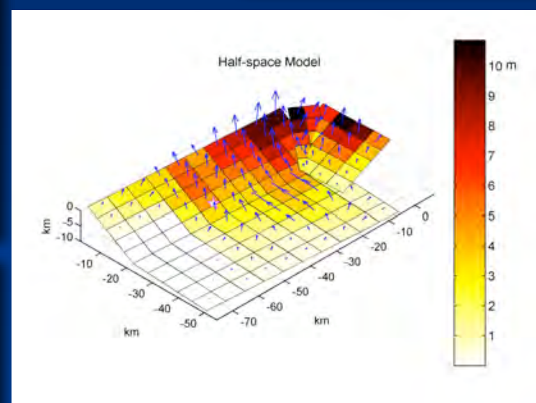
- GPS networks
- Satellite radar interferometry

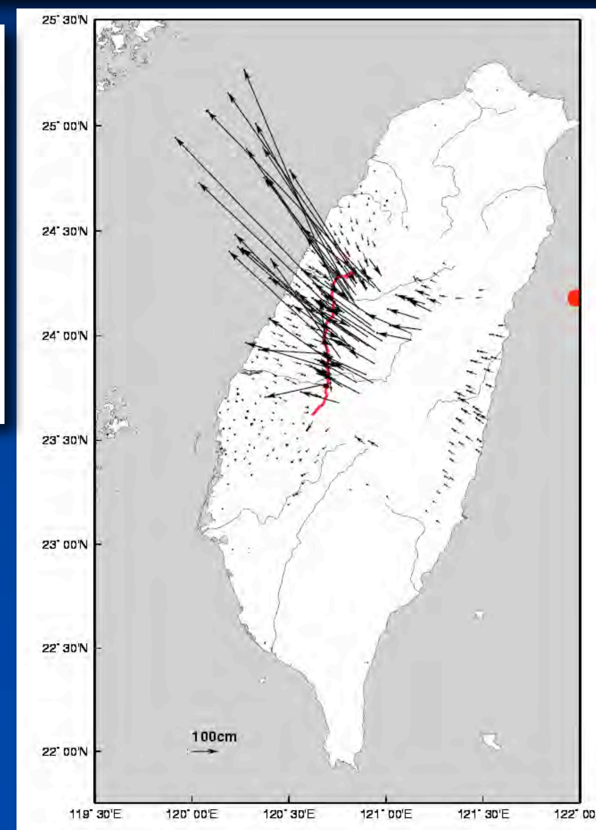


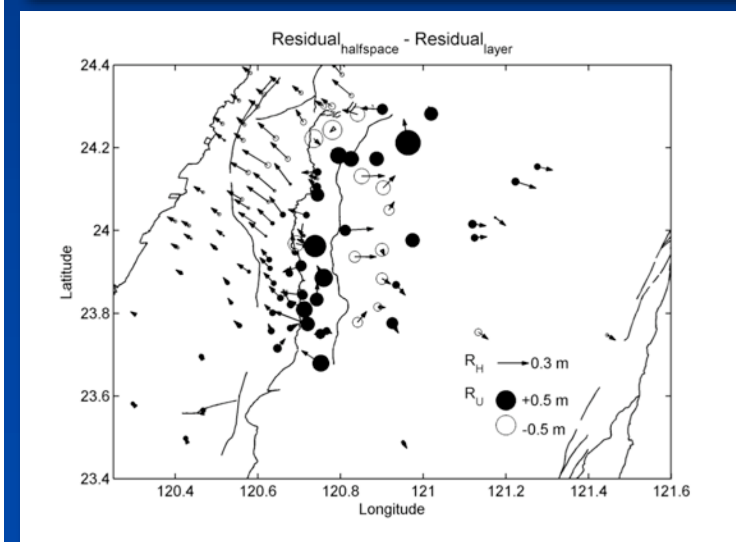
Modern data sets highlight geometric complexity











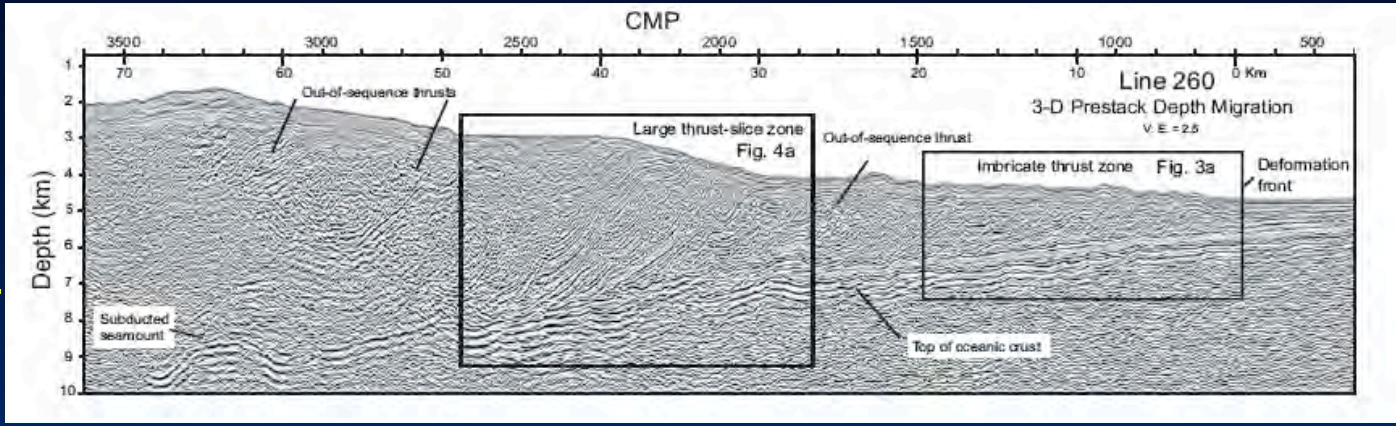
- Explosion of data
- Geometric complexity
- Rheologic complexity

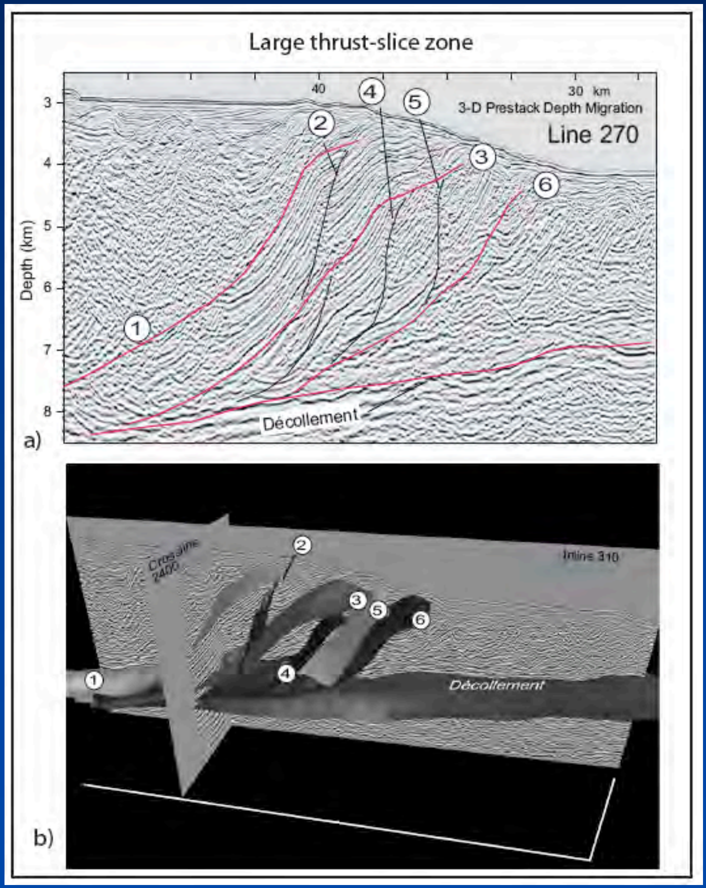
Yaru Hsu+

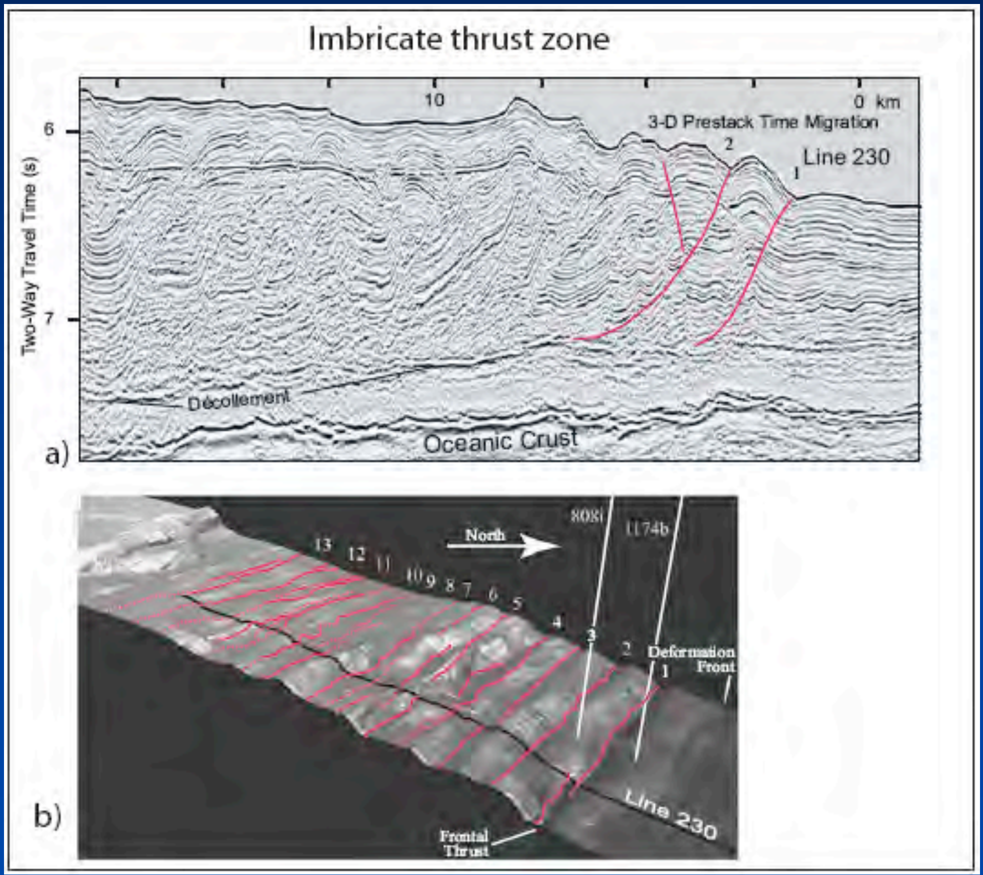
Start with this…

Structure of the forearc

Faults, material, etc.

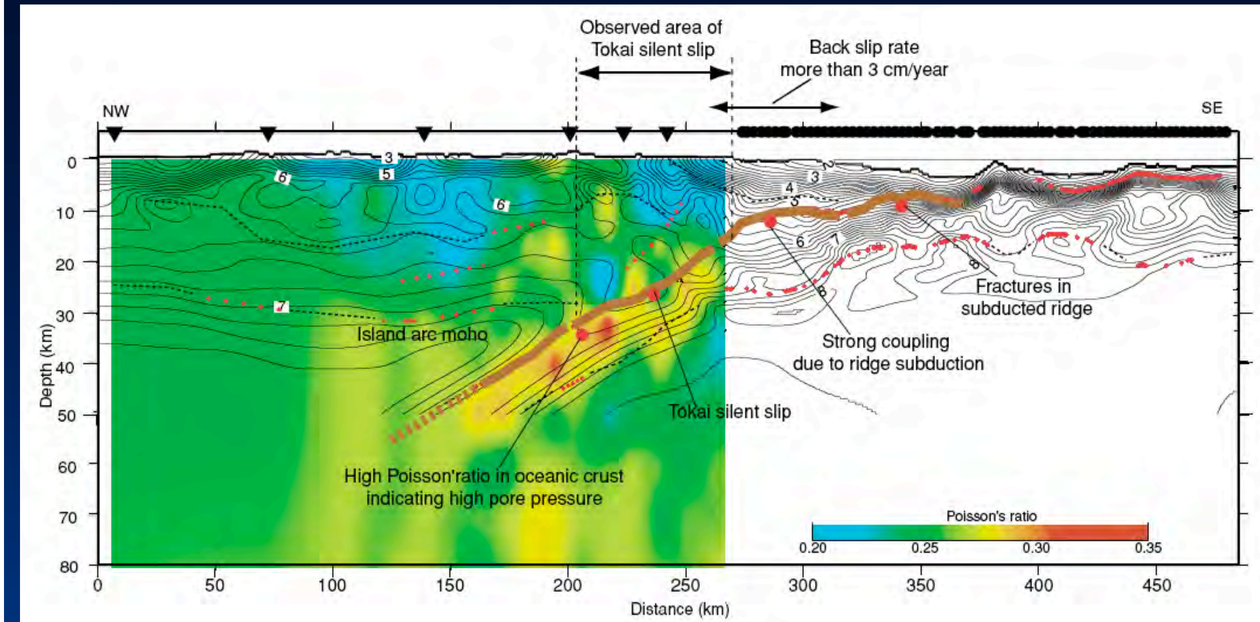


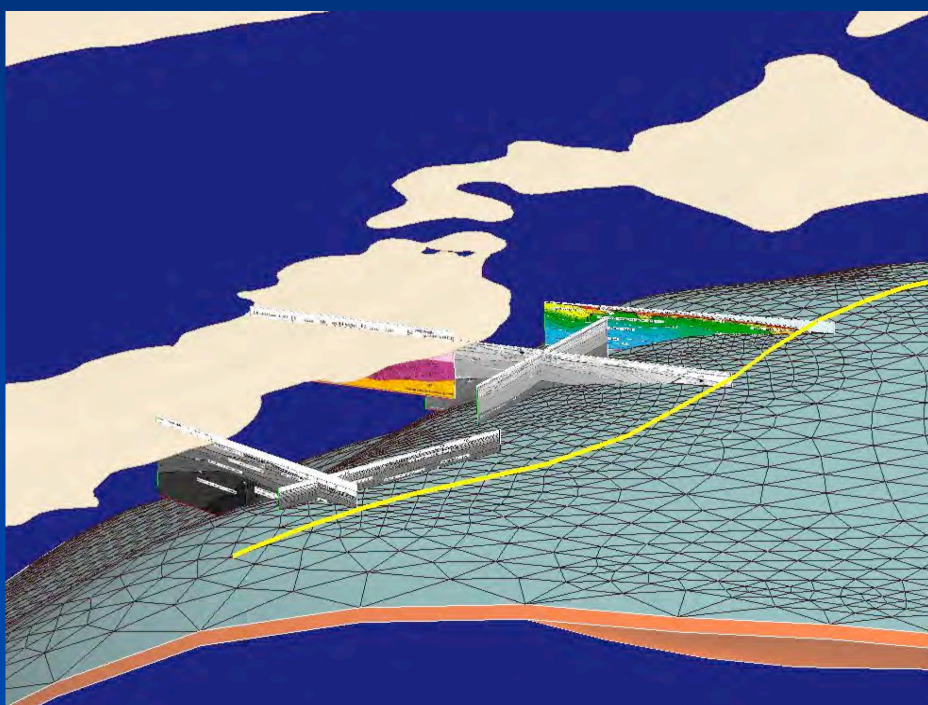


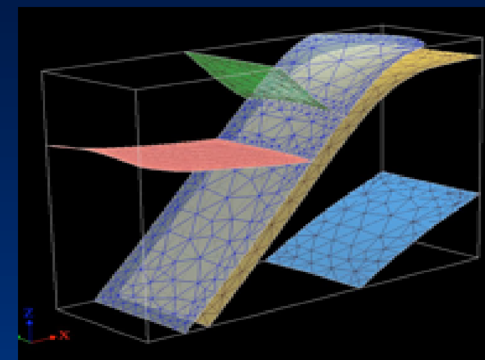


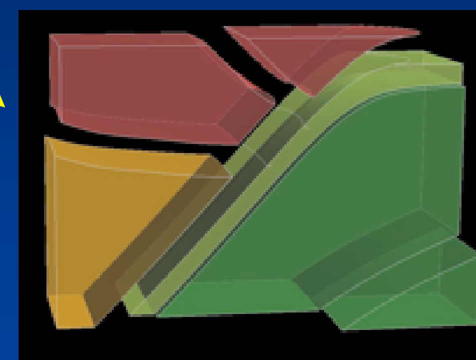
Bangs et al., 2005

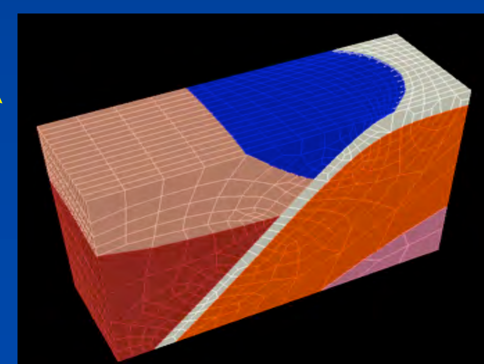
The Meshing Challenge





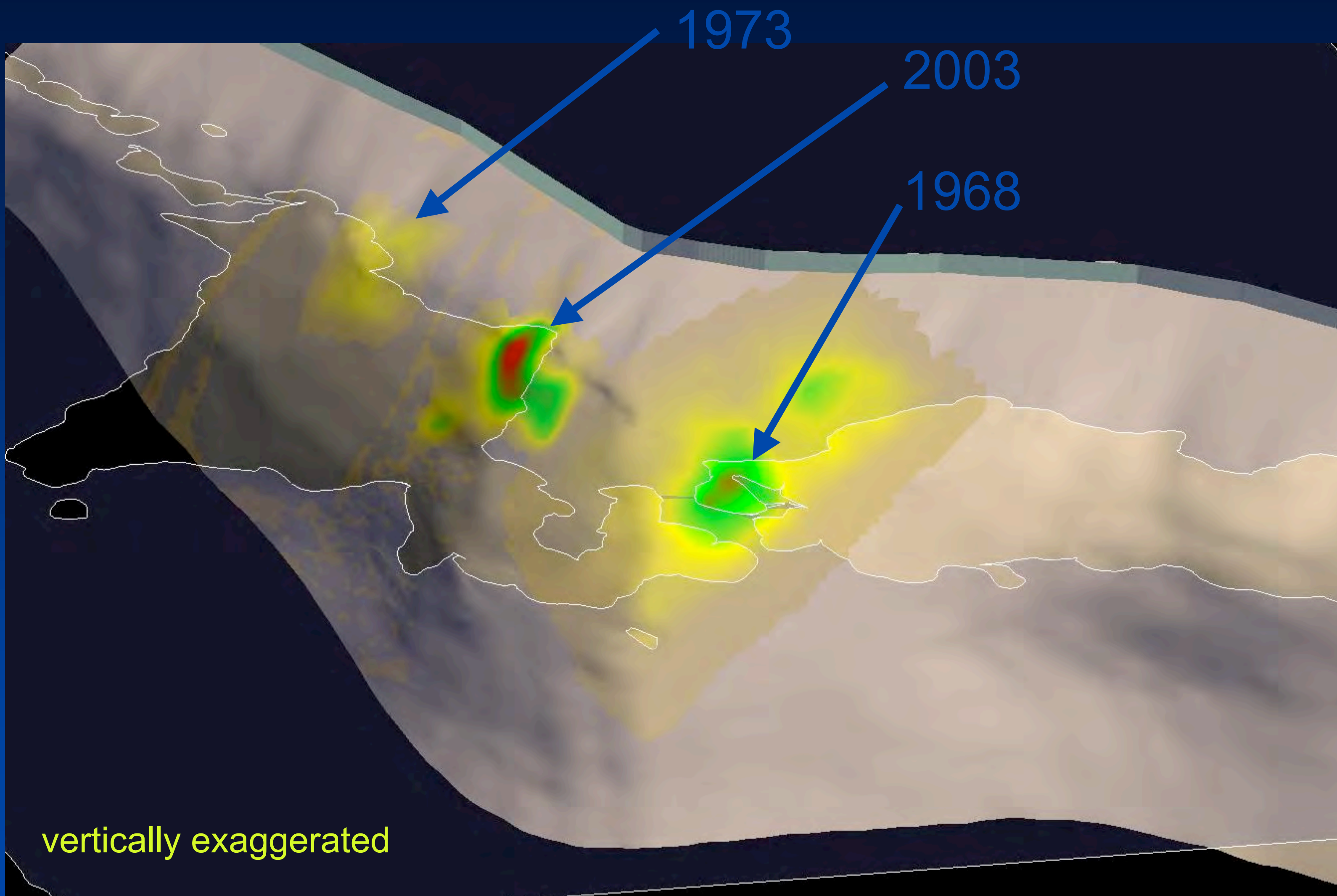






Bookkeeping Materials + properties + interfaces

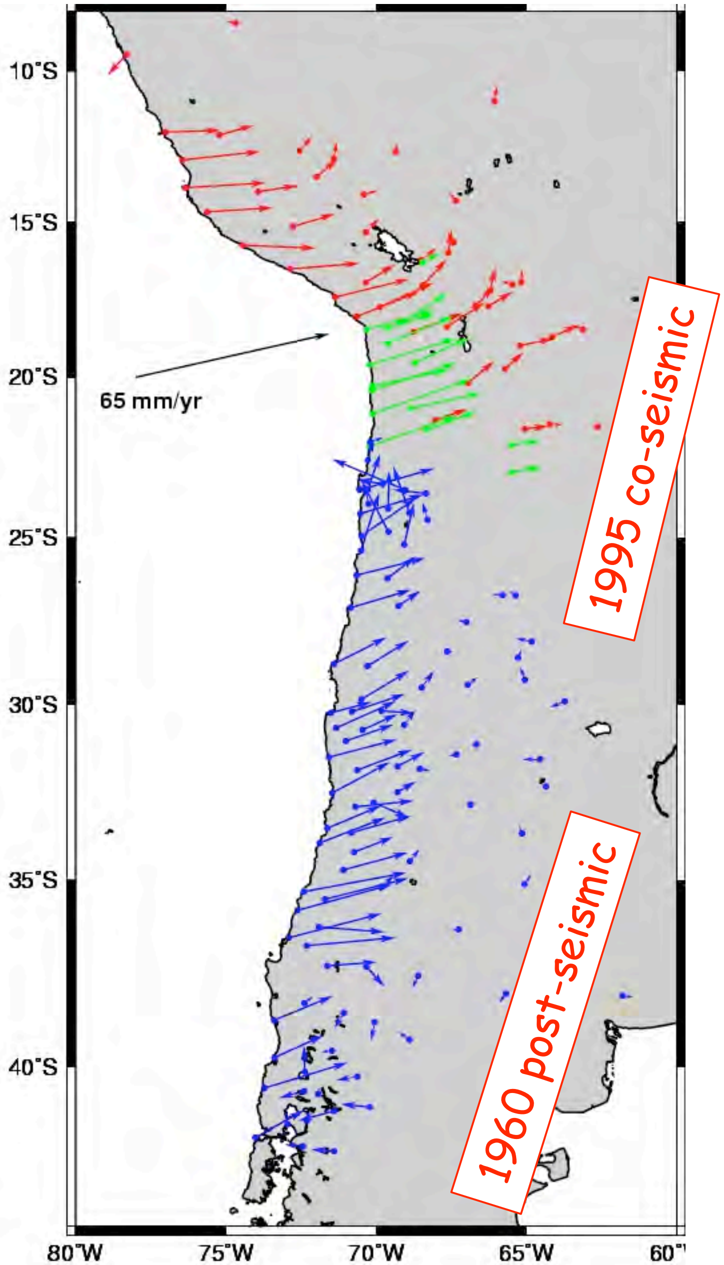
gOcad

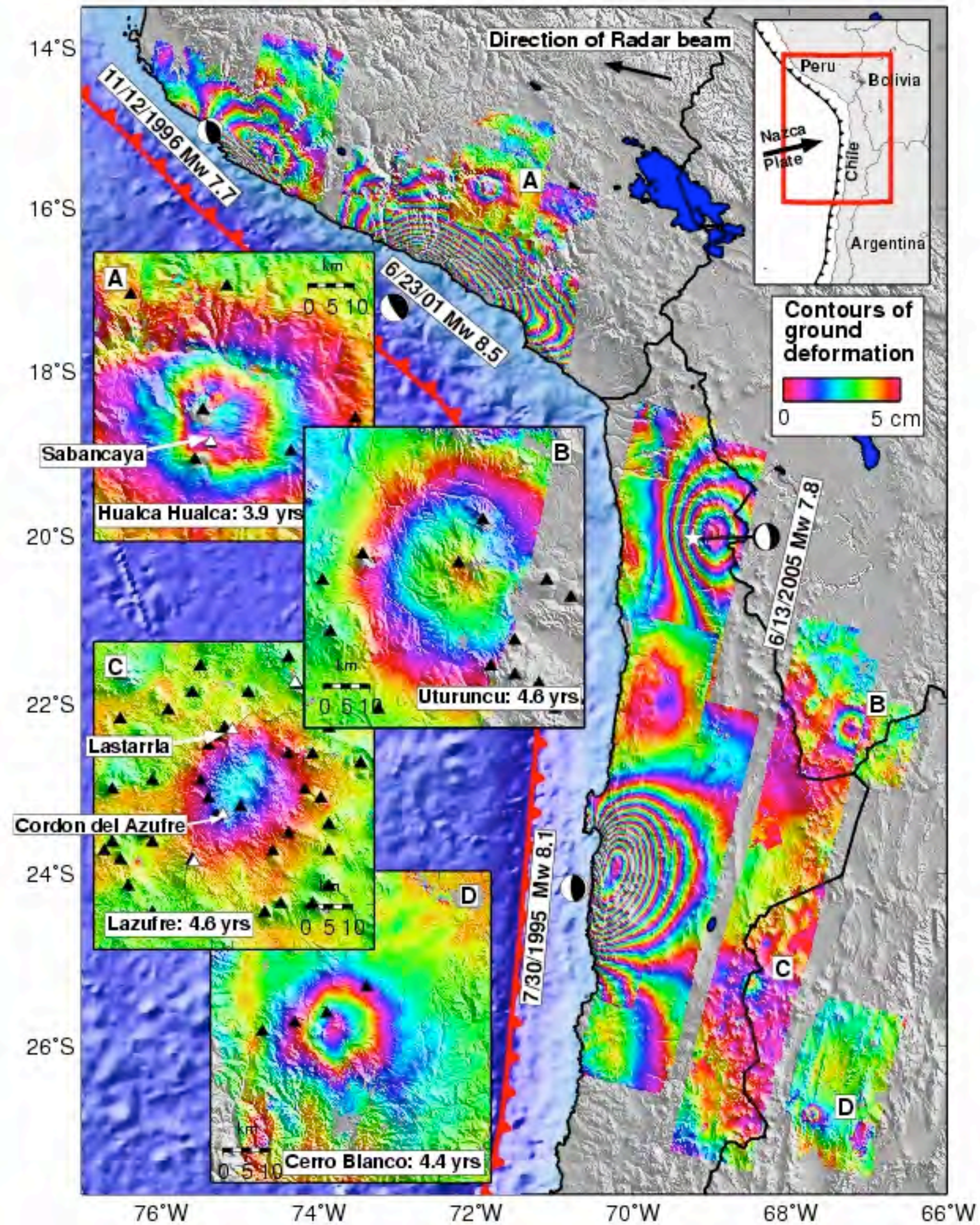


Eric Hetland

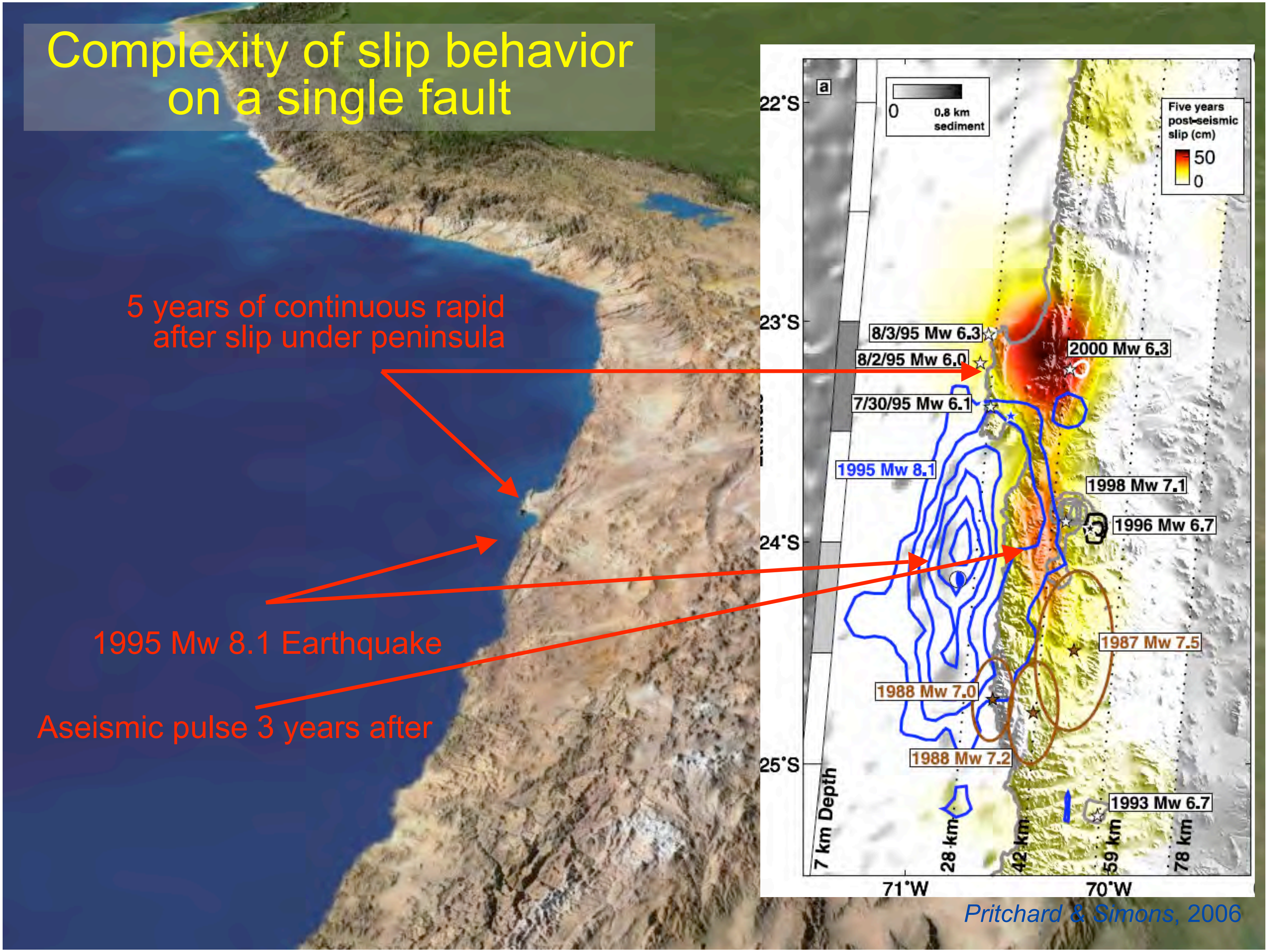
slip models from Yamanaka and Kikuchi (2002)

Fault zone rheological complexity





Matt Pritchard +


Complexity of slip behavior on a single fault
5 years of continuous rapid after slip under peninsula
1995 Mw 8.1 Earthquake
Aseismic pulse 3 years after
a
0
0.8 km sediment
Five years post-seismic slip (cm)
50
0
22°S
23°S
24°S
25°S
71°W
70°W
8/3/95 Mw 6.3
8/2/95 Mw 6.0
7/30/95 Mw 6.1
2000 Mw 6.3
1995 Mw 8.1
1998 Mw 7.1
1996 Mw 6.7
1987 Mw 7.5
1988 Mw 7.0
1988 Mw 7.2
1993 Mw 6.7
7 km Depth
28 km
42 km
59 km
78 km
Pritchard & Simons, 2006

Complexity of slip behavior on a single fault

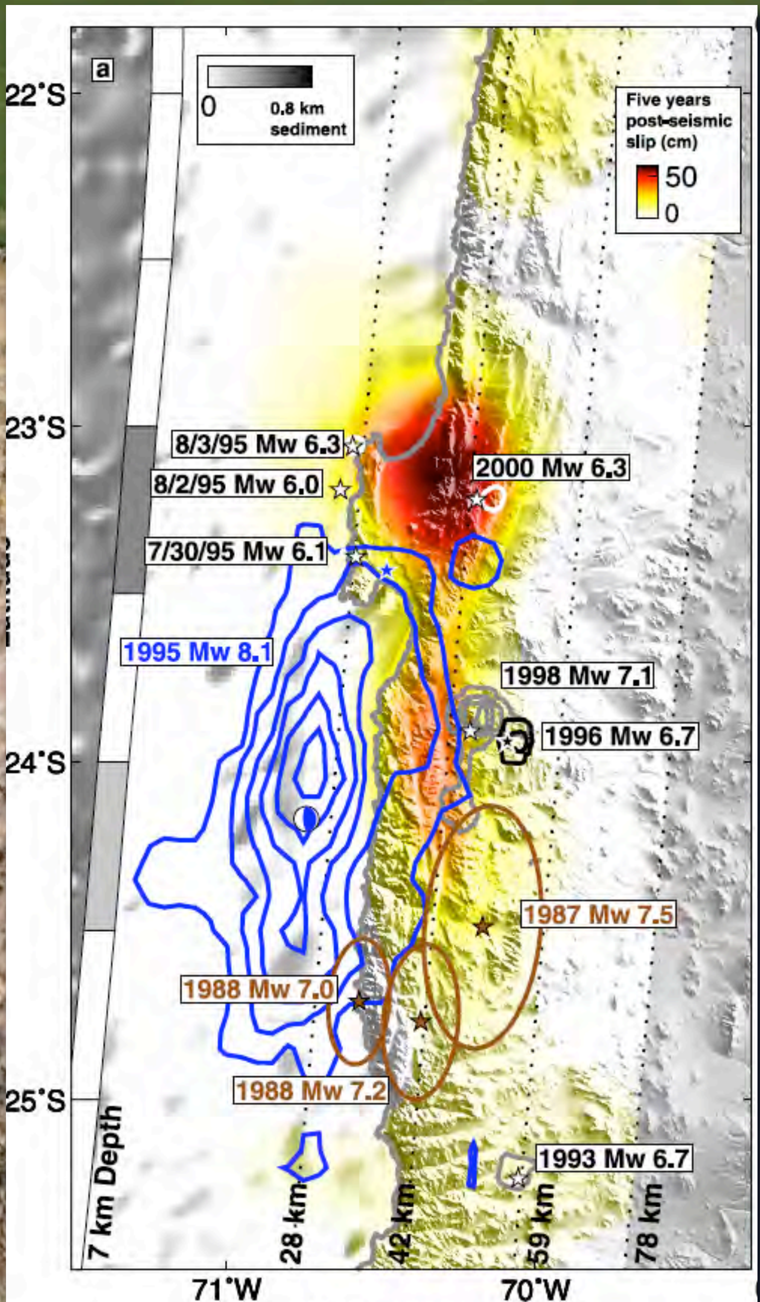
➲ Negligible coseismic slip at the hypocenter (Previous/next earthquake? Probably not)

➲ Centroid at ~ 30-km-depth

➲ Along strike variability in behavior

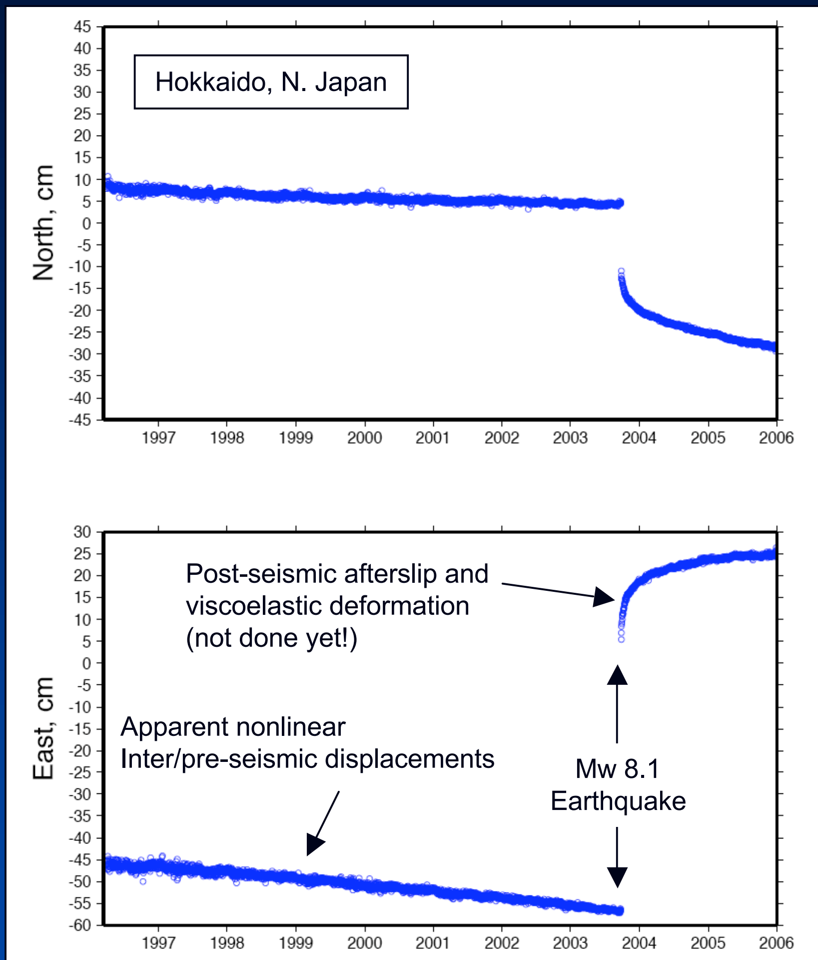
➲ Aftershocks surround the aseismic patch

➲Correlation with long-lived geologic Structure



Pritchard & Simons, 2006

The Seismic Cycle



- Where is elastic stress accumulating to be released in future earthquakes?
- What are the mechanics of the fault and surrounding regions?
- What is the connection to permanent inelastic deformation (e.g., topography)?

Issues in Seismic-cycle modeling

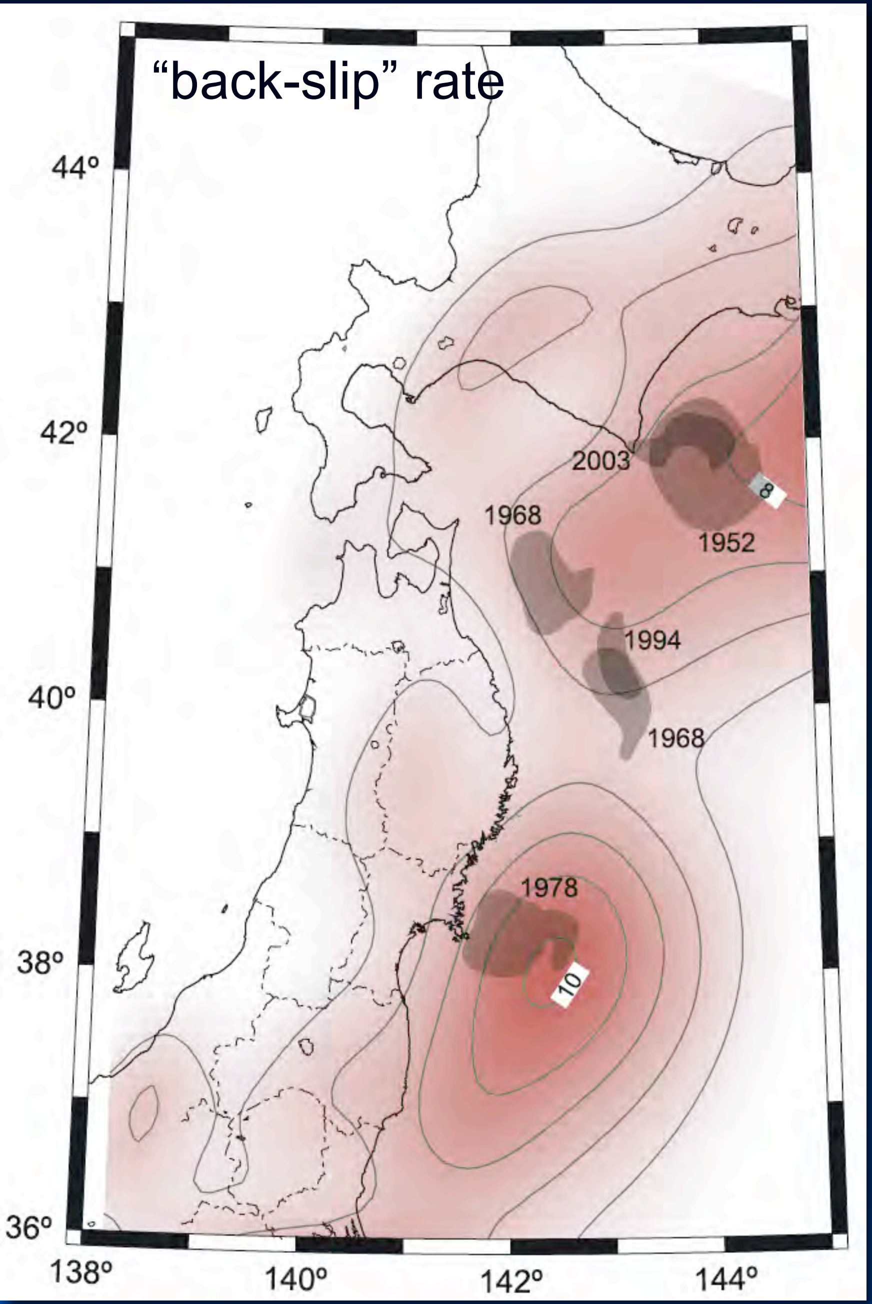
Example:

Interseismic Subduction Zones

Invert GPS velocities for the "*coupling coefficient*"

- $v_{bs} = v_T$: coupled (C=1)
- $v_{bs} = 0$: uncoupled (C=0)

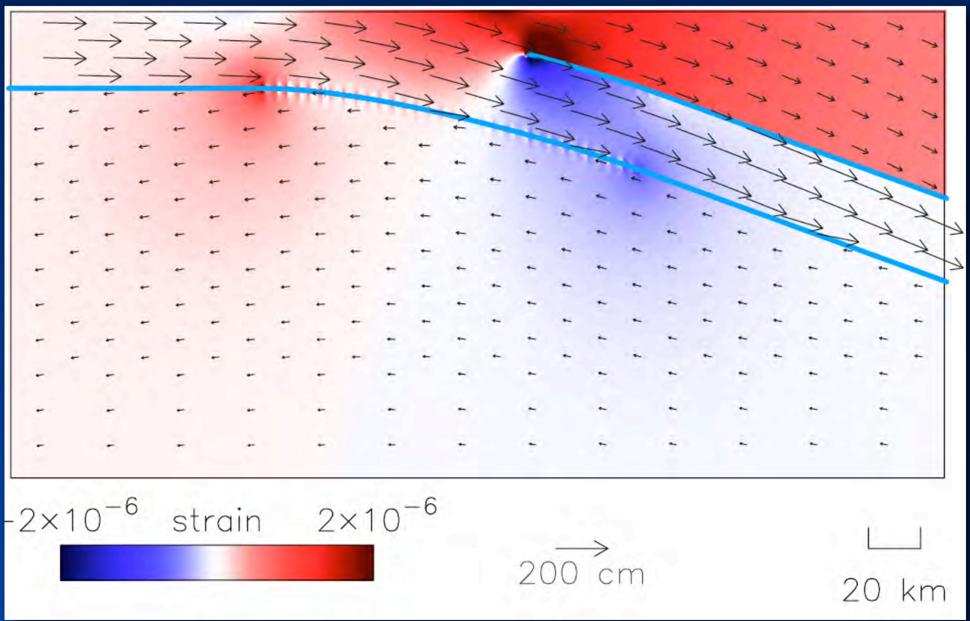
It is time to go beyond purely kinematic models!

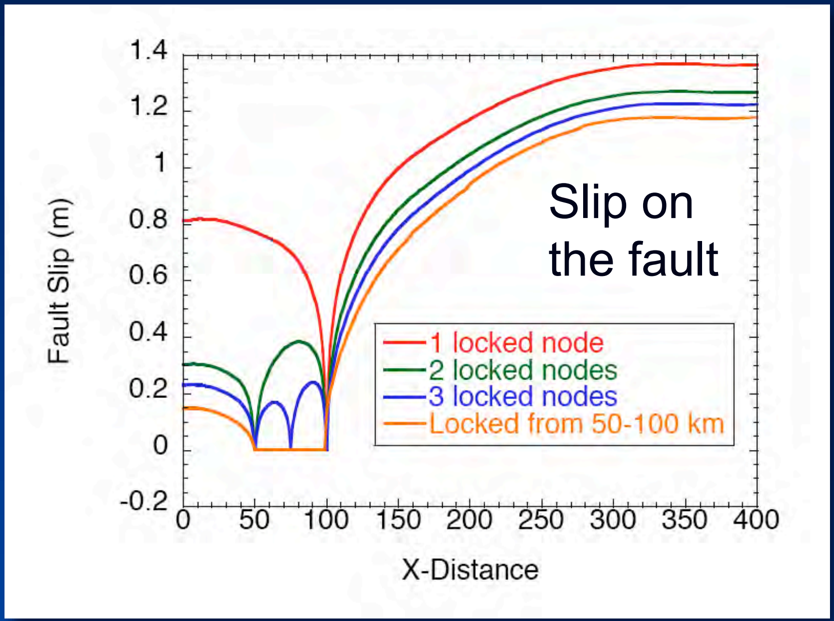


Suwa et al., 2006

Stress Shadowing

Not slipping ≠ Coupled

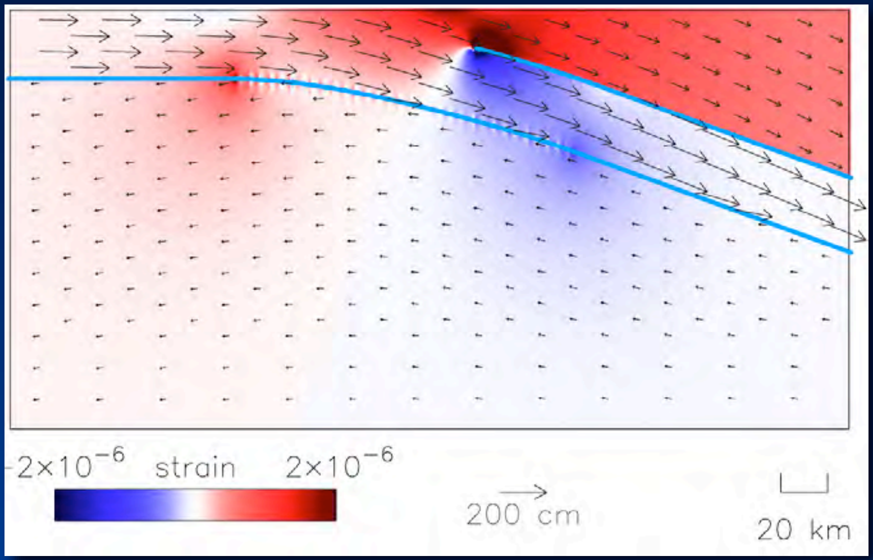


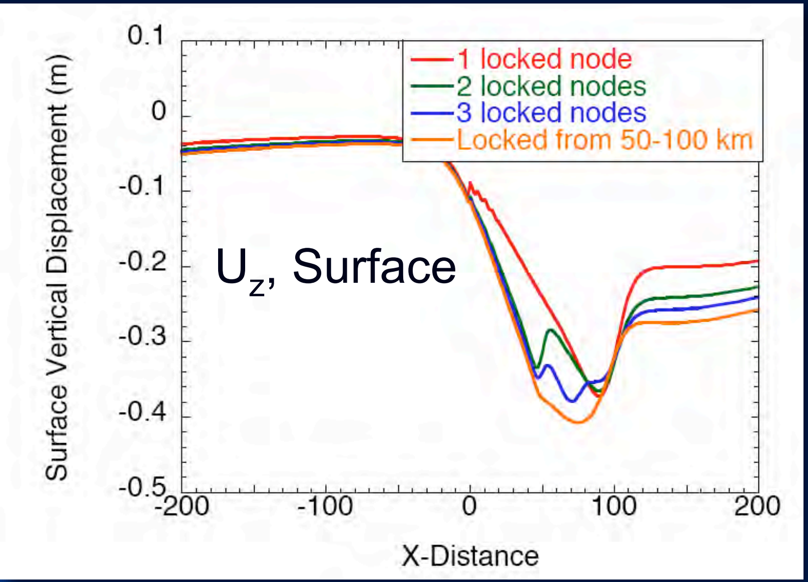


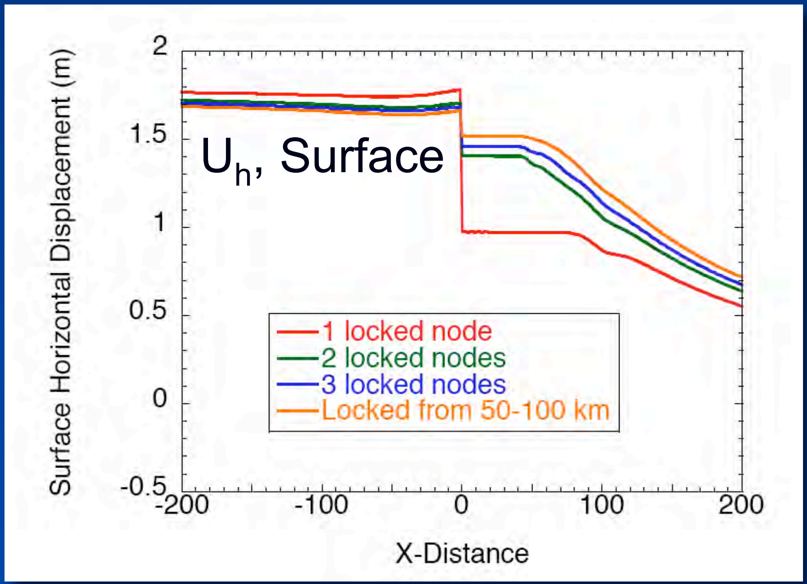
Charles Williams, 2005

- 2D FEM models
- 2D pinning (a line asperity, not a point) - Caution with stresses
- Zero shear tractions updip of the pin(s)
- Driven motion on the downdip portion of the plate
- A single pin has a dramatic influence

Observational Challenges



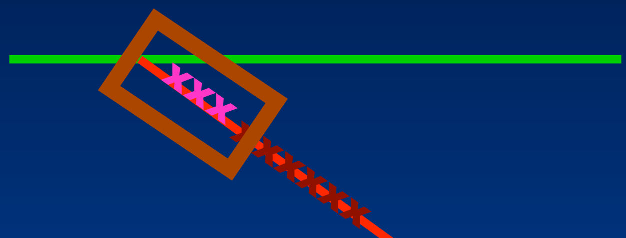


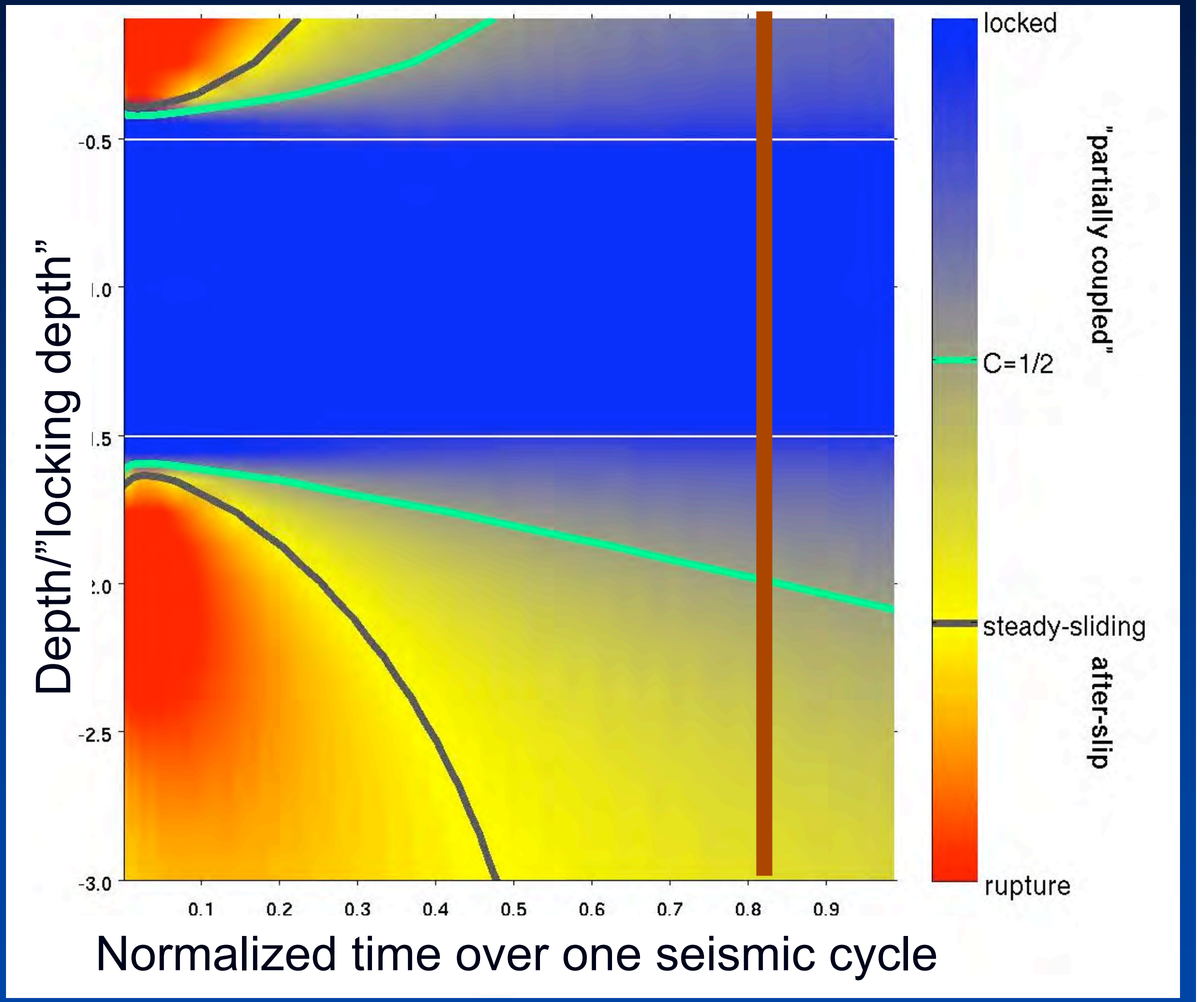


- Where are the observations usually made? On land, usually X>100km
- Updip resolution very challenging
- We really need both horizontals and verticals, and test rheological hypothesis

Charles Williams, 2005

Apparent variation of coupling through an interseismic period





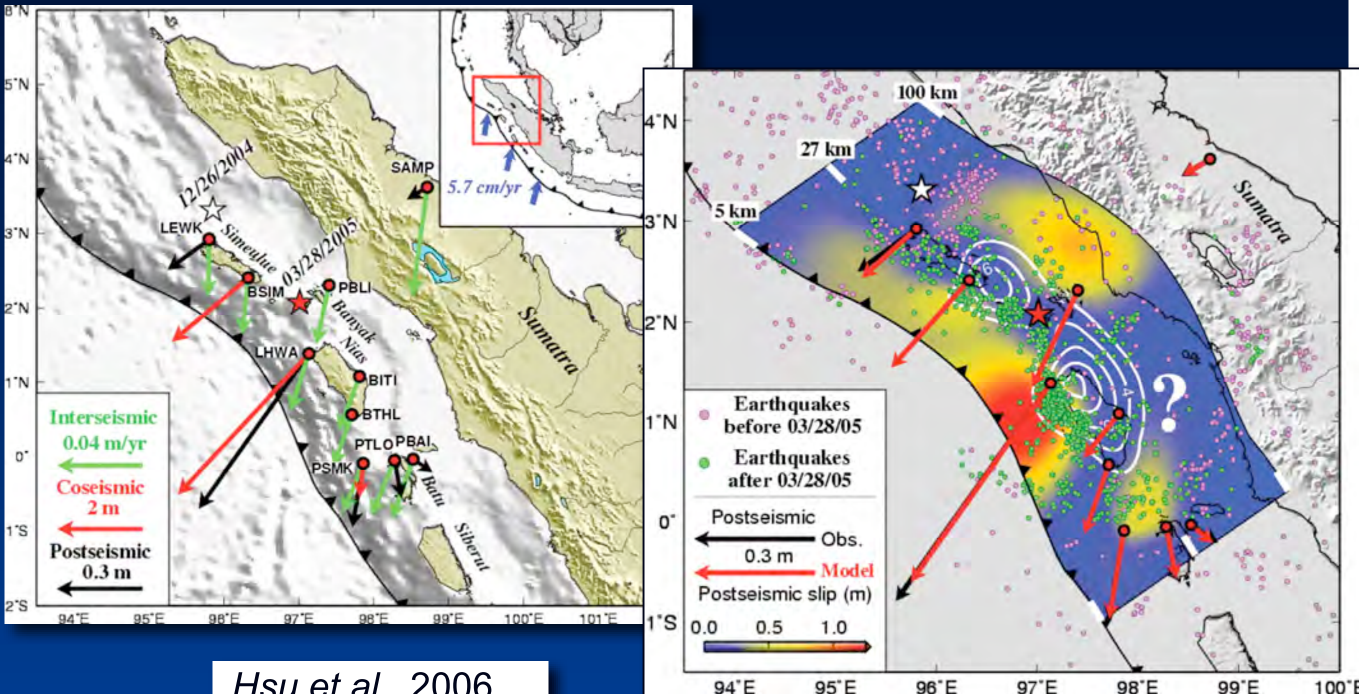
- Quasi-static 2D or 3D fault slip model (no earthquake rupture dynamics)

- Green Functions: BEM or FEM

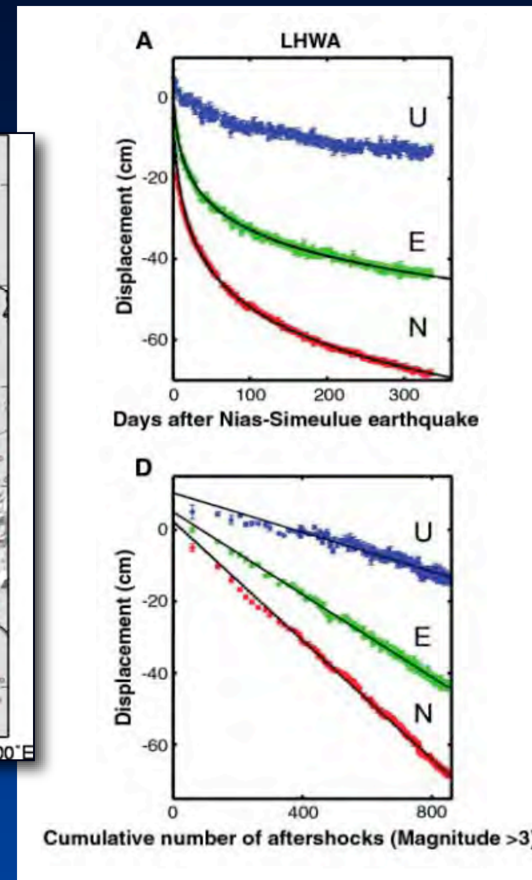
- Fault rheology: Linear viscous, non-linear viscous, or R&S frictional

Eric Hetland

2005 M_w 8.7, Nias Earthquake



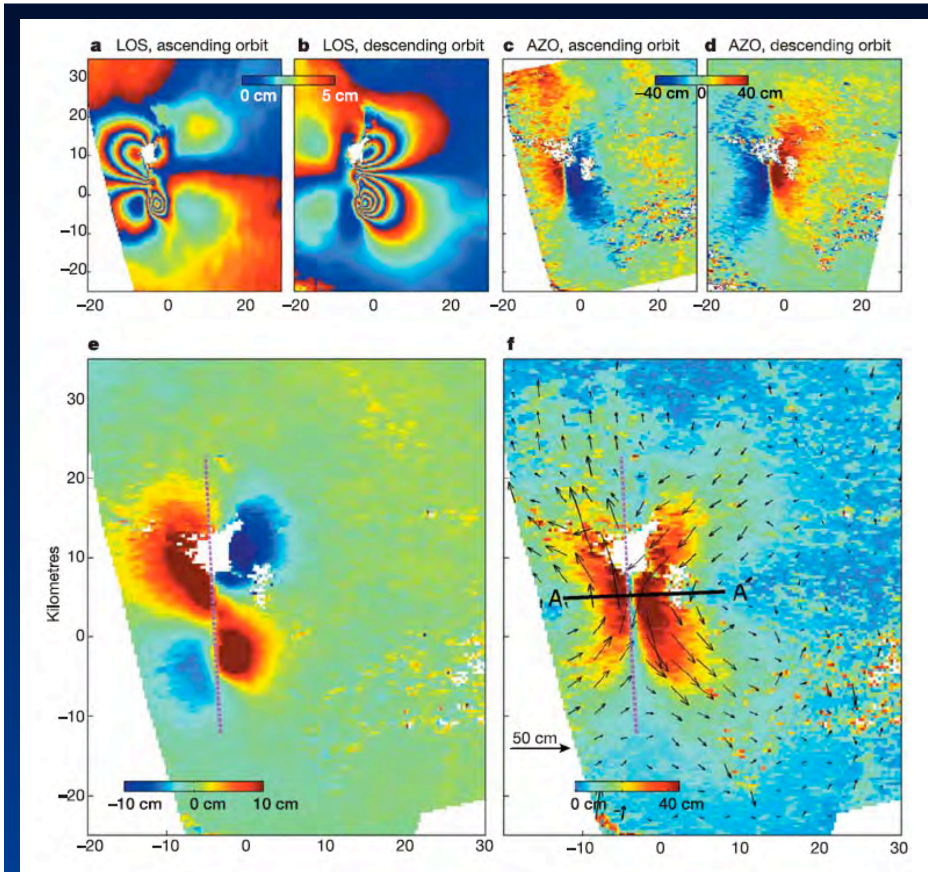
Hsu et al., 2006

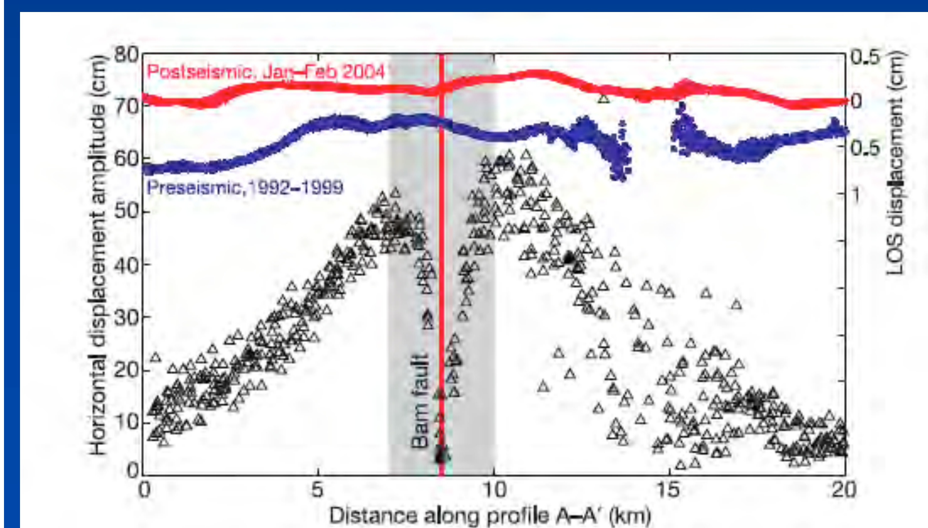


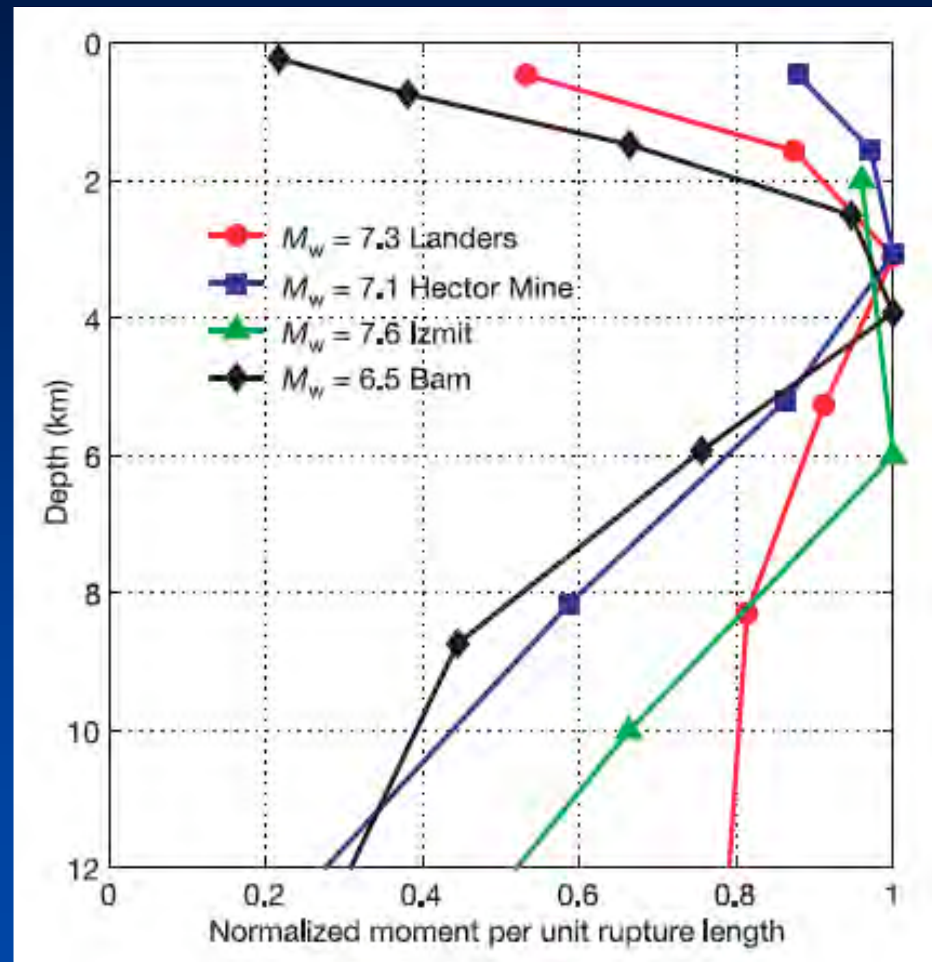
- ➲ Near-trench GPS data provide strong constraints on updip behavior
- ➲ Slip highly heterogeneous in space (rheologic complexity)
- ➲ Coseismic and postseismic show little overlap
- ➲ Log(t) afterslip consistent with velocity strengthening frictional slip on fault
- ➲ Linear relationship EQ vs Slip implies same functional form
- ➲ Afterslip appears to control aftershock production

Off fault rheological complexity

2003 Mw 6.6 Bam, Iran
The role of damage (e.g., Jim's talk)







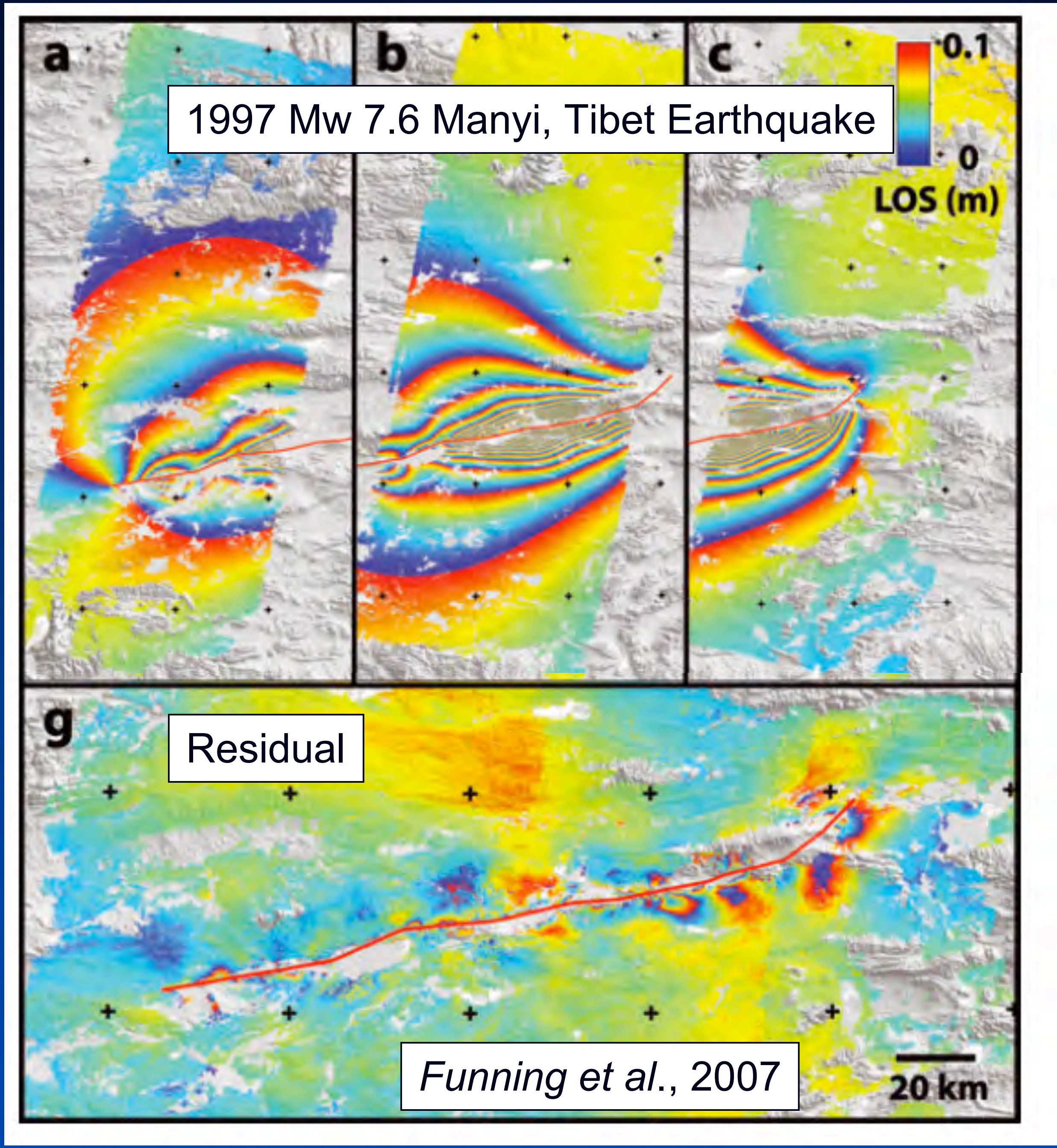
Fialko et al., 2005

Need high spatial resolution at shallow depths

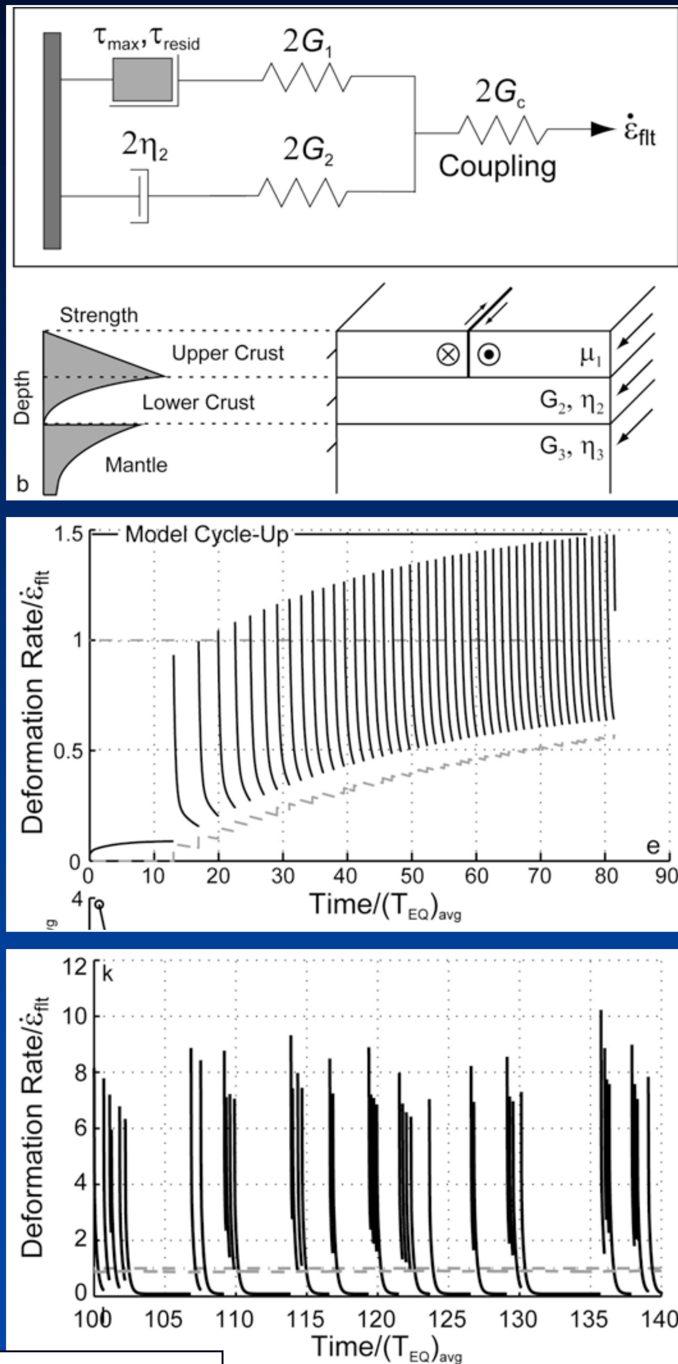
Deeper depths not clear

How much of the residual is elastic vs inelastic?

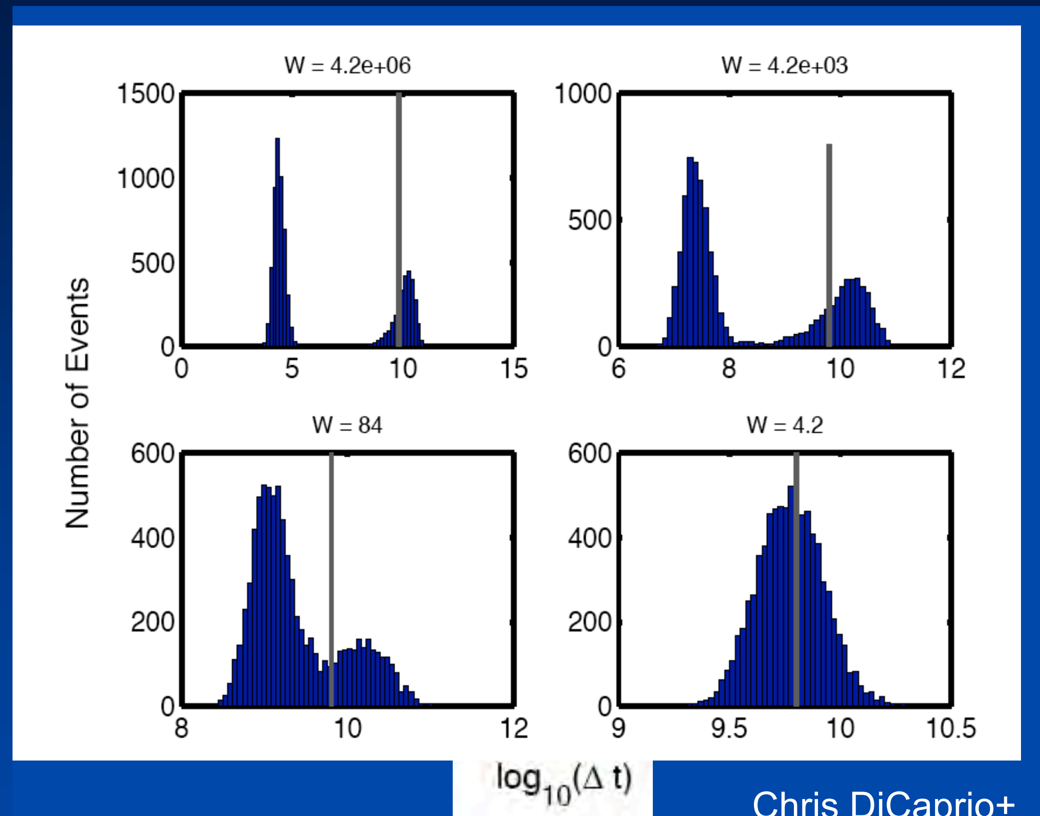
Presumably we need highly variable mesh sizes to efficiently capture variations in stress both on and off the fault



The role of history



Kenner & Simons

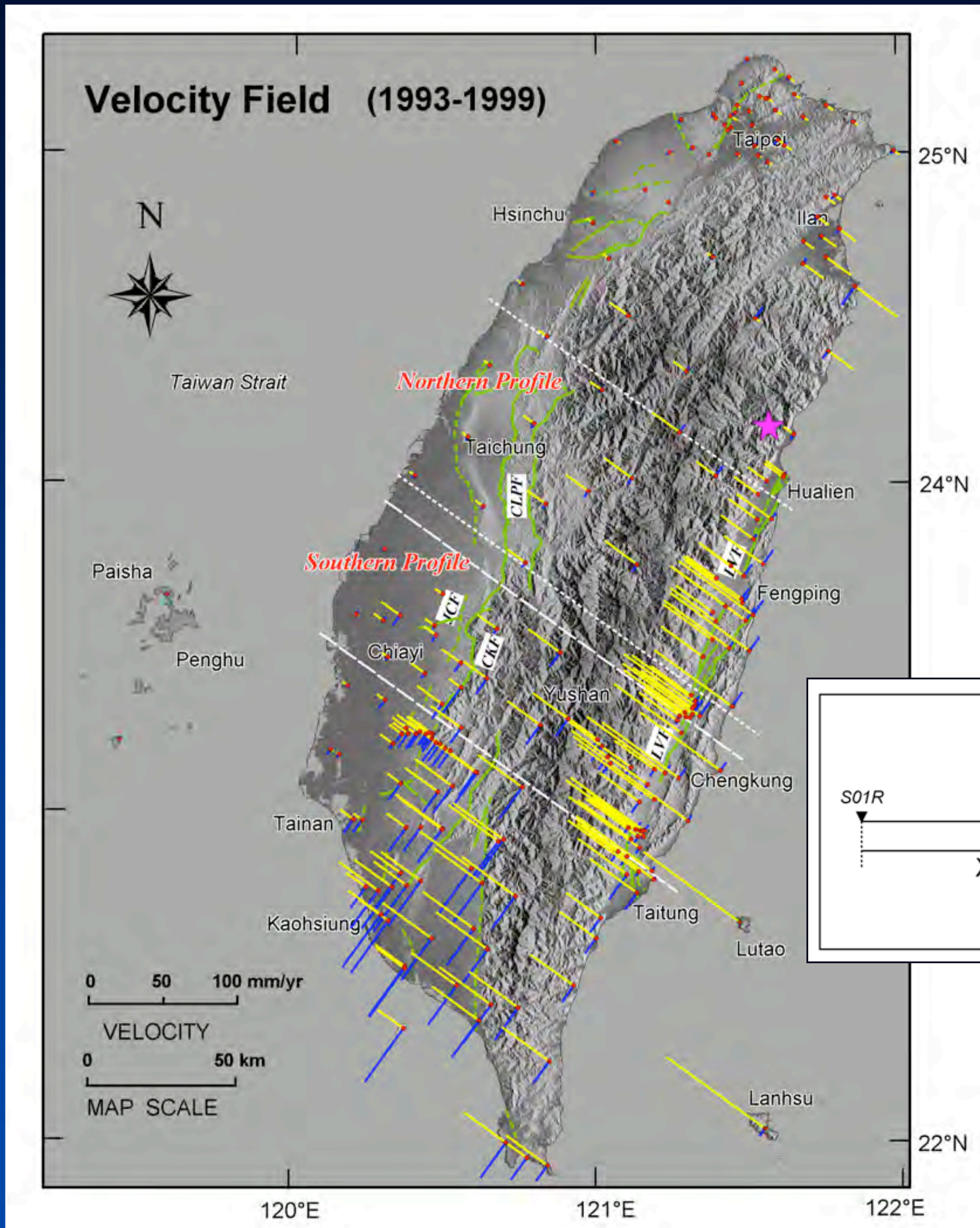


Chris DiCaprio+

- Systems with memory need internally consistent pre-stress (frequently ignored - bad)
- Hard to do for geometrically realistic models

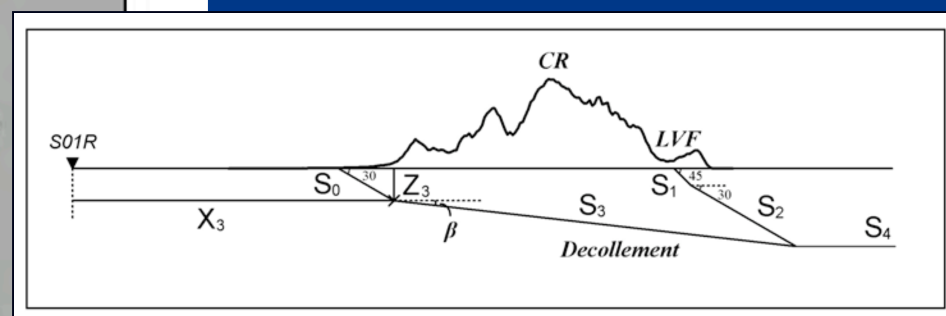
The importance of bridging time scales

From earthquakes (seconds to 10^2 of yrs)
to geology (10^5 to 10^6 yrs)

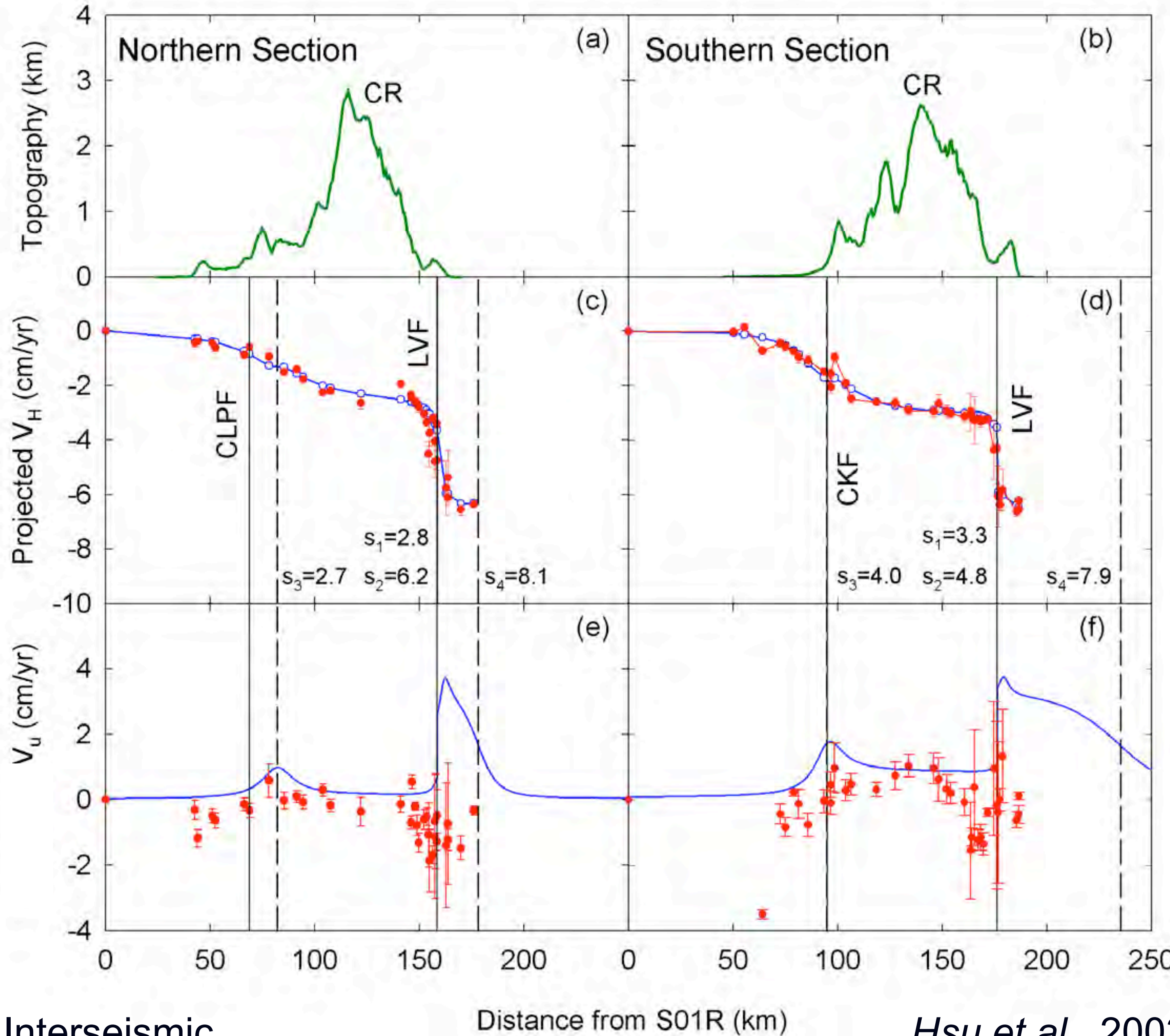


From interseismic to geologic time scales

Invert for:
- Location of western dislocation (X_3, Z_3)
- Dip of S_3
- Slip on S_1, S_2, and S_3

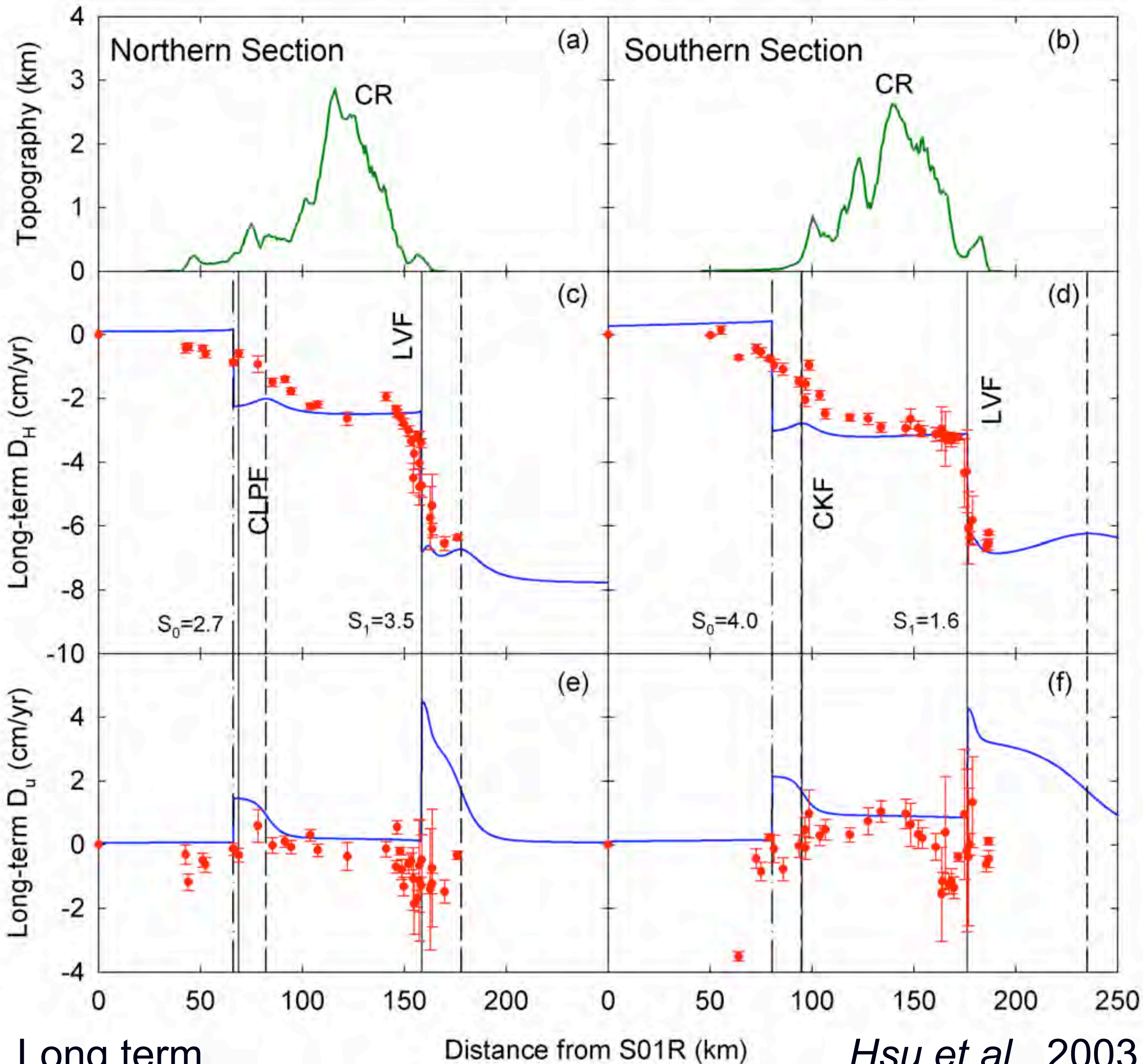


Hsu et al., 2003



Interseismic

Hsu et al., 2003



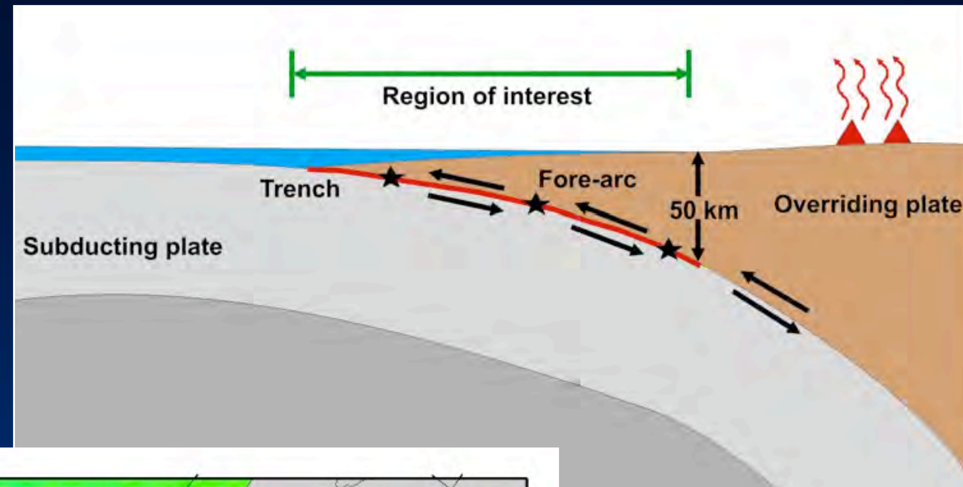
Long term

Hsu et al., 2003

TPGA & Earthquakes

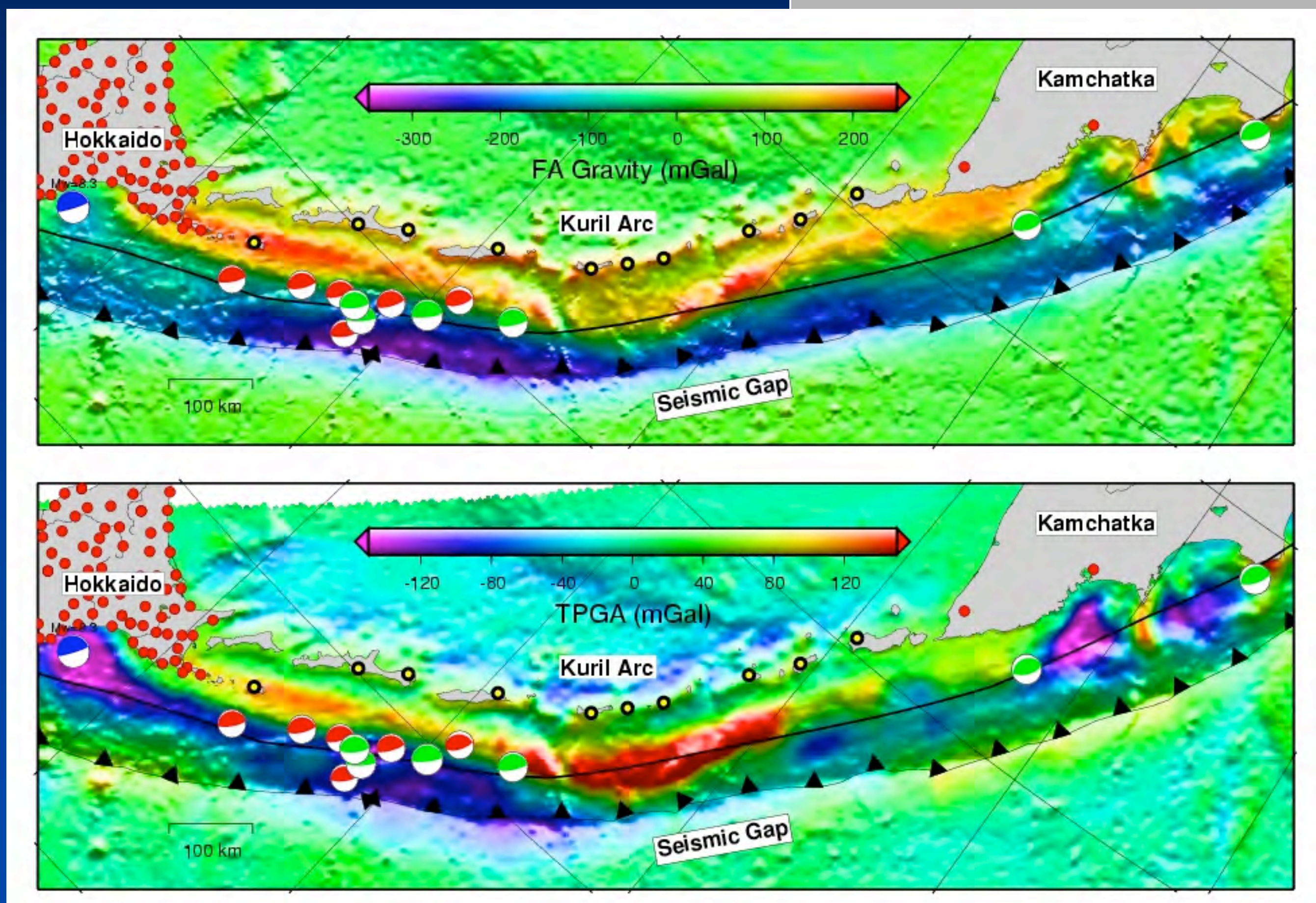
TPGA = Trench Parallel Gravity Anomaly

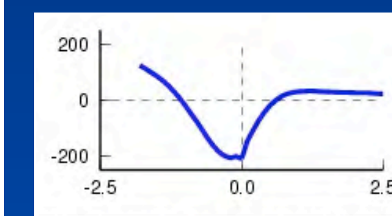
Remove average profile of gravity perpendicular to the subduction zone.



Free Air Anomaly

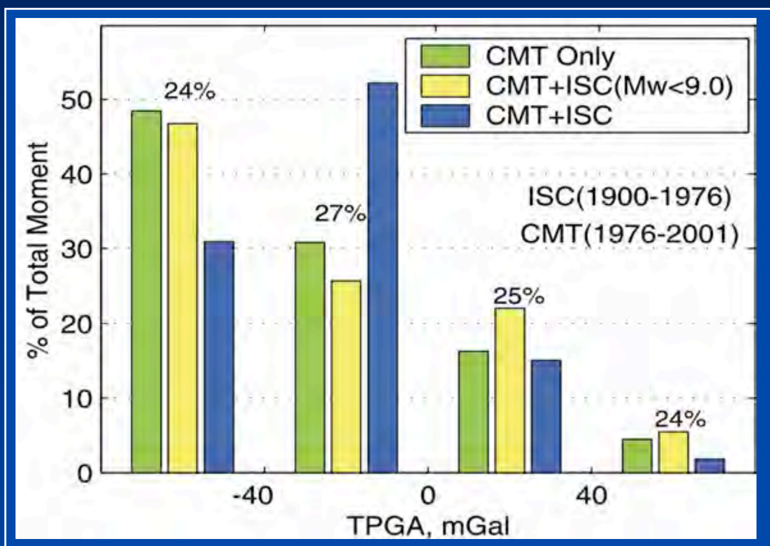
TPGA





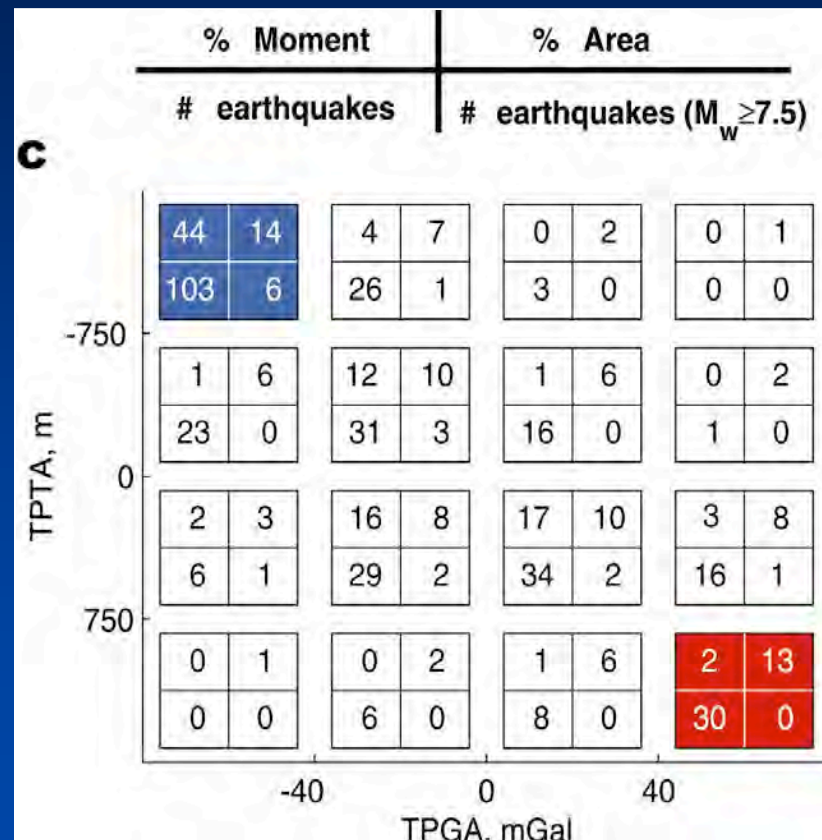
What is the characteristic TPGA for areas with large earthquakes?

Global approach
Trench Parallel Gravity Anomaly (TPGA)

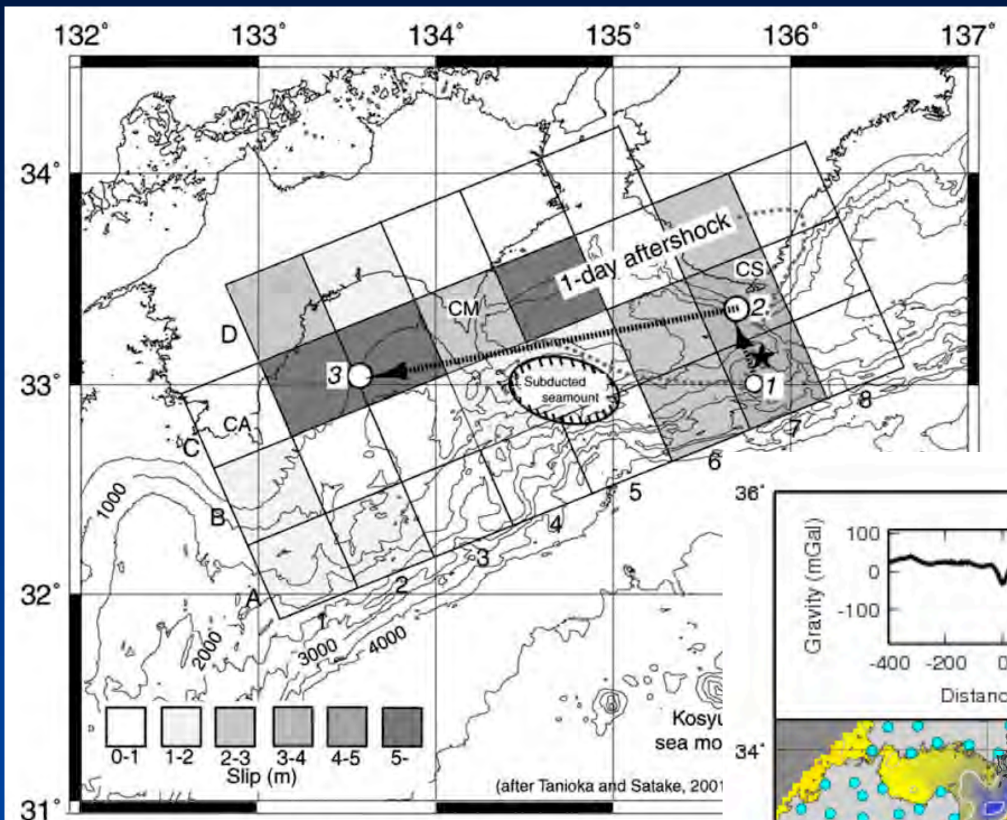


Song & Simons, 2003

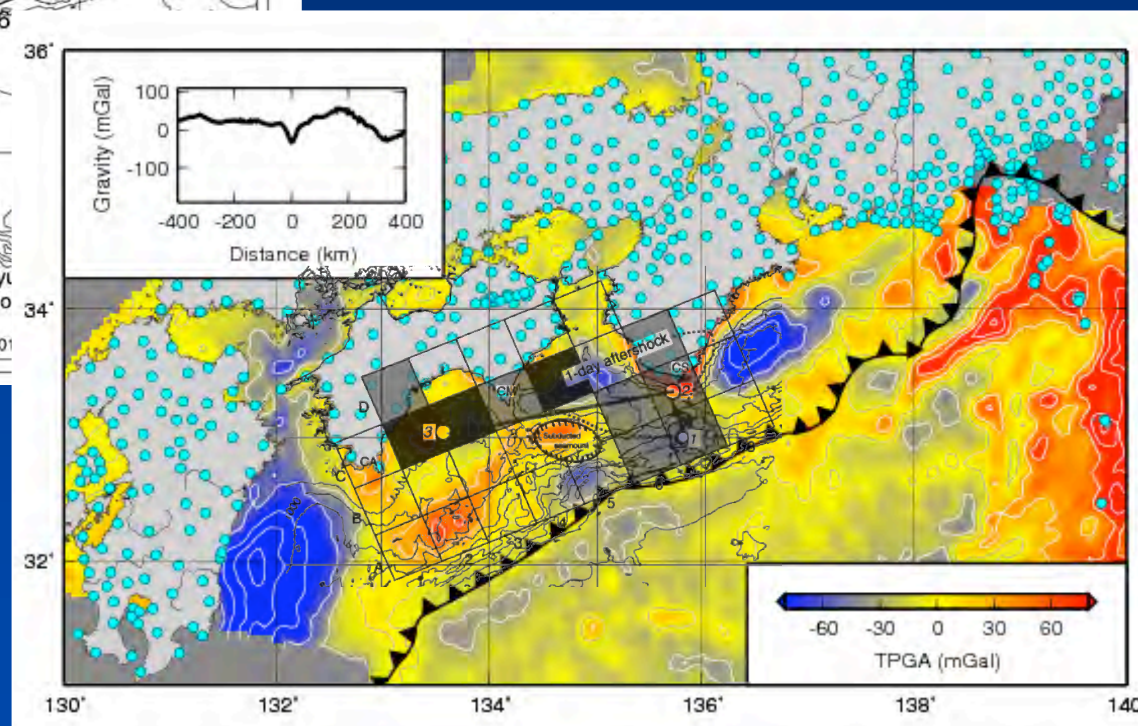
Gravity & Topography



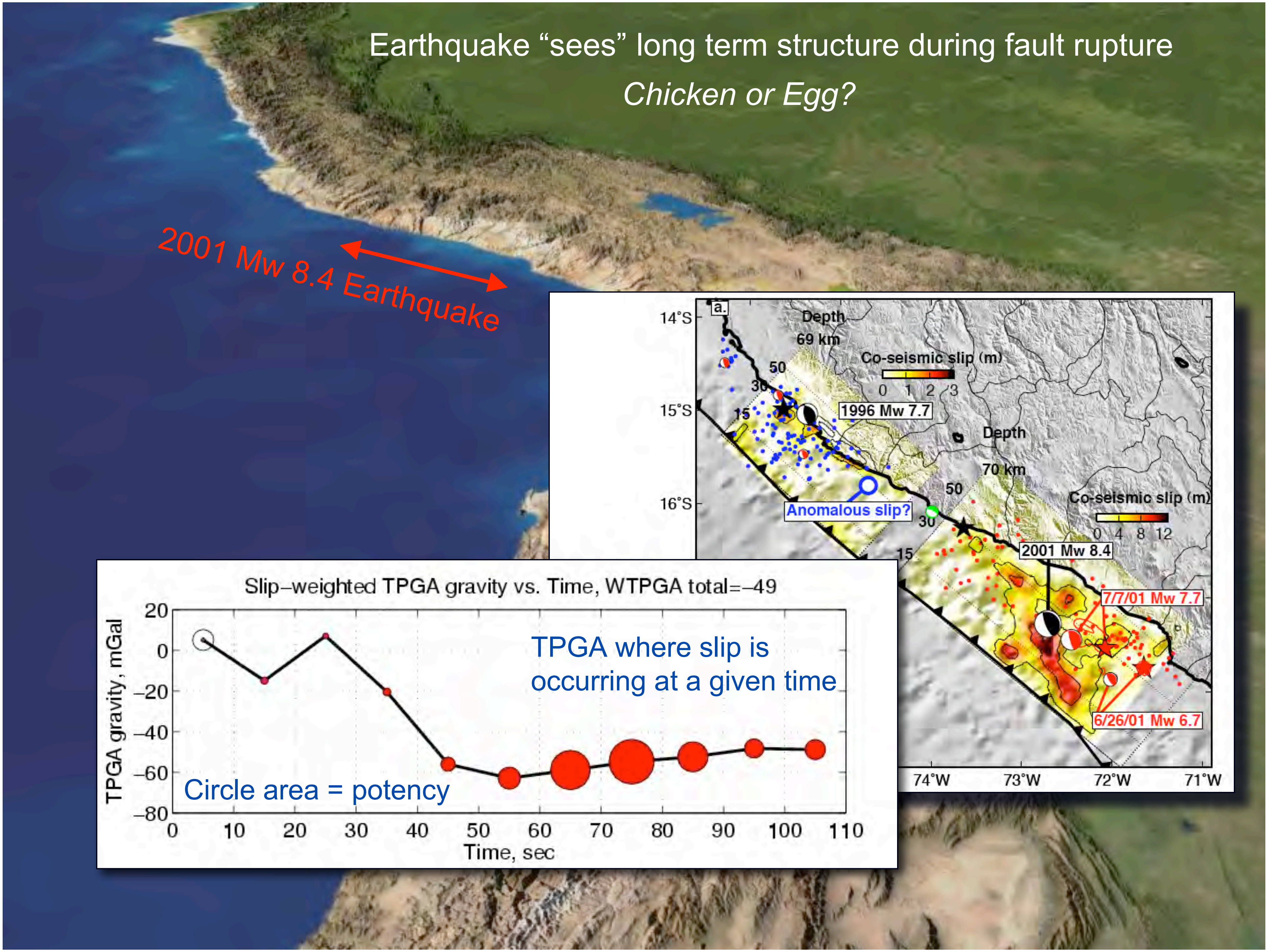
Example: TPGA in Nankai, Japan



1946 Mw 8.4 Nankai, Japan

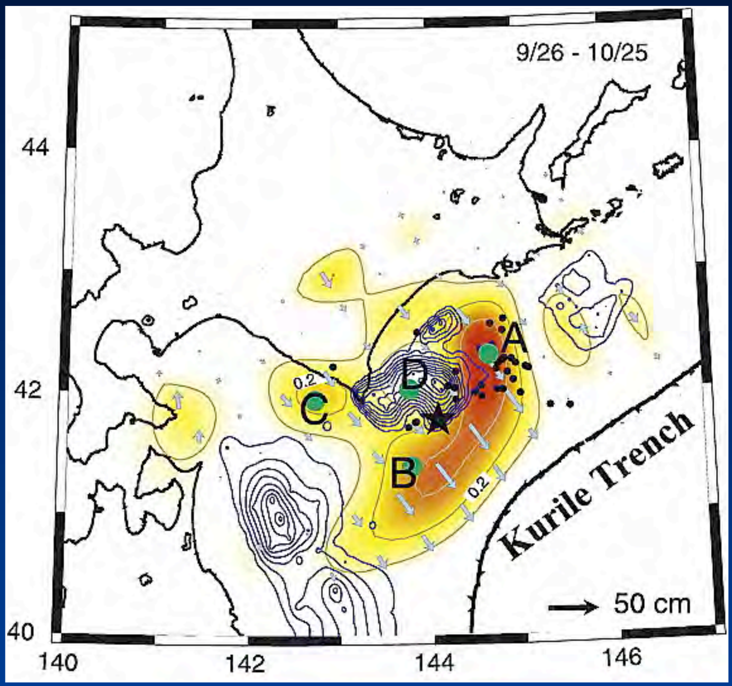


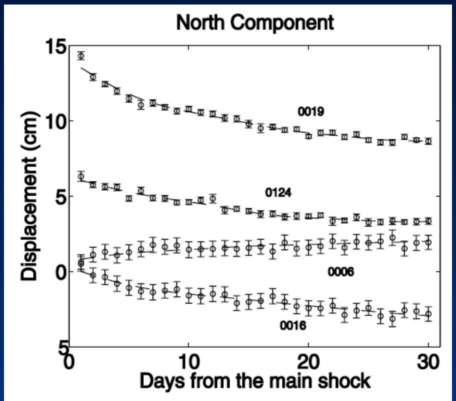
Kodaira et al., 2002



Earthquake "sees" long term structure during fault rupture
Chicken or Egg?
2001 Mw 8.4 Earthquake
a.
14°S
15°S
16°S
Depth
69 km
Co-seismic slip (m)
0 1 2 3
1996 Mw 7.7
Depth
70 km
Anomalous slip?
Co-seismic slip (m)
0 4 8 12
2001 Mw 8.4
7/7/01 Mw 7.7
6/26/01 Mw 6.7
74°W
73°W
72°W
71°W
Slip–weighted TPGA gravity vs. Time, WTPGA total=–49
TPGA gravity, mGal
Time, sec
TPGA where slip is occurring at a given time
Circle area = potency

2003 Mw 8.3 Tokachi-Oki, Japan



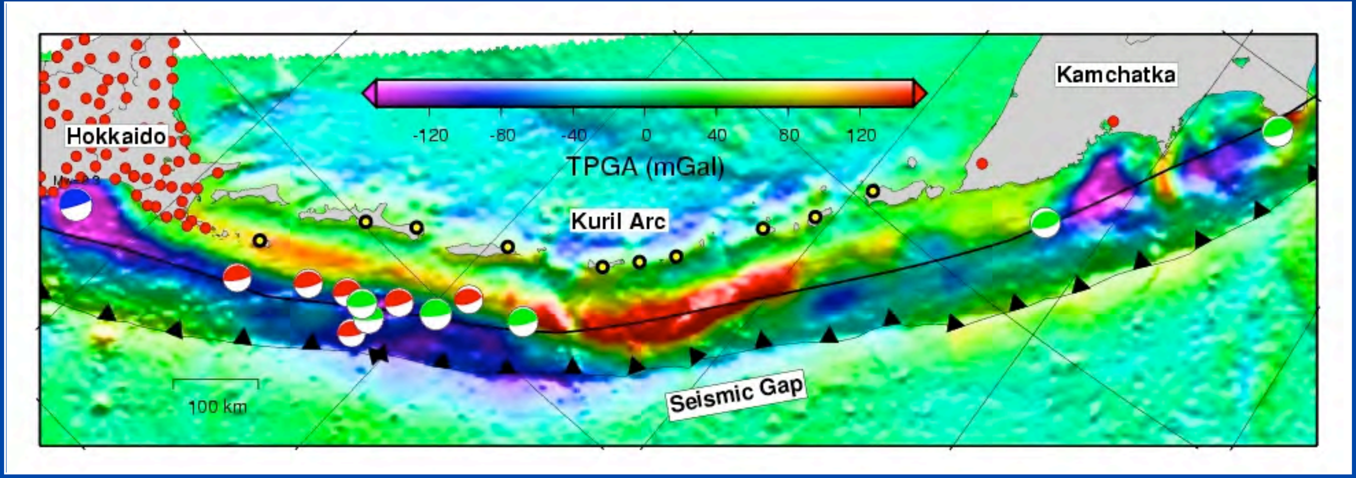


1952, 1968, 2003 coseismic
Yamanaka & Kikuchi, 2004

2003 postseismic,
Miyazaki et al, 2004

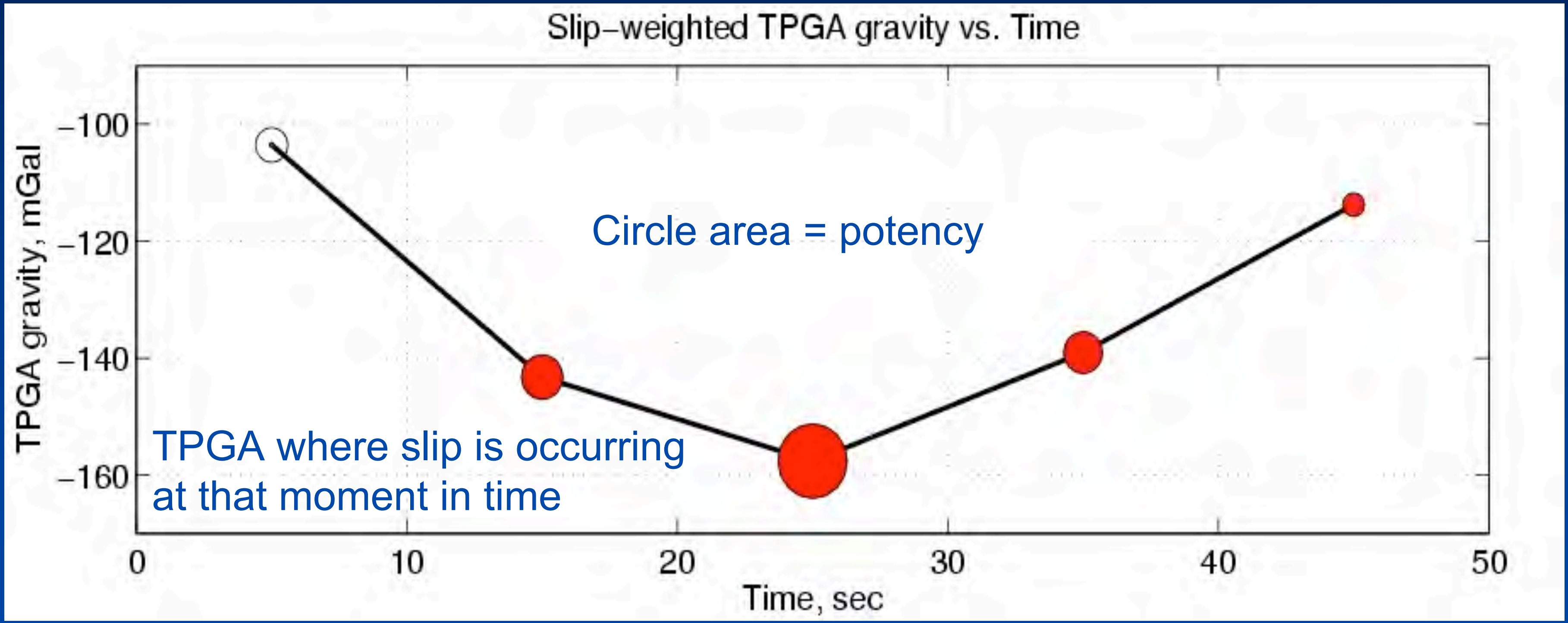
See also *Baba et al.*, 2005

- ➲Negligible slip at hypocenter
- ➲Frictional properties vary rapidly along strike
- ➲Qualitative fit with region of low TPGA



Characteristic TPGA During the Evolution of Rupture

2003 Mw 8.3 Tokachi-Oki
WTPGA = -133 mGal



Nucleates at relatively higher TPGA, most potency (moment) at lower TPGA

Challenges

1. Geometric complexity
   - Meshes, BCs,…

2. Rheologic complexity
   - Non-linear viscous
   - Fault zone friction
   - Damage

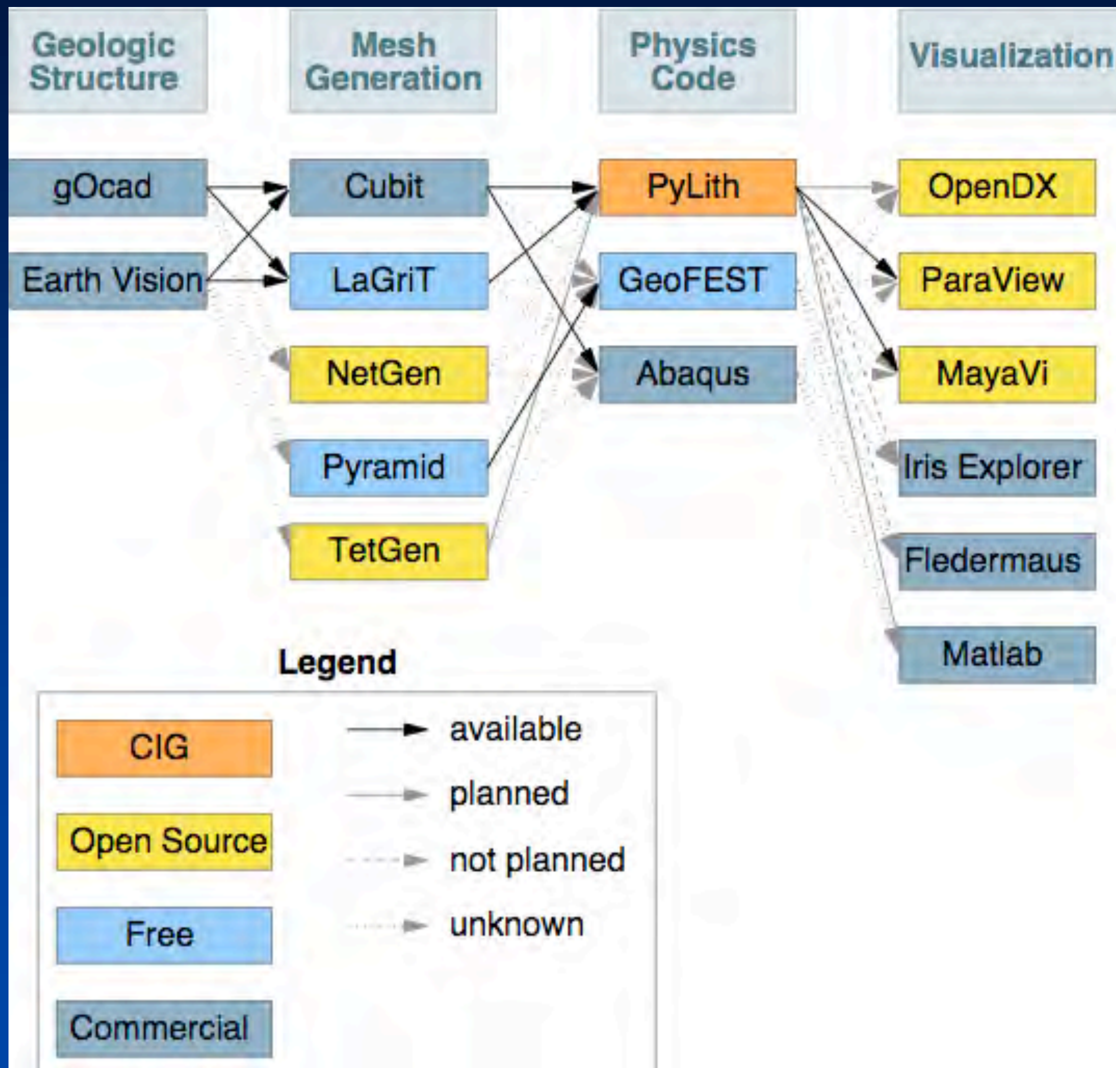
   - 1 & 2 -> work flow issues

3. Transitioning from kinematic to dynamic realism

4. Mix of time and length scales (seconds - 10^6 years)
   - Efficient (f(t)?) meshes
   - Time stepping
   - Mix of solvers

5. Parameter Estimation

The Workflow Challenge



Brad Aagaard