Going Beyond an Elastic Halfspace

"CIG Short-Term Crustal Dynamics"

- Perspective of a user / observationalist
- *N*-1 workshops (LANL, CSM)

NSF (SCEC, CIG, EarthScope) & NASA

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Seismological Laboratory

Caltech

Potential (Generic) Targets

- Modeling the earthquake cycle in a plate boundary system while resolving both single events (at least quasi-statically) and the integrated effects of many events

- Modeling volcano dynamics

- Modeling glacier flow (ice sheets and mountain glaciers)

Primary timescale of interest is that during which there are not large scale changes in system geometry (a.k.a. “short term”)

Beyond building toy models, we are focused on challenges associated with modeling real geodetic observations

Outline

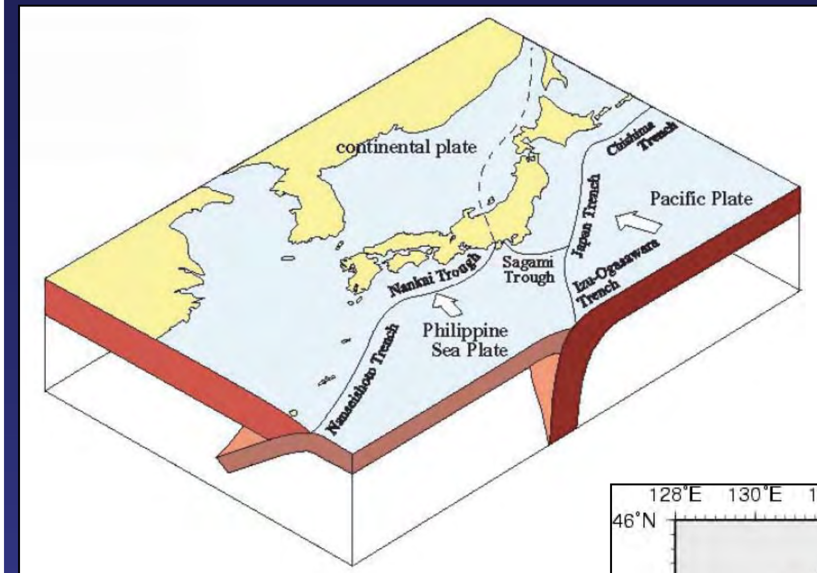
Observational motivation (50%) and associated modeling challenges (50%)

- Rheological complexity (visco-elasto-plastic / volumes and surfaces)
  - Memory $\Rightarrow$ Internally consistent pre-stress
  - Non-linear bulk and fault rheologies
  - Temporal complexity/consistency $\Rightarrow$ sec's to 10^6 years

- Spatial complexity
  - Meshing
  - Rheology (geometric compatibility)

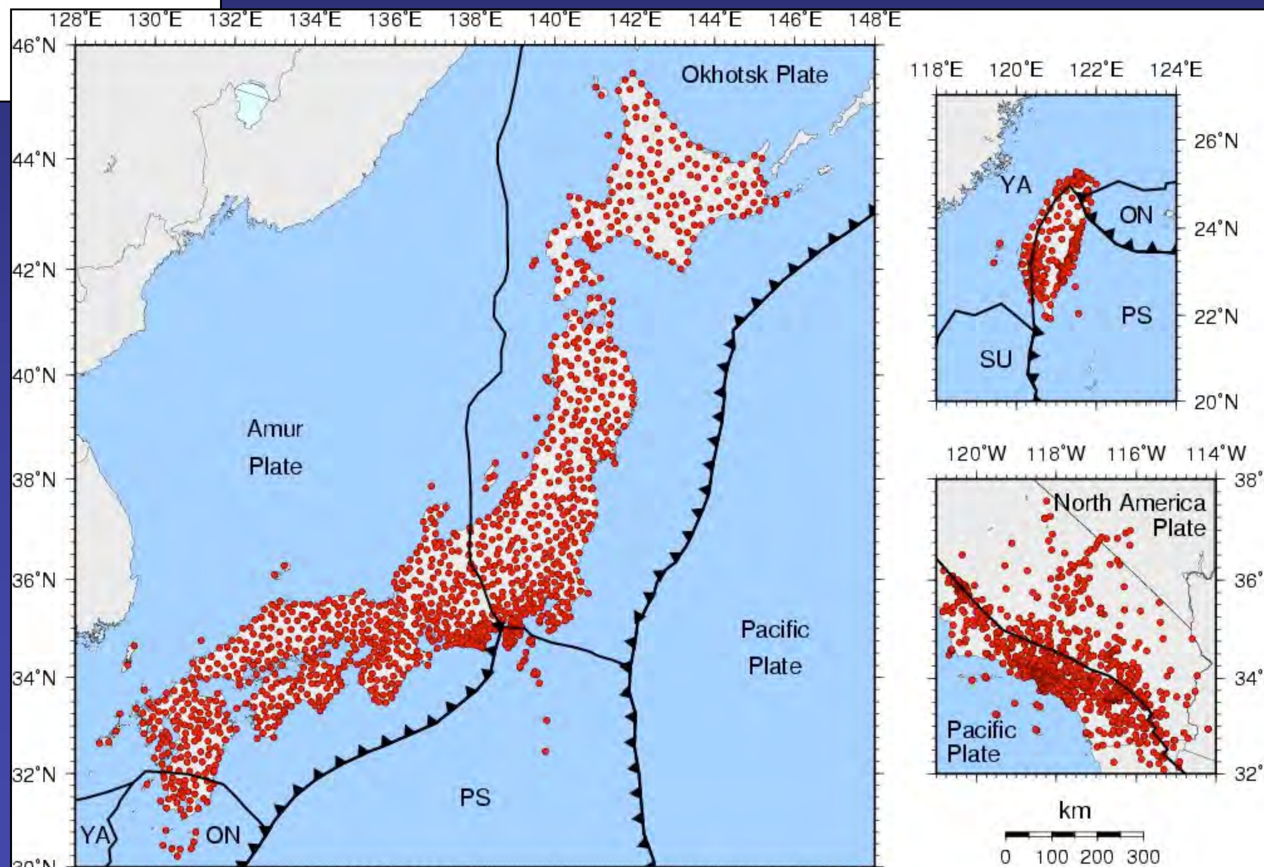
- The link to observations - parameter estimation

- Tag team with Brad Aagaard



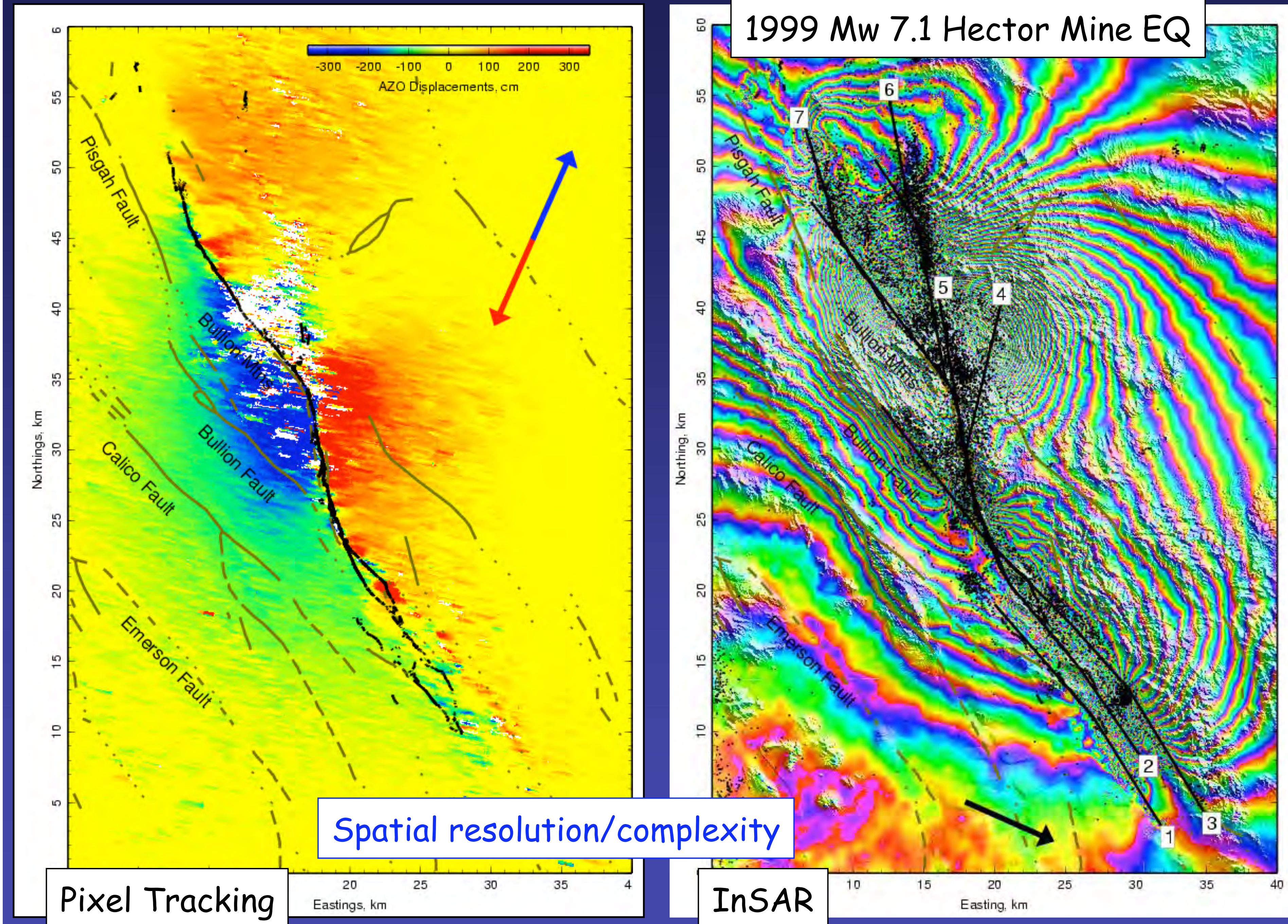
Modern Geodesy- The impetus

Temporal and spatial resolution
- GPS networks
- Satellite radar interferometry



Examples:
- California strike slip
- Subduction zones

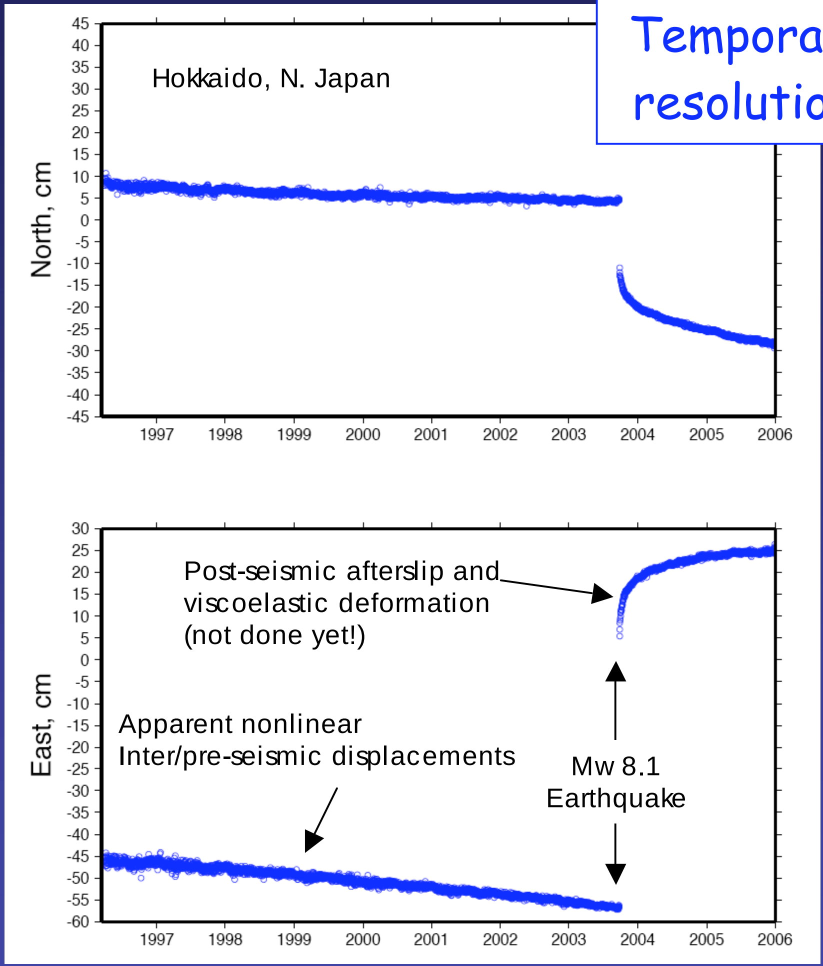
1999 Mw 7.1 Hector Mine EQ



Spatial resolution/complexity

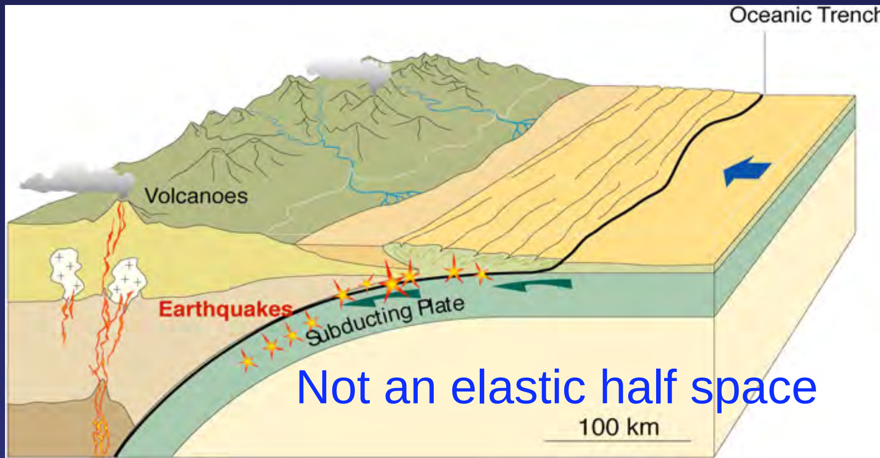
The Seismic Cycle

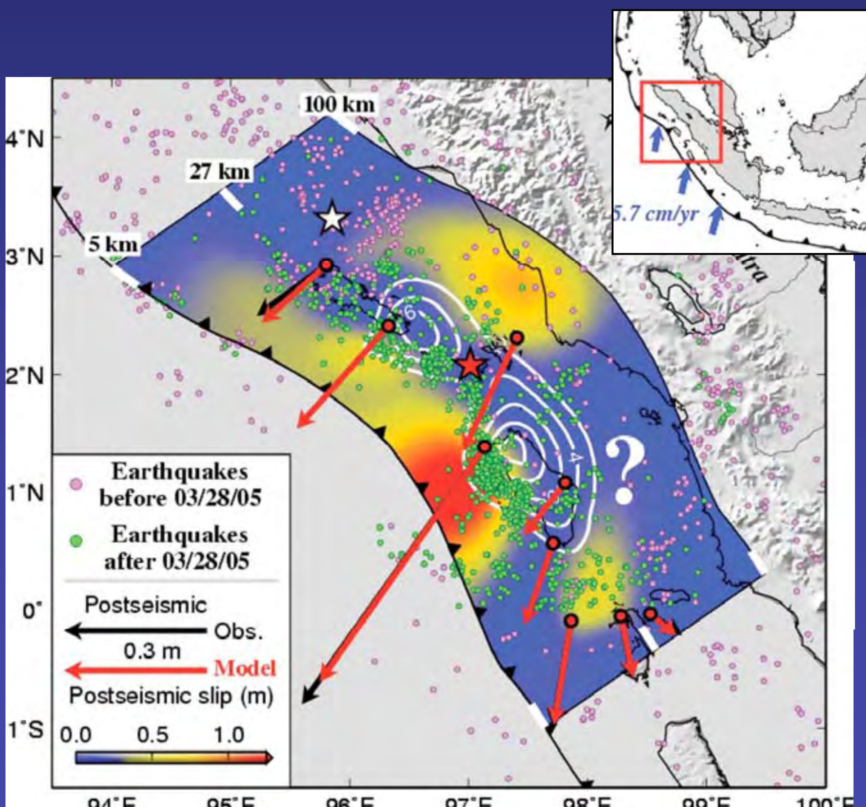
Temporal (and spatial) resolution/complexity

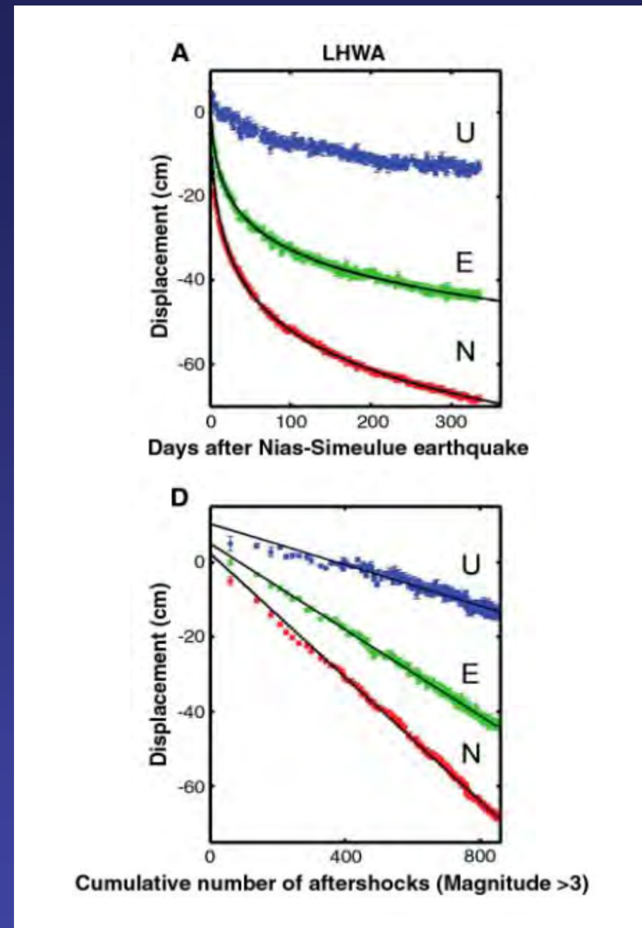


- Where is elastic stress accumulating to be released in future earthquakes?
- What are the mechanics of the fault and surrounding regions?
- What is the connection to permanent inelastic deformation (e.g., topography)?

2005 Mw 8.7 Simuelue/Nias (Sumatra) EQ







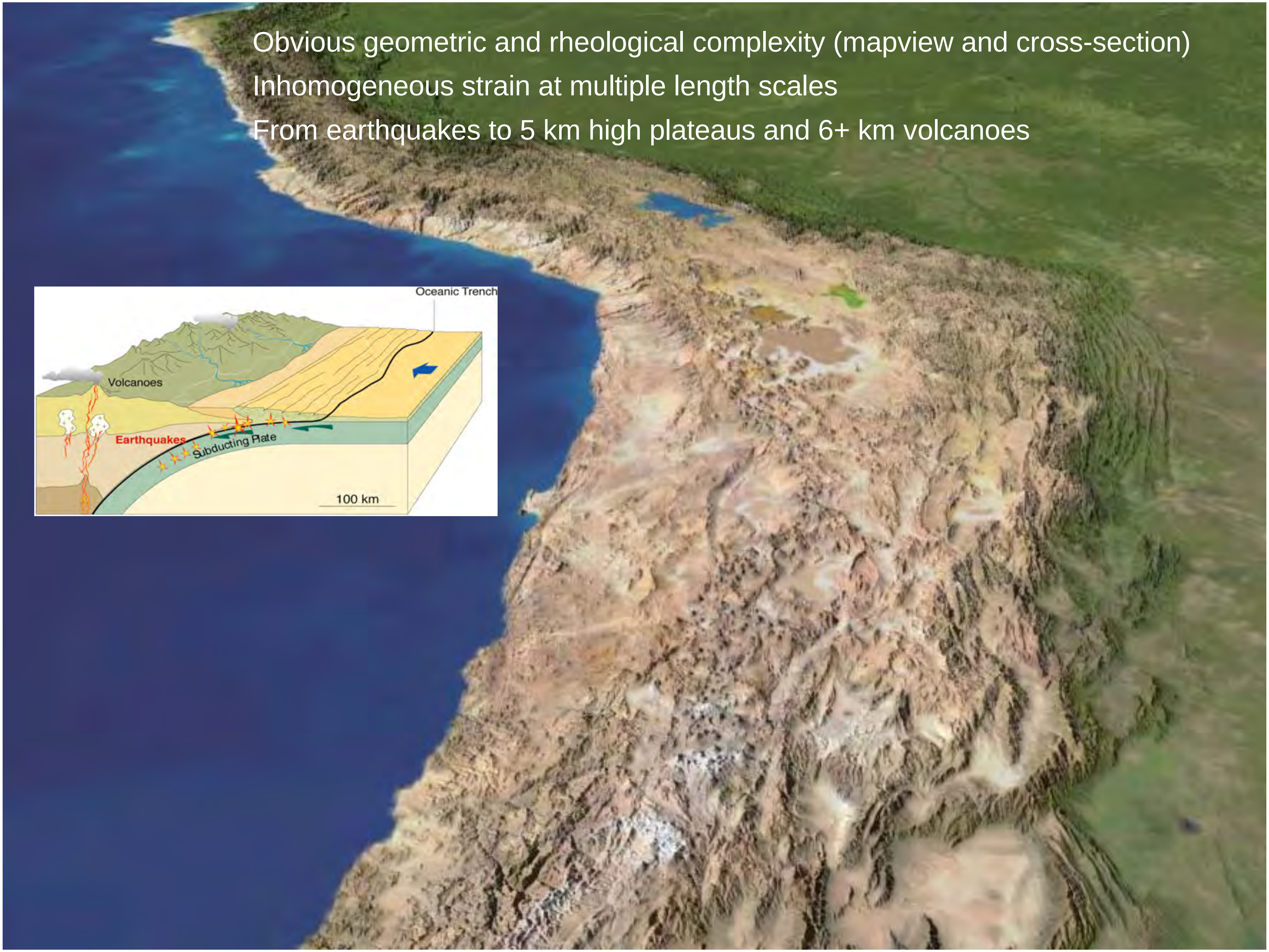
Hsu et al., Science, 2006

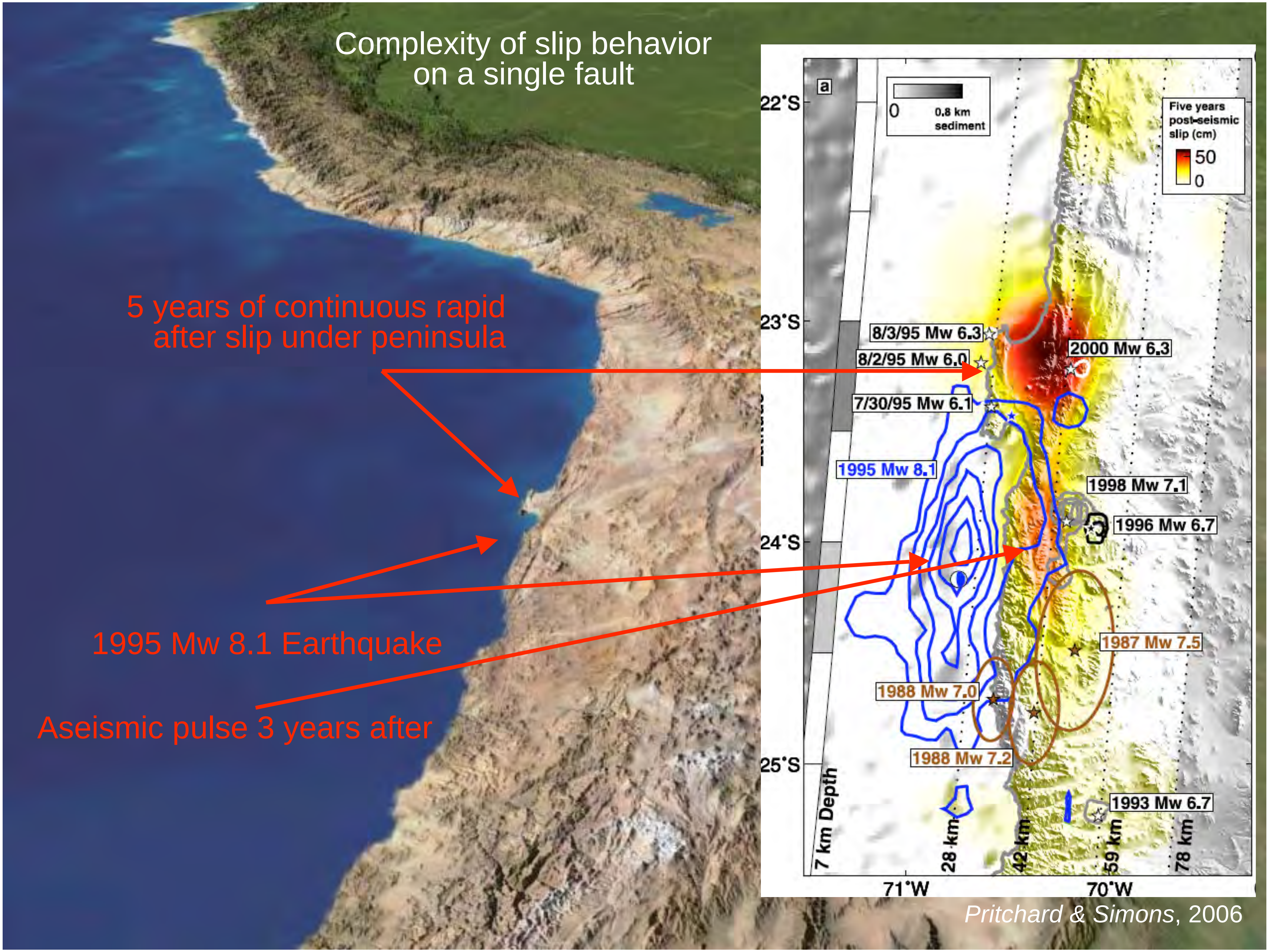
- log(t) afterslip suggests velocity strengthening frictional slip on fault
- Afterslip controls aftershock production
- Behavior very heterogeneous in space

Obvious geometric and rheological complexity (mapview and cross-section)

Inhomogeneous strain at multiple length scales

From earthquakes to 5 km high plateaus and 6+ km volcanoes

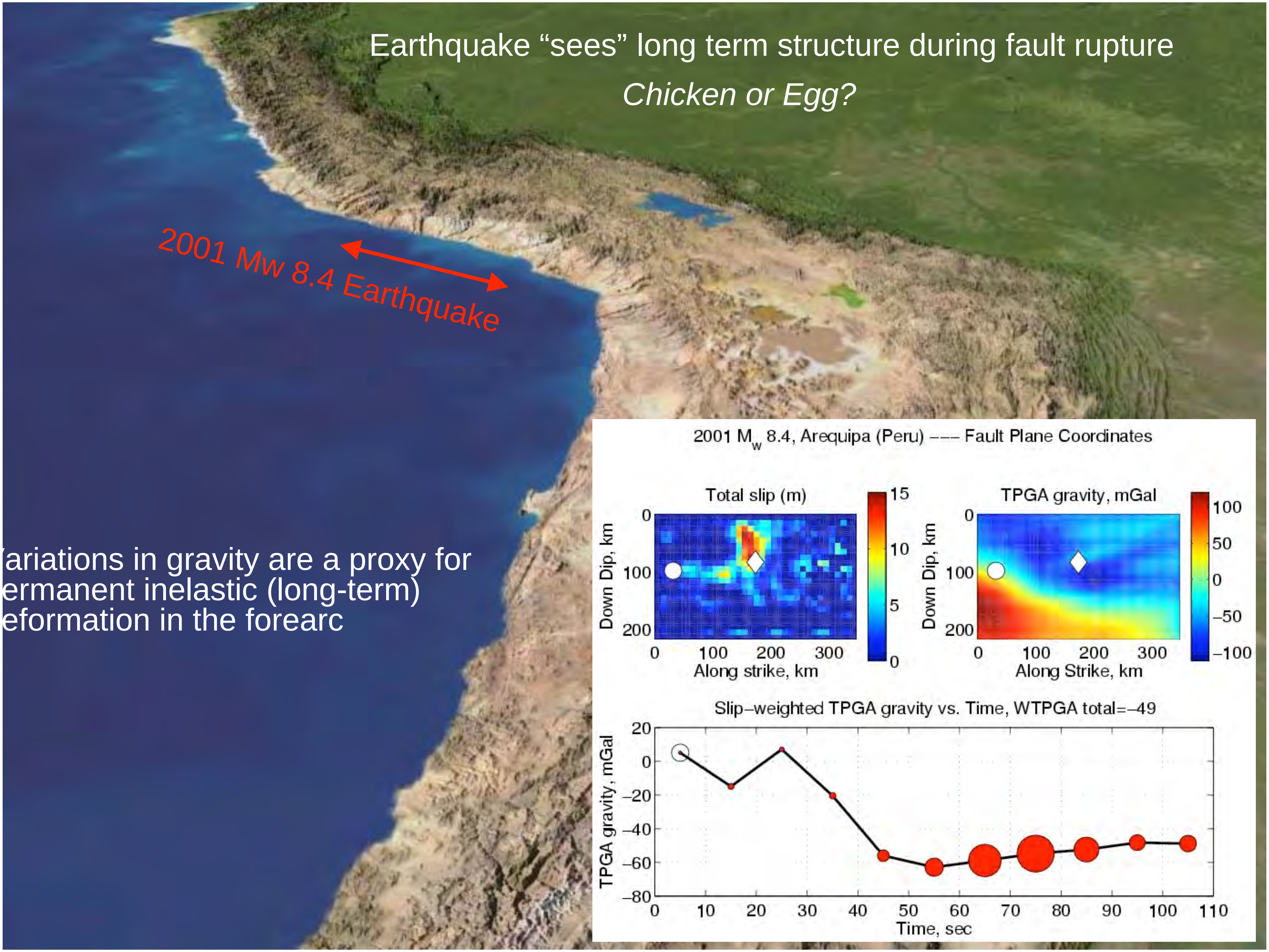




Complexity of slip behavior
on a single fault
5 years of continuous rapid
after slip under peninsula
1995 Mw 8.1 Earthquake
Aseismic pulse 3 years after
a
0
0.8 km
sediment
Five years
post-seismic
slip (cm)
50
0
22°S
23°S
24°S
25°S
71°W
70°W
8/3/95 Mw 6.3
8/2/95 Mw 6.0
7/30/95 Mw 6.1
2000 Mw 6.3
1995 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

Earthquake “sees” long term structure during fault rupture

Chicken or Egg?



ariations in gravity are a proxy for
ermanent inelastic (long-term)
eformation in the forearc

Rheology Issues

Thus far :

• All coseismic and postseismic examples are kinematic models (I.e., they invert for fault slip

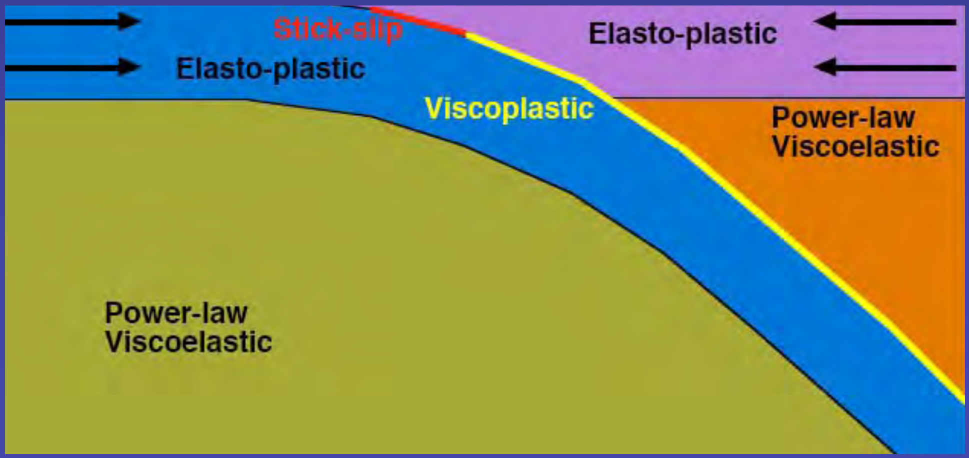
• They don't let it evolve according to physics of friction) and they adopt either elastic half-spaces, or horizontally layered elastic halfspaces (no inelasticity)

None of these examples:

• Adopt 3D varying rheological properties (not even 3D elastic)

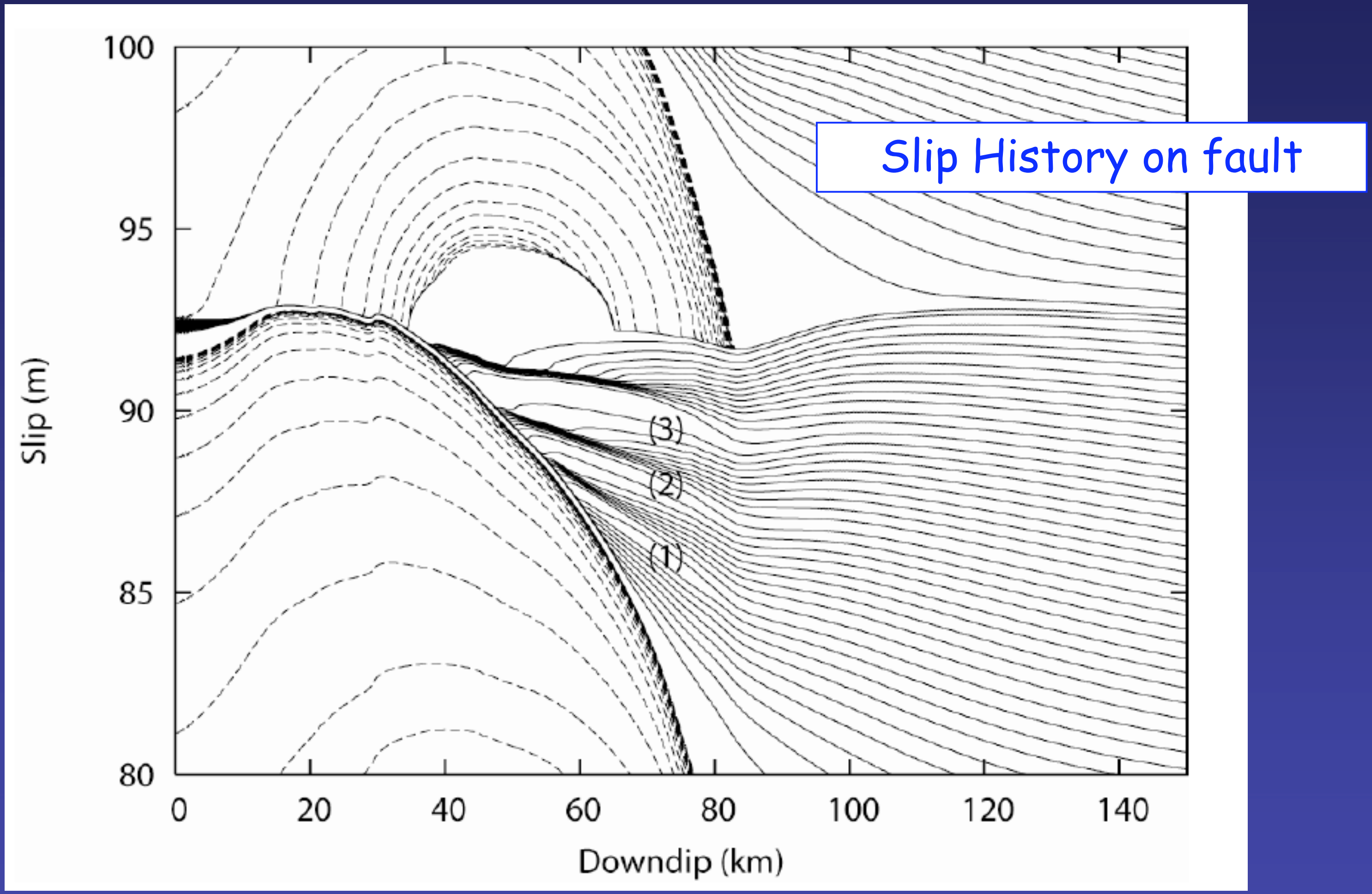
• Consistently explore the relationship between earthquakes, afterslip, and the long-term evolution of the plate boundary

A potential goal



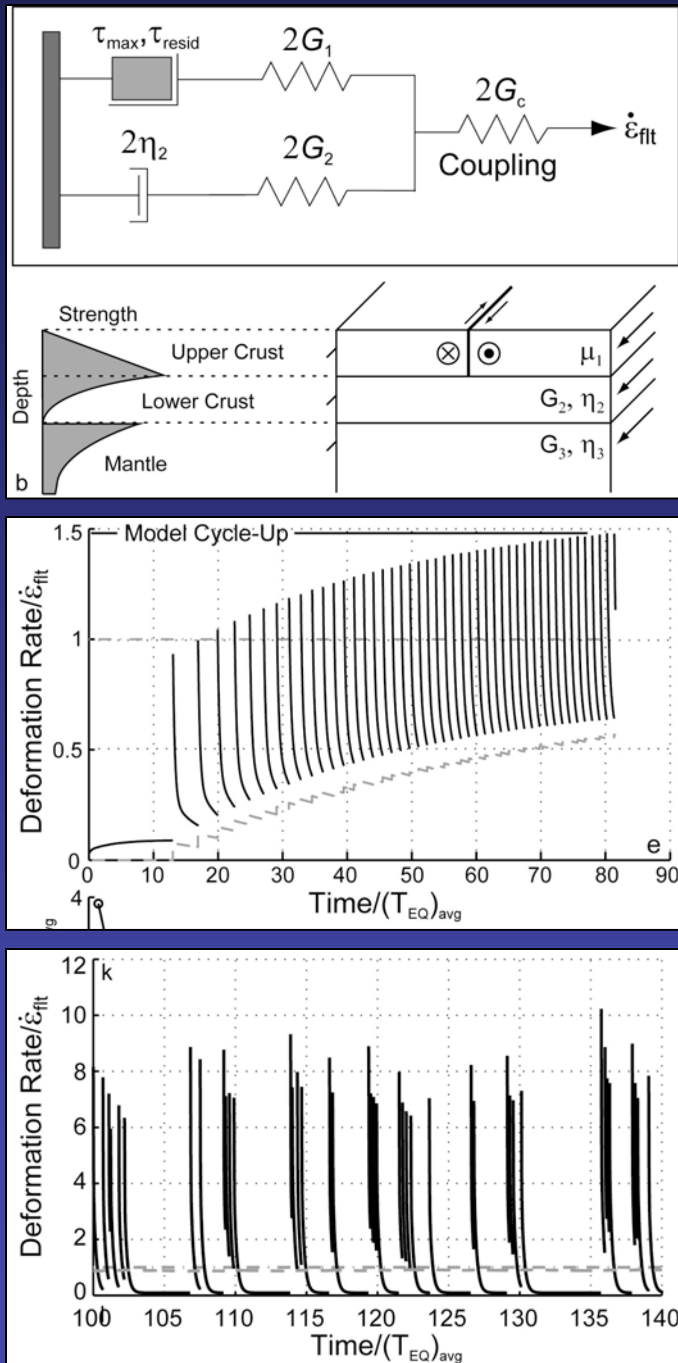
Charles Williams, 2005

“Real Friction”

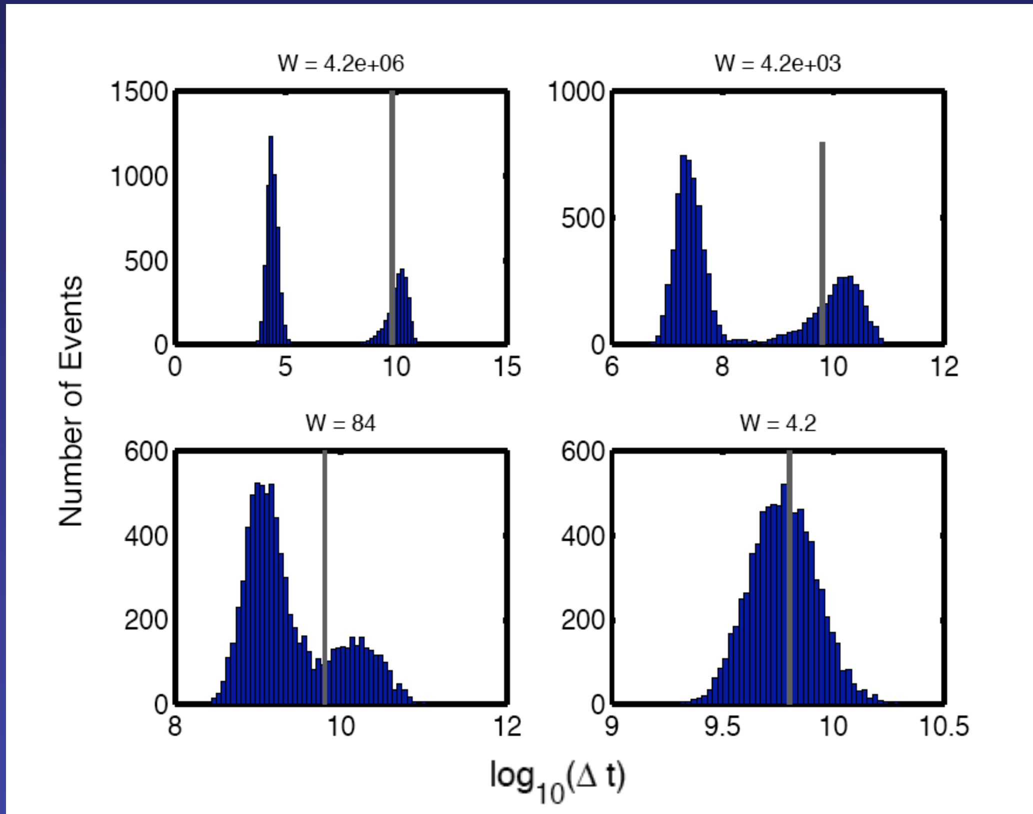


Liu & Rice, 2006

Challenge: How do we go beyond planar faults in an elastic half space?



Problems with more complex rheologies:
A simple motivating example - 1D & 2D



- Systems with memory need internally consistent pre-stress (normally ignored - bad)

- Role of noise: Effectively a pre-stress issue

Spin Up / Noise Implications

Even if interested in system response from just 1 earthquake,

one needs to spin up and look at N^{th} event.

Approach

Linear rheology

$\Rightarrow$ Generate one characteristic space/time Green's function for EQ plus delayed response (analytic or FEM)

$\Rightarrow$ Add *N* events with appropriate time lags until steady-state is reached

Nonlinear rheology

$\Rightarrow$ Run for a long time

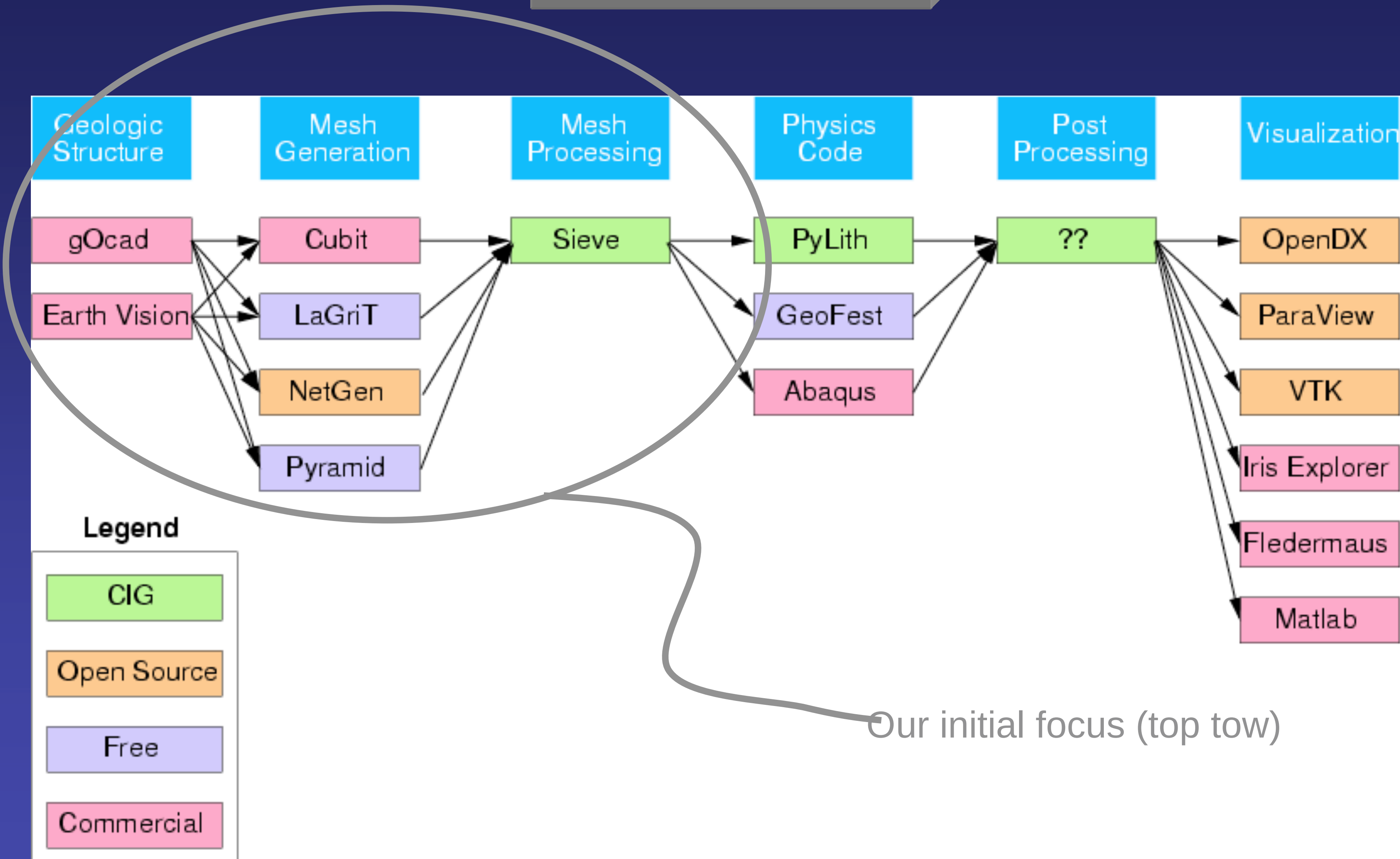
- expensive - mesh distortion issues

Noise

$\Rightarrow$ Run for a long time with many realizations

- real expensive - mesh distortion issues

Workflow



Brad Aagaard

Simplified Workflow

gocad ⇨ mesher ⇨ FEM

done by experts

done by experts

meshing expert takes output from the gocad expert, some back-and-forth…

communication: each person not entirely in fully aware of work in the other step, there may be replicated tasks…

costly: need to be able to pay the experts to do the work…

Simplified Workflow (the way we are doing it):

gocad ⇨ mesher ⇨ FEM

done by the inexperienced

same person (graduate student)

done by the inexperienced

in theory, one person can do the entire work-flow

with help from experts and the experienced

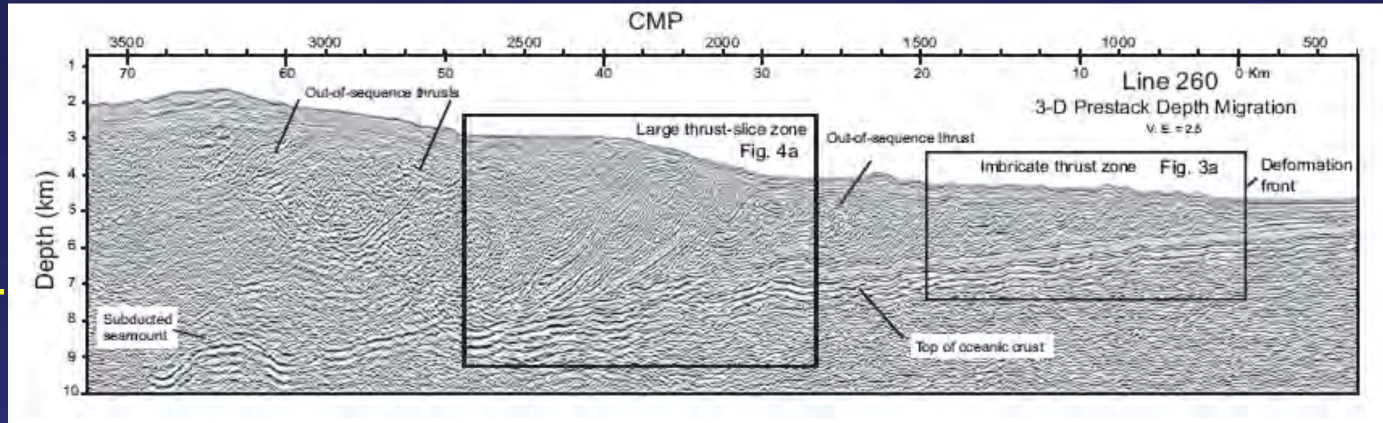
inexperience = not necessarily the best way to do things

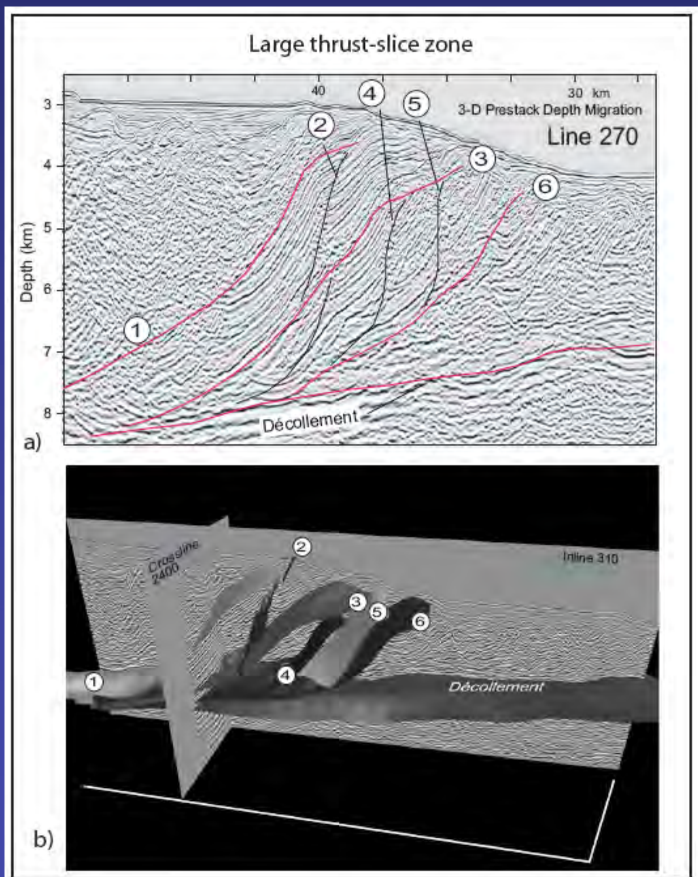
Geologic Complexity
and
Meshing Challenges (I)

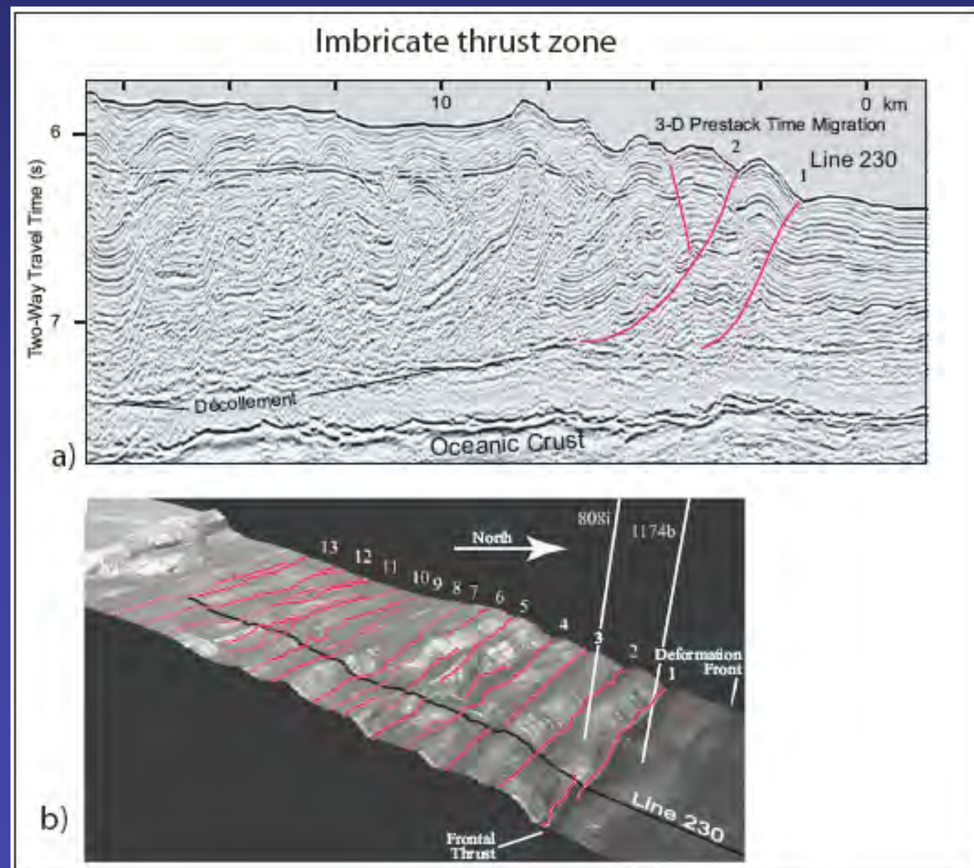
Start with this…

Structure of the forearc

Faults, material, etc.

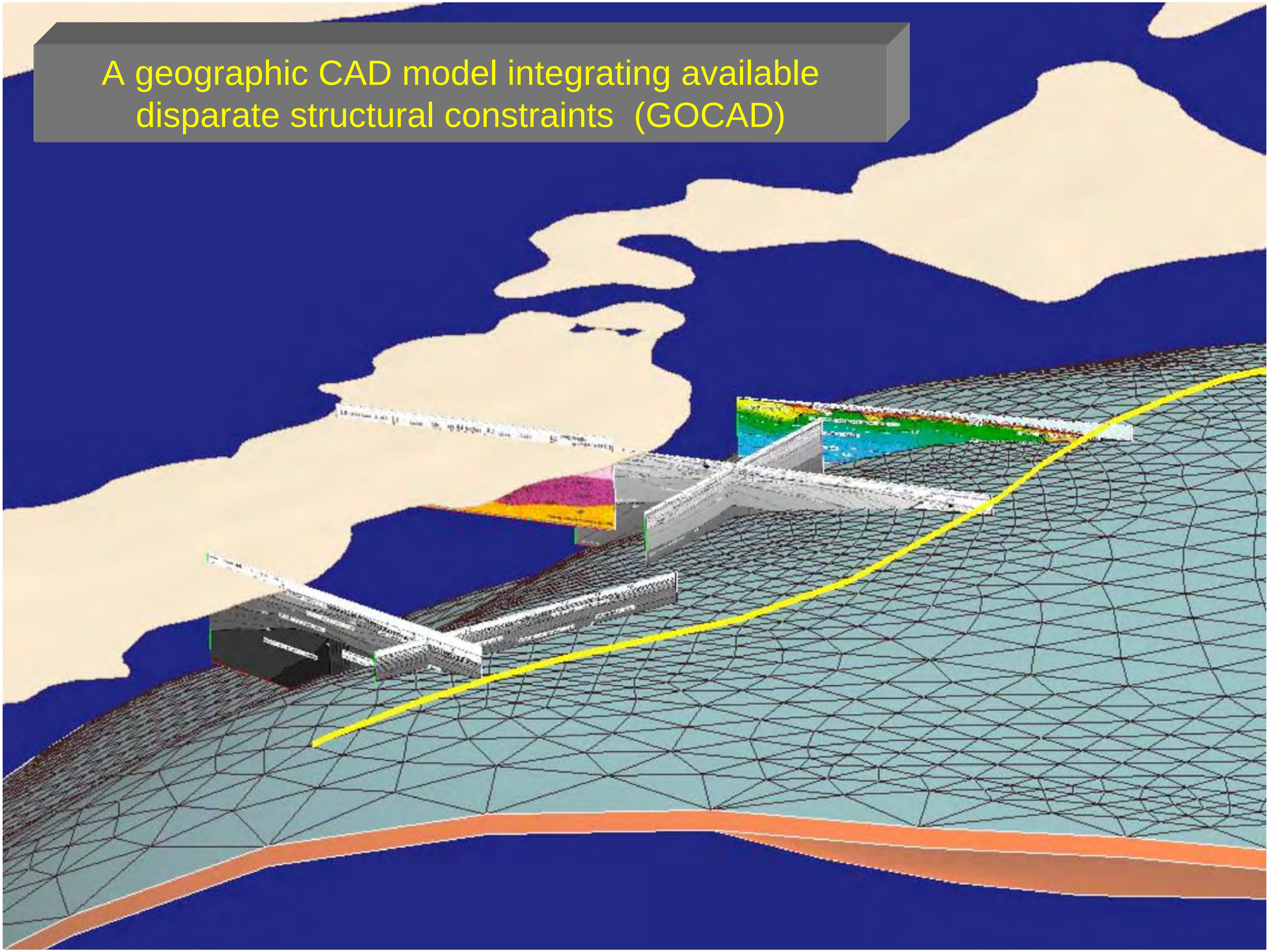




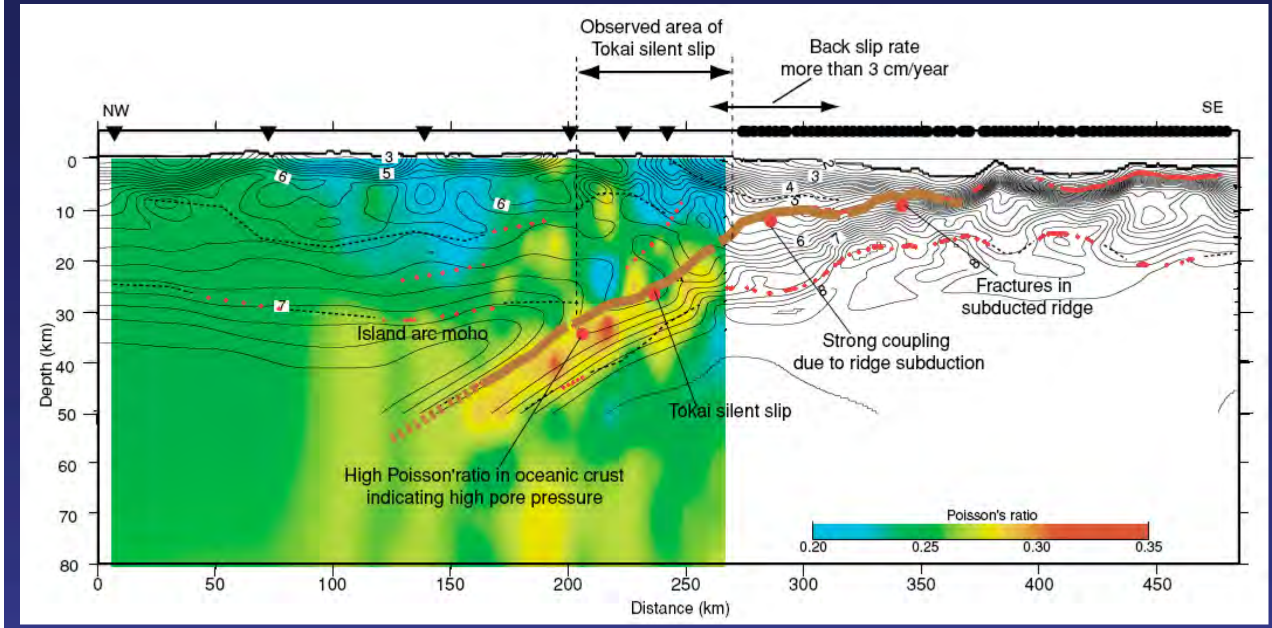


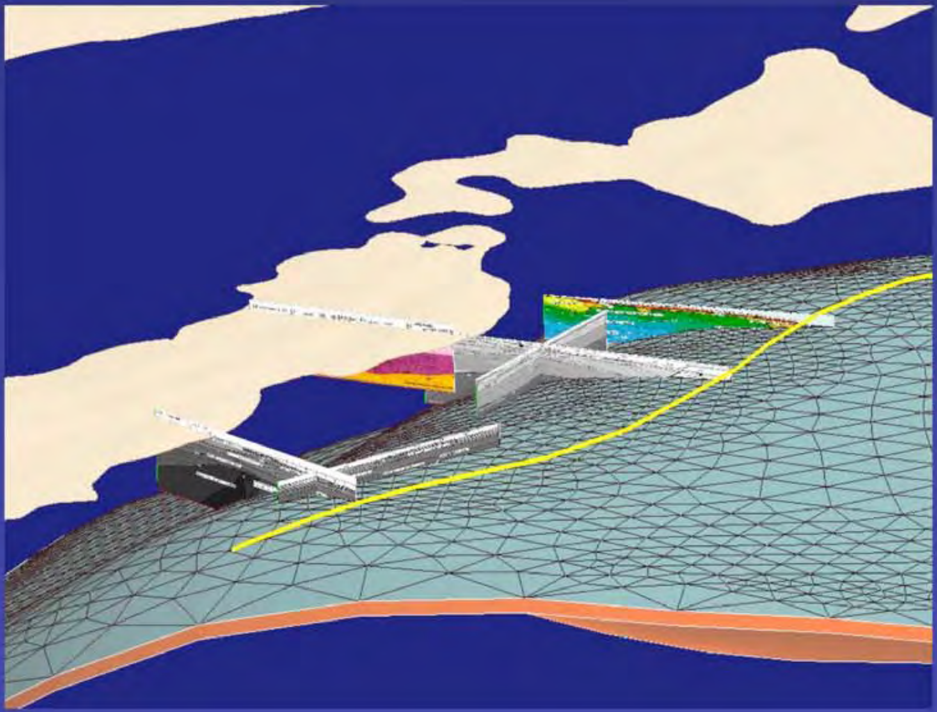
Bangs et al., 2005

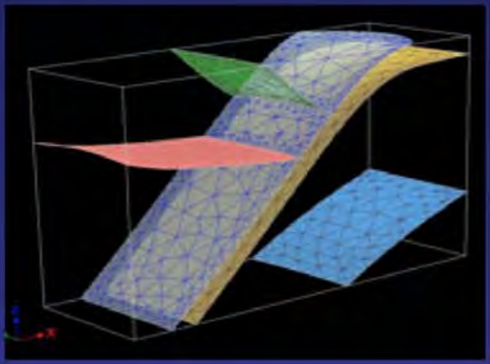
A geographic CAD model integrating available disparate structural constraints (GOCAD)

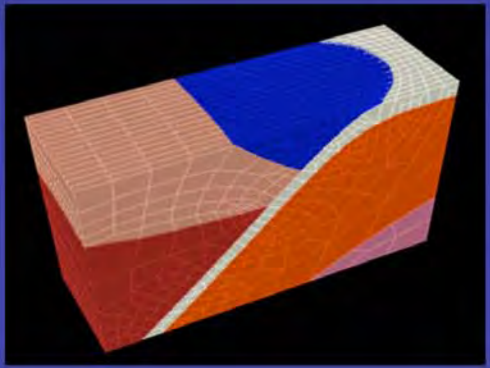


The Meshing Challenge





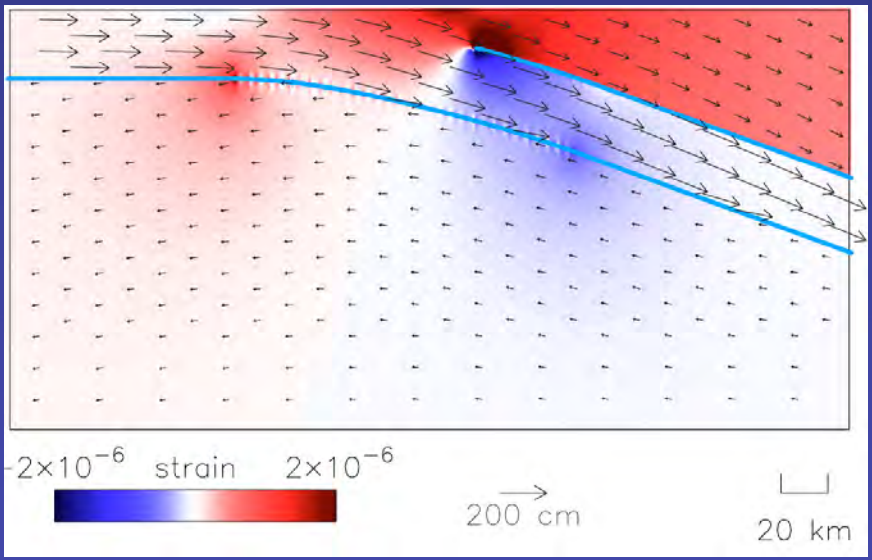




Bookkeeping
Materials +
properties +
interfaces +
Gocad/Cubit/PyLith

Meshing Challenges (II)

- Geometric compatibility (damage) at fault intersections
- Sufficient quality for relevant physics on selected internal interfaces
- Efficient meshes:
  - ❖ E.g., resolution decreasing with distance from dislocations tips as a function of strain/strainrate - analytically predictable
  - ❖ Time-dependent meshes (time from last EQ?) with both refinement and coarsening (could deal with previous problem automatically)



Charles Williams, 2005

Summary Challenges (I)

Efficient and transparent workflow (bookkeeping)

- Geologically informed CAD (agility, data integration, surface definition, coordinate projections,…)
- Meshing
- Discretely / continuously varying material properties
- Solver

Meshing

- Respecting the geology
- Resolution that intelligently varies according to physics
- Time-dependence
  - ❖ geometric compatibility
  - ❖ non-stationary resolution
- Partitioning of mesh for parallel implementation

Summary Challenges (II)

Rheology

- Visco-elasto-plastic in volume
- Rate-state friction on fault
- Non-planar faults
- Poroelasticity
- Range of time-scales suggests need to switch between solvers (seismic, short-term, long-term) with obvious issues:
  - ❖ When to switch?
  - ❖ Mesh to mesh errors
  - ❖ Load balancing

Model Parameter Fitting (small to medium models)

- Linear: Use of FEM for Green's functions (3D structure)
- Nonlinear: Monte Carlo simulations on parallel machines
  - ❖ Structure code to save "state" to minimize overhead