CIG: Short-Term Tectonics

State of the union

Mark Simons
Seismological Laboratory, Caltech

Brought to you by:

Workshop 1: Mission Statement (2002)

- Build tools to understand fundamental earthquake physics (coseismic)
- Build tools to understand the response to single earthquakes (postseismic)
  - infer rheology and constrain structures
- Build tools to simulate fault system interaction
  - transient interaction among faults
  - regional strain and stress field evolution
- Make realistic predictions for longer time scale processes
  - topography
  - Holocene+ fault slip rates
- Enable tackling large problems while providing a useful tool for all
  - modern documented software for modern computer architectures
  - free and open source
  - do not reinvent the wheel (don’t write your own solver)
  - stay close to the data

A Potentially Expanded Set of Targets

- Modeling the earthquake cycle in a plate boundary system while resolving both single events and the integrated effects of many events
- Volcano deformation
- Glacier flow (ice sheets and mountain glaciers)? (PyLith, GALE,…?)

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, focus on challenges associated with modeling real geodetic observations

Community Summer 5-day Workshops

Where (Goldilocks):

- Caltech: 2002 – too close to sea level
- LANL: 2003, 2004, 2005*** – too much security hassle
- Colorado School of Mines: 2006, 2007, 2008, 2009 – mmmm Coors

Who:

- 60+ participants each of the last few years
- About 70% graduate students, postdocs, and junior faculty

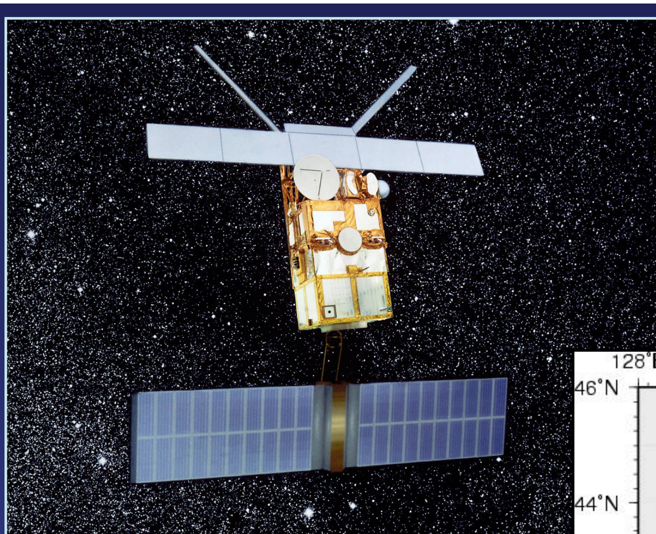
Content (modeled on the old LANL mantle convection workshops):

- technical focus: workflow, meshing, solvers, visualization
- tutorials / demonstrations
- in and out of discipline talks
- definition of community software priorities (≠ consensus science)
- “tinker time”
- community building (collaborations, future jobs,…)

*** Beginning of CIG involvement

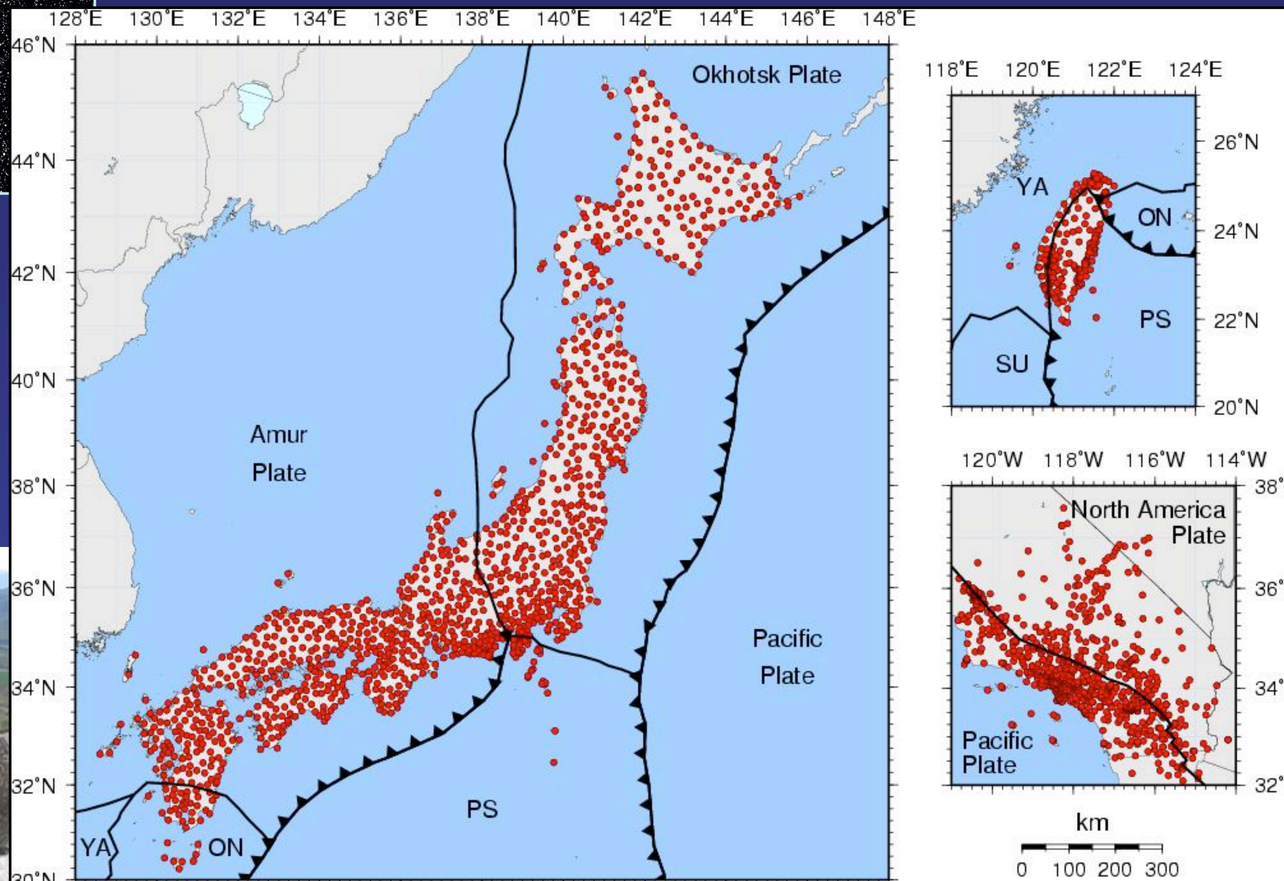
Challenges

- Rheological complexity
  - Non-linear bulk and fault rheologies
  - Memory ⇒ Internally consistent pre-stress
  - Temporal complexity/consistency ⇒ sec's to 10^6 years
- Spatial complexity
  - Meshing (realistic geometries)
  - Rheology (geometric compatibility)
- The link to observations – forward models and parameter estimation



Modern Geodesy – The Impetus

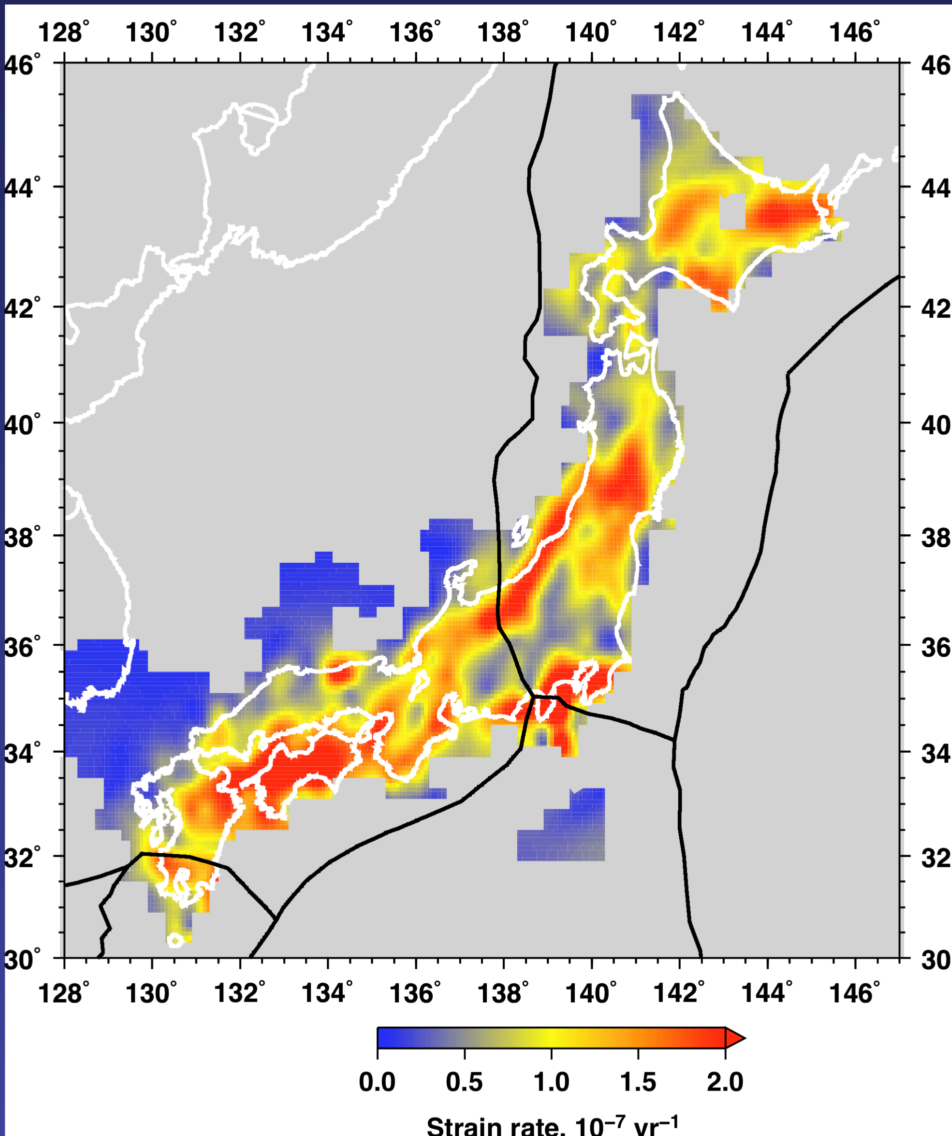
An explosion in temporal and spatial resolution



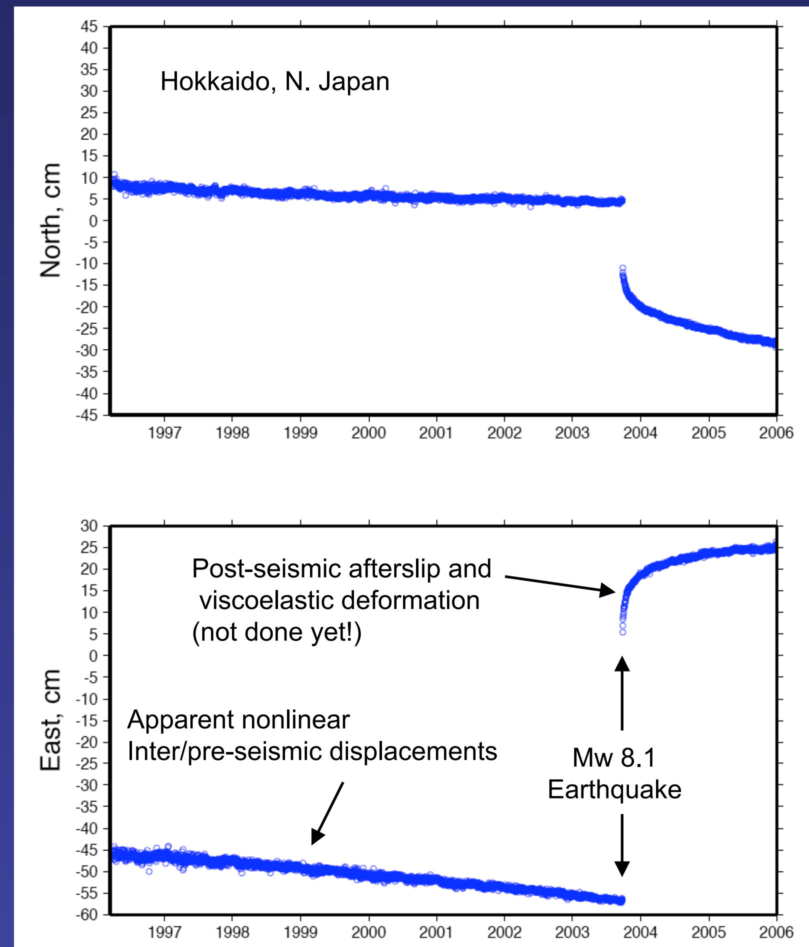
Carl Tape

GPS, InSAR & seismology (if necessary)

Spatial & temporal resolution/complexity

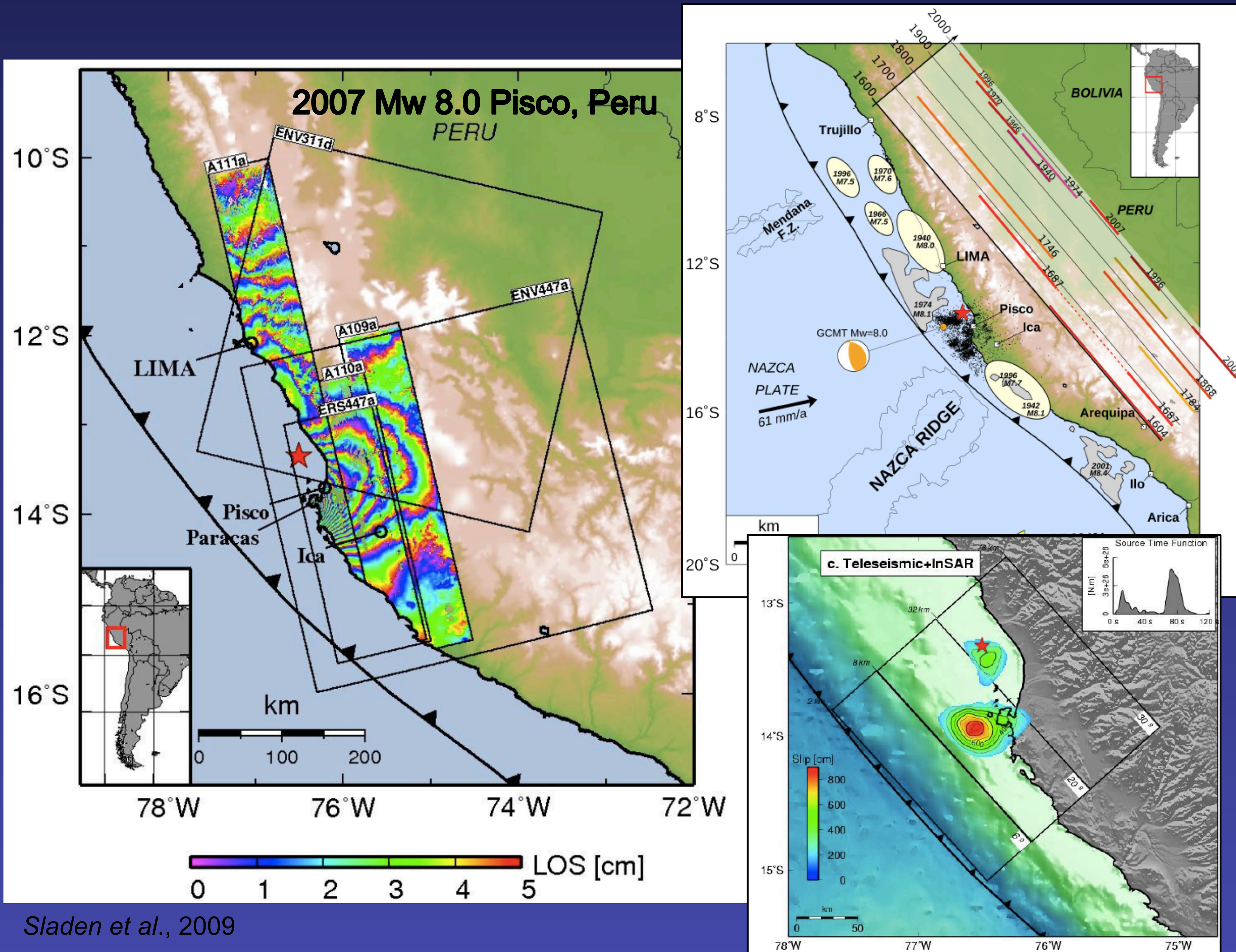


Carl Tape

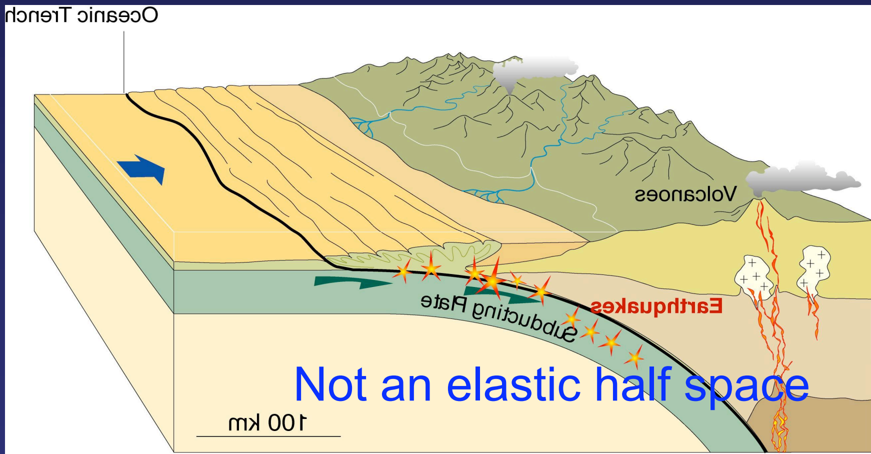


Sue Owen

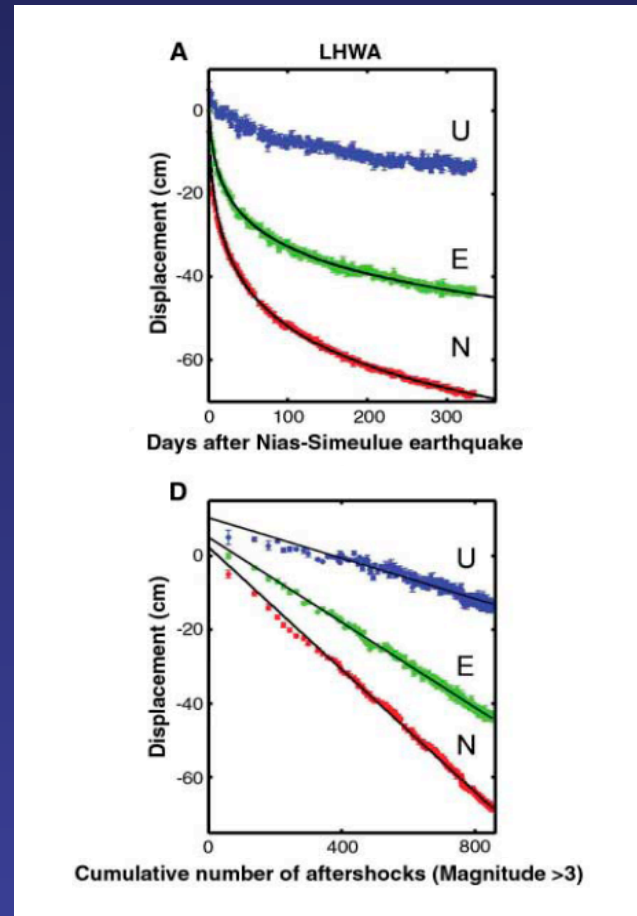
- Where is elastic stress accumulating to be released in future earthquakes?
- What are the mechanics of the fault and surrounding regions?
- What is the connection to permanent inelastic deformation (e.g., topography)?

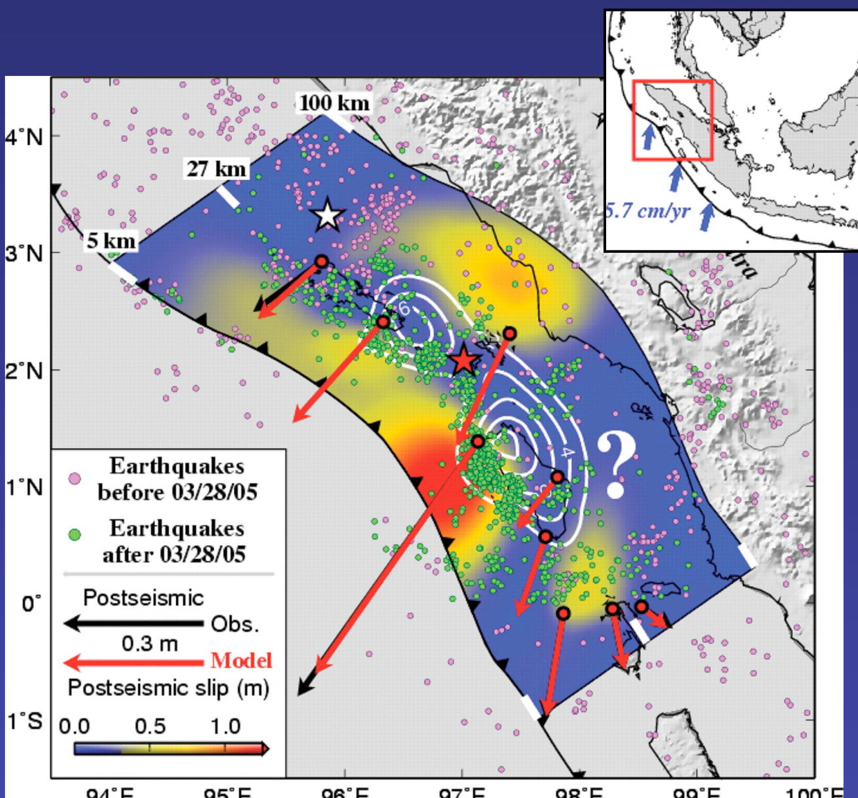


Sladen et al., 2009



2005 Mw 8.7 Simuelue/Nias (Sumatra) EQ

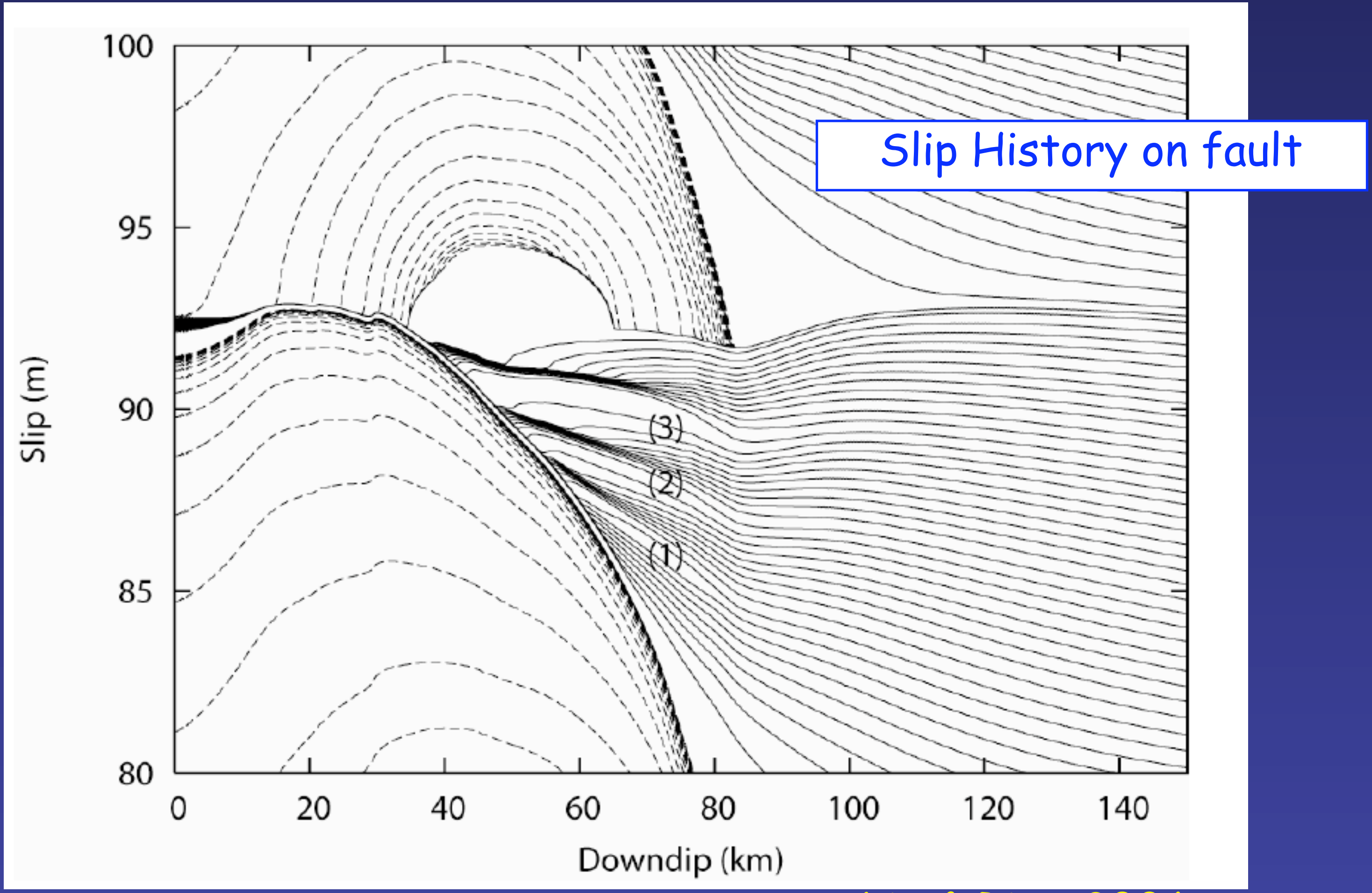




Hsu et al., Science, 2006

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

"Real Friction"

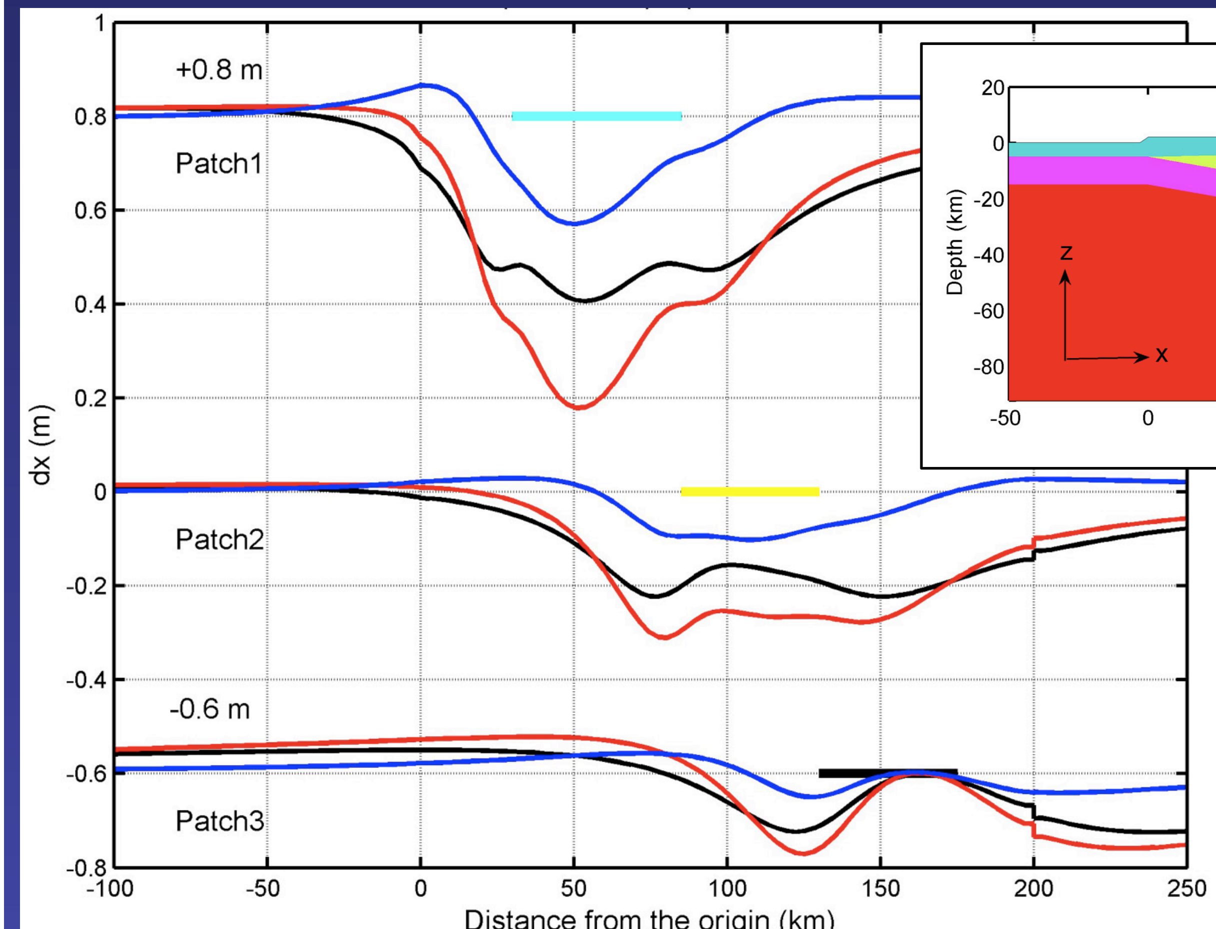


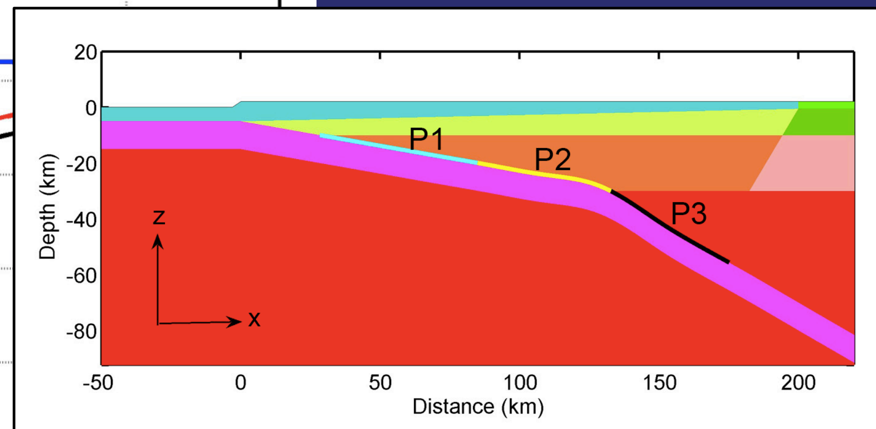
Liu & Rice, 2006

Challenge: Time to go beyond planar faults in an elastic half space

A rare PyLith example of something not doable semi-analytically

A systematic exploration of the role of 3D elastic structure on predicted geodetic observations





Comparison of horizontal displacements predicted from an elastic half space and from a 3D elastic model as a function the location of fault slip.

One can fit data reasonably well with either model, but with a different distribution of fault slip.

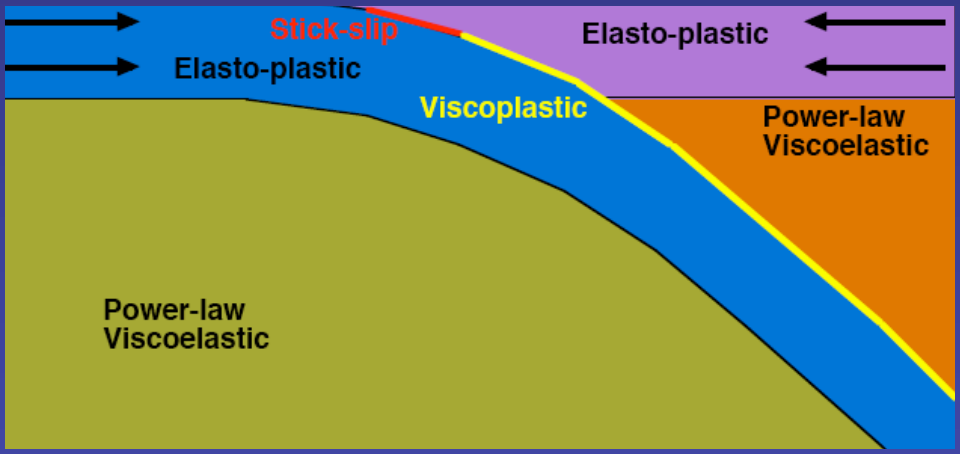
From *Ya-Ju Hsu*

Rheology Issues

Thus far :

- Most coseismic and postseismic examples are kinematic models
  - they do not invert for fault slip or attempt to obey proposed rheological behaviors
- Most models adopt either elastic half-spaces or horizontally layered elastic halfspaces
  - no 3D structures, no inelasticity
- Single time scale
  - Consistency of earthquakes, afterslip, VEP, and the long-term evolution of the plate boundary?

A potential goal



Charles Williams, 2005

Prestress (spin up)

Even if interested in system response from just 1 earthquake, the need for a consistent pre-stress requires spin up – but this presents its own problems

Approach

Any linear rheology

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

⇒ Add *N* events with appropriate time lags until steady-state is reached

Any nonlinear rheology

⇒ Run for a long time

- expensive - mesh distortion issues

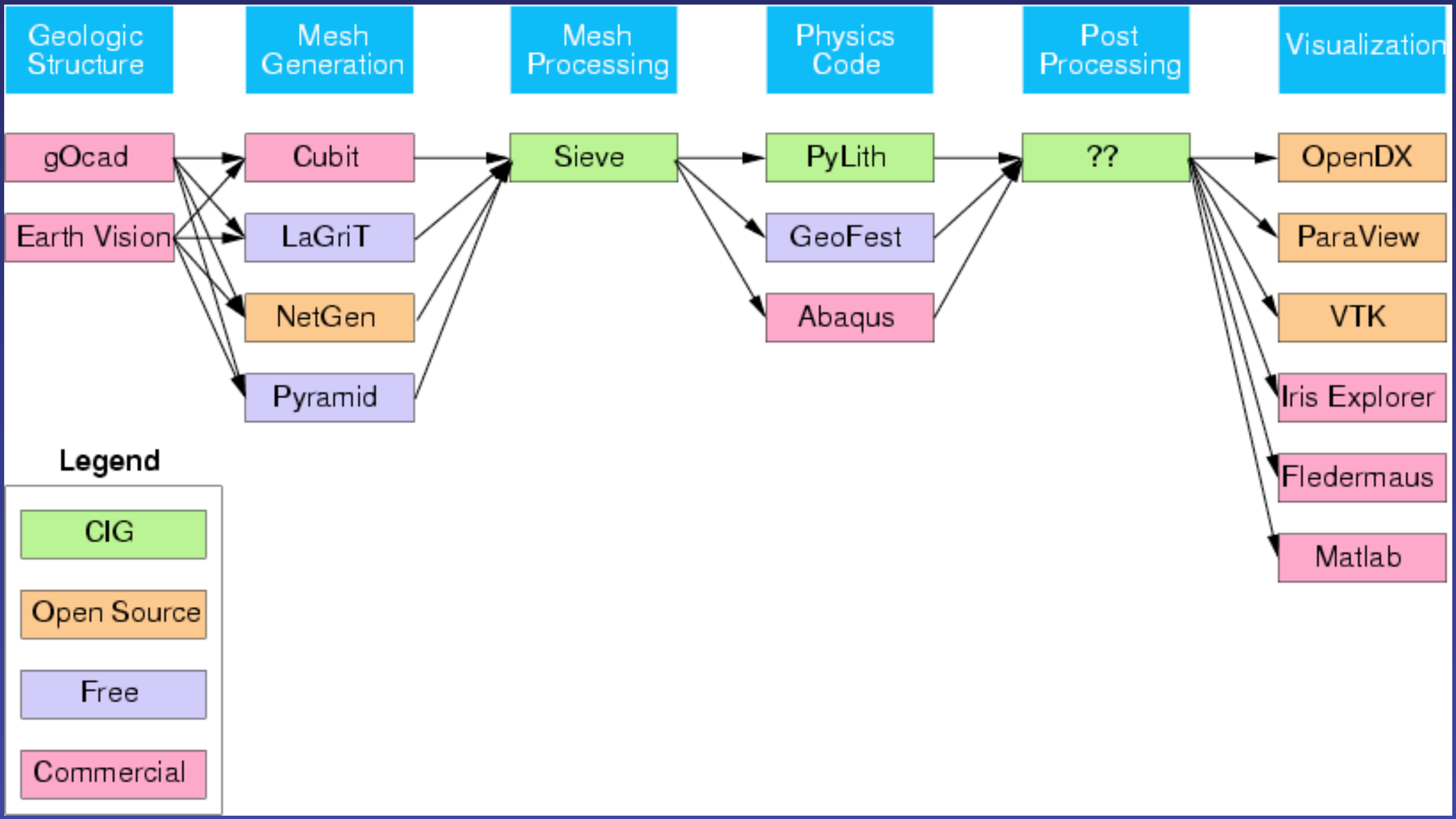
Uncertainty in conditions (noise)

⇒ Run for a long time with many realizations

- real expensive - mesh distortion issues

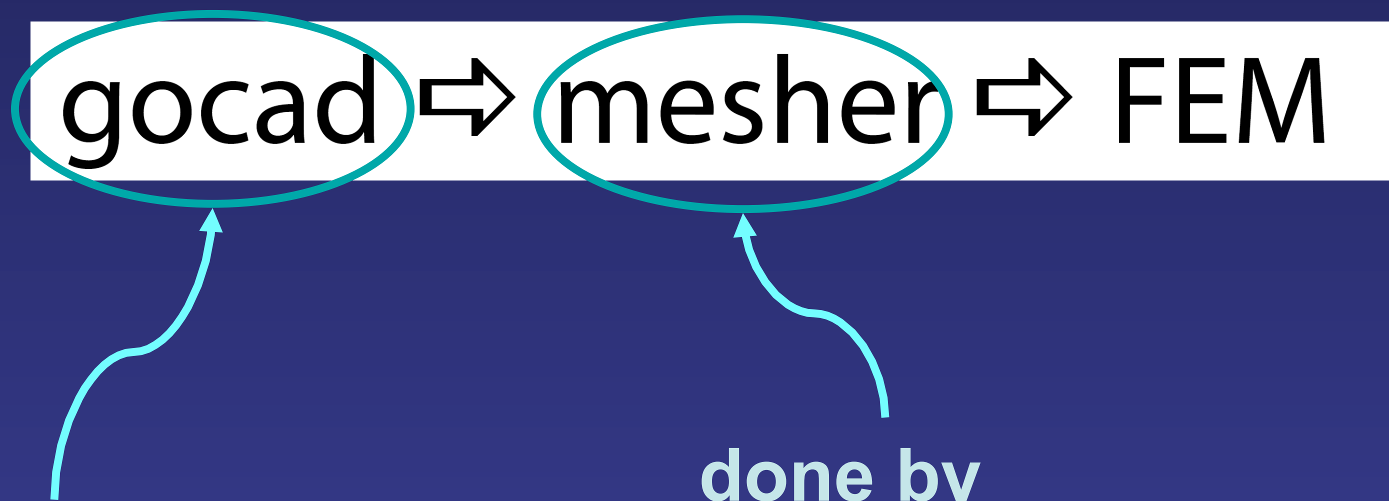
Workflow

A recurring theme of our group



Brad Aagaard

Simplified Workflow



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

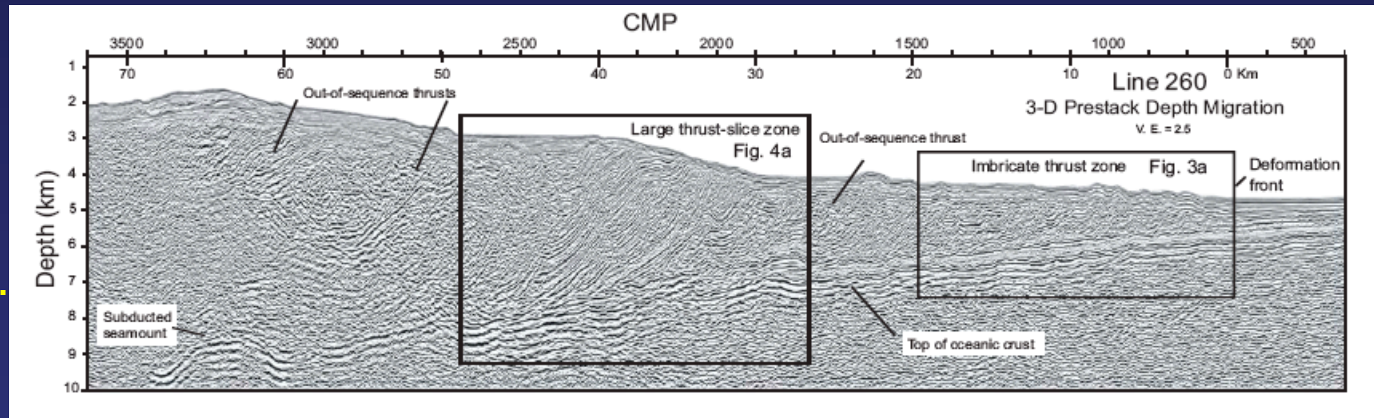
with help from experts and the experienced

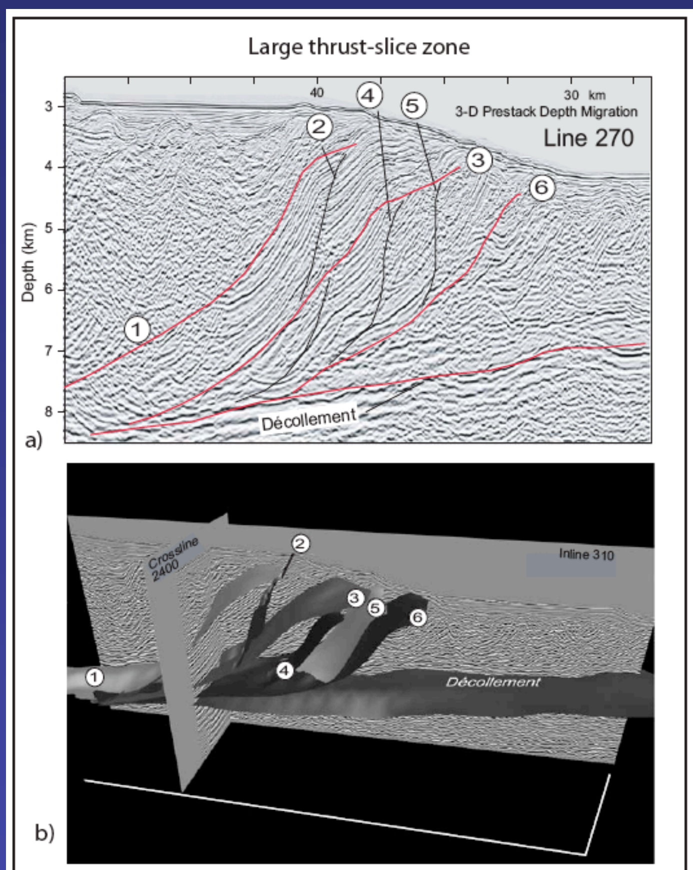
inexperience = not necessarily the best way to do things

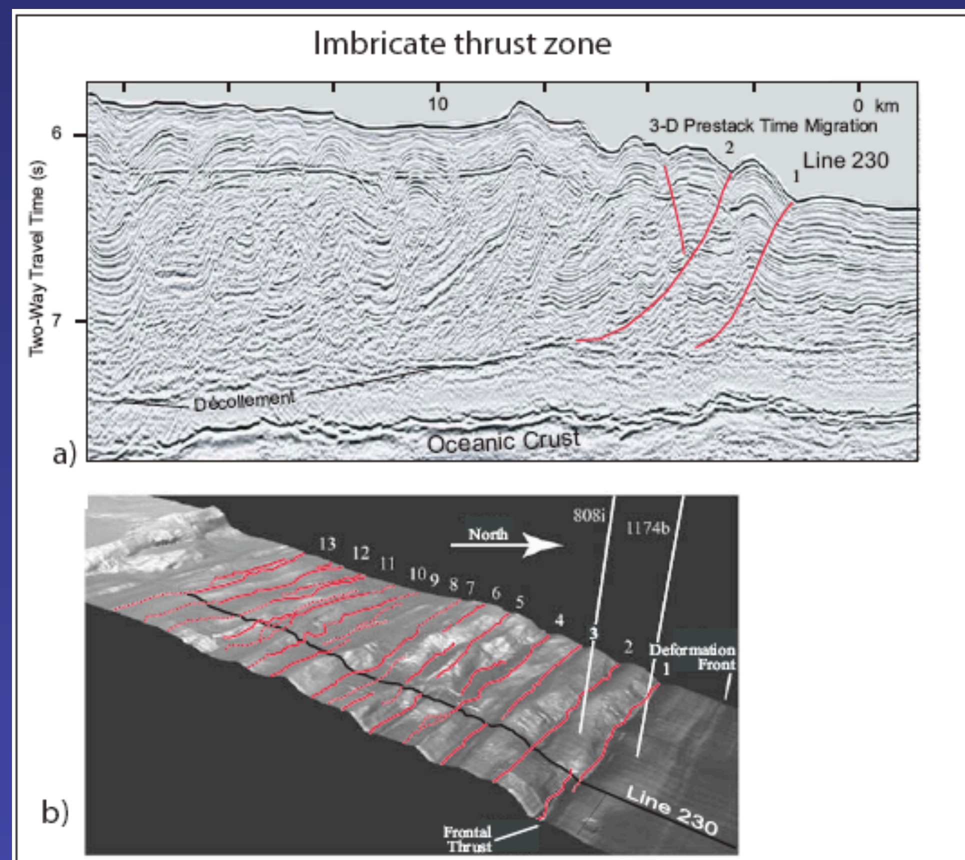
Start with this…

Structure of the forearc

Faults, material, etc.

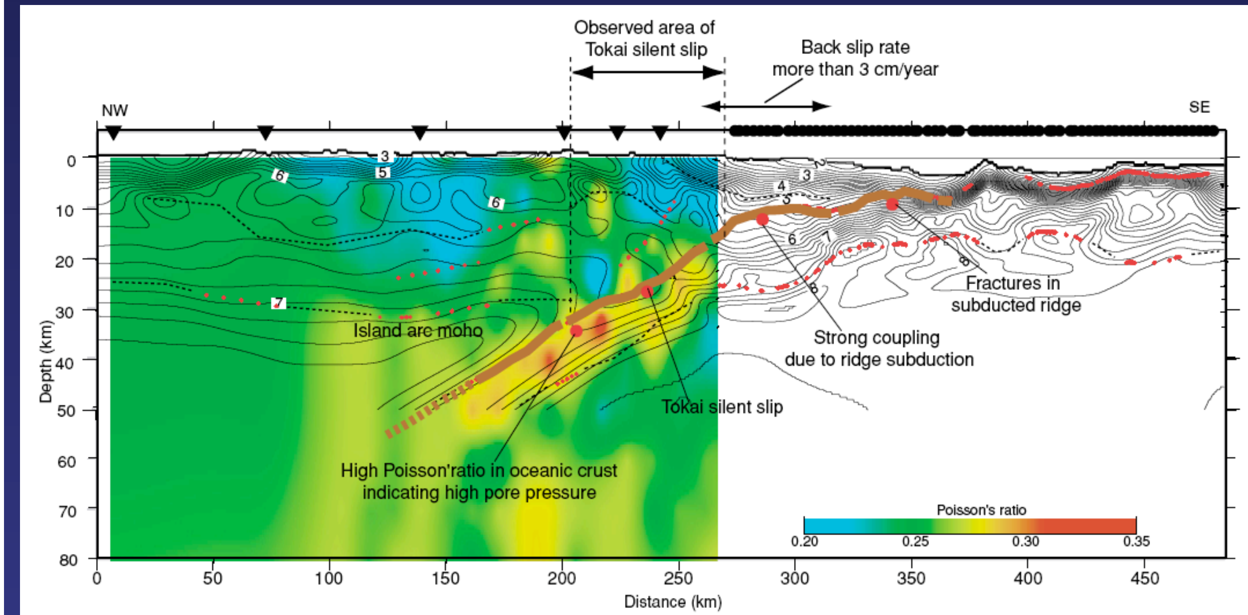


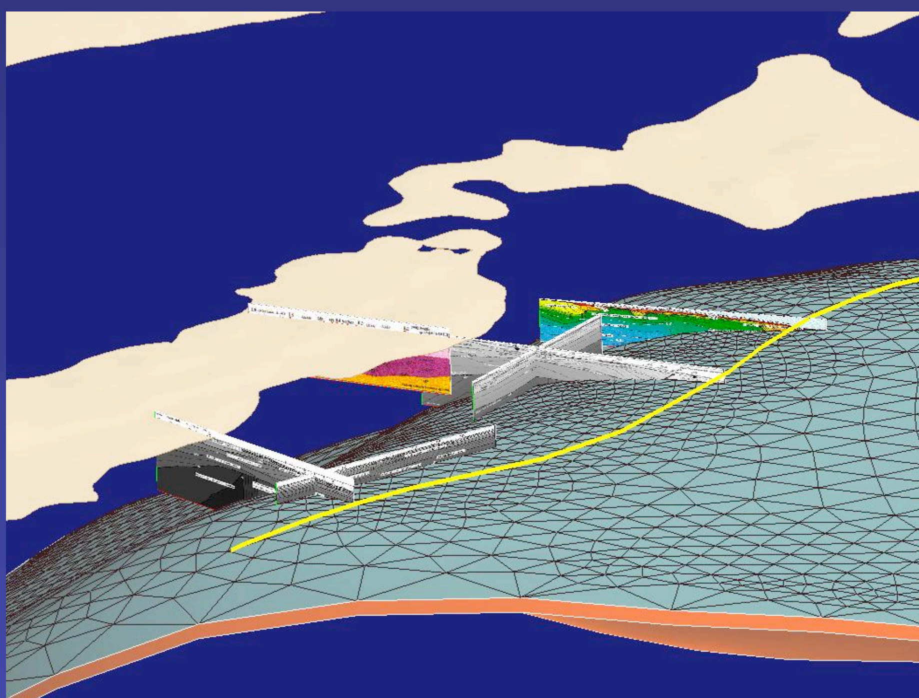


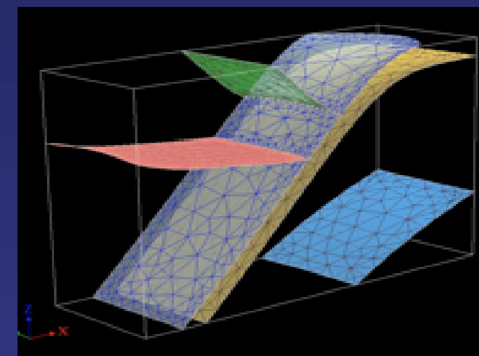


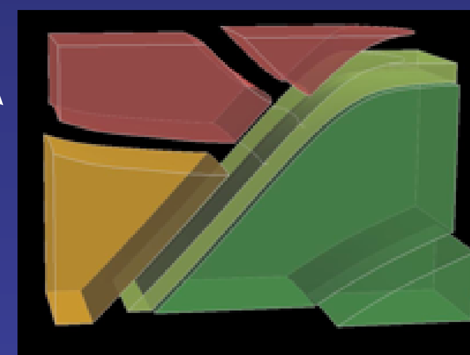
Bangs et al., 2005

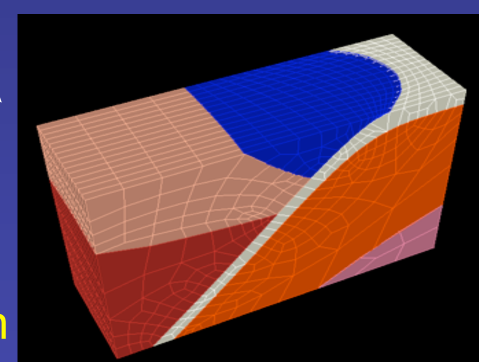
The Meshing Challenge









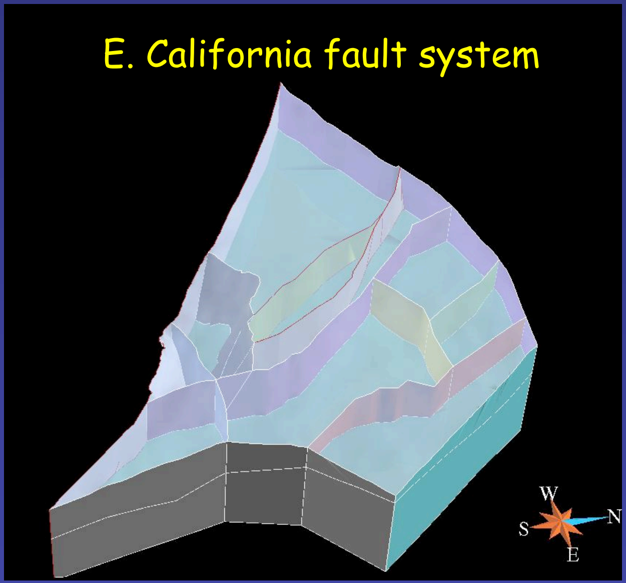


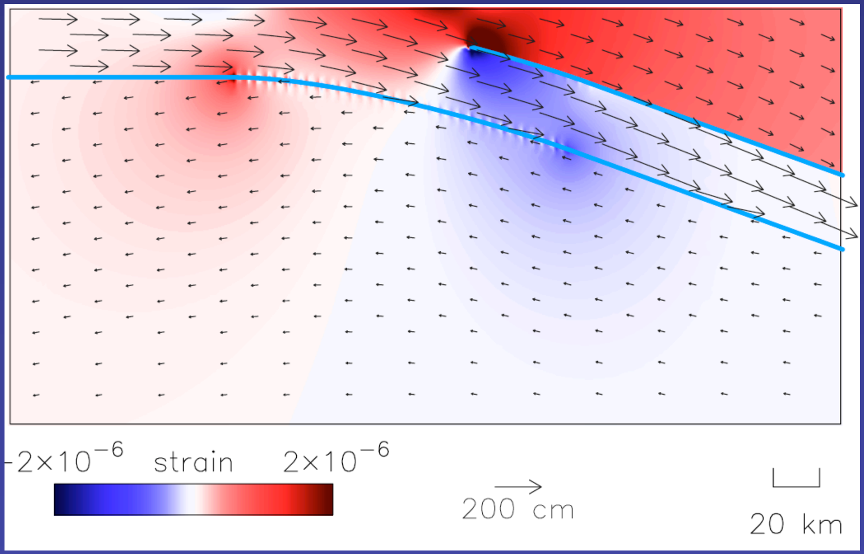
Bookkeeping

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
  - 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)

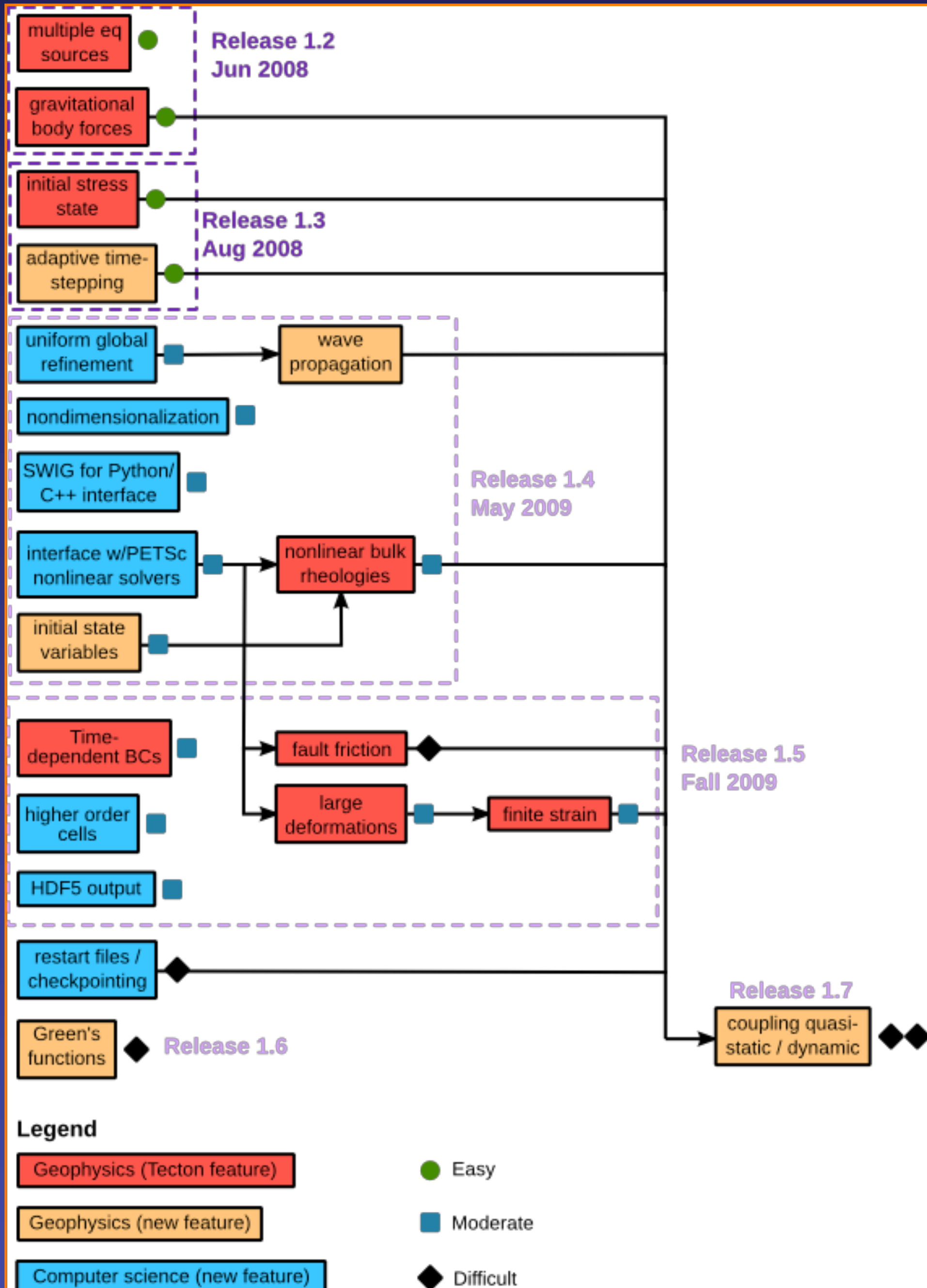
Rheology

- 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
- Adjoint approach?

PyLith Development



Code History

- Tecton
- Lithomop
- Pylith 0.8
- EqSim
- Pylith 1.0 ++

3 Brave Musketeers

- Brad Aagaard
- Charles Williams
- Matt Knepley

All part timers.

Searching for d'Artagnan.

Thoughts/Lessons From PyLith Development

- Currently has great unrealized potential but requires implementation of existing capabilities in Tecton and EqSim to induce more widespread acceptance. PyLith needs core stability to enable community participation and encourage intellectual investment.

- Tecton was developed over many years of work. While PyLith 1.x has been developed for a little over 2 years. Note that PyLith 1.x was built from scratch.

- PyLith is more than a modern version of Tecton. Is is much more advanced code in many aspects, including implementation of the physics, user interface, and flexibility. Its ability to handle both dynamic and quasi-static simulations will open many avenues for exploring earthquake physics.

- Considerable time and effort has been spent on the development of Sieve which has undergone more than one major overhaul in order to improve its performance. Identifying performance issues has taken a lot of time.

- Choice of Pyrex to provide the C++/Python interface was not ideal. Switching to SWIG (in progress) will result in easier builds from source and less maintenance for the developers.

- Developing PyLith with unit testing takes at least 2x time as developing without unit testing. However, the end result is much better and worth the effort.

Ad Hoc Steering Committee

- Brad Aagaard, USGS (Chair)
- Oliver Boyd, USGS
- Andrew Freed, Purdue University
- Carl Gable, LANL
- Brad Hager, MIT ***
- Rowena Lohman, Cornell University
- Greg Lyzenga, Harvey Mudd College
- Mark Simons, Caltech
- Charles Williams, GNS Science, NZ

*** Recently stepped off