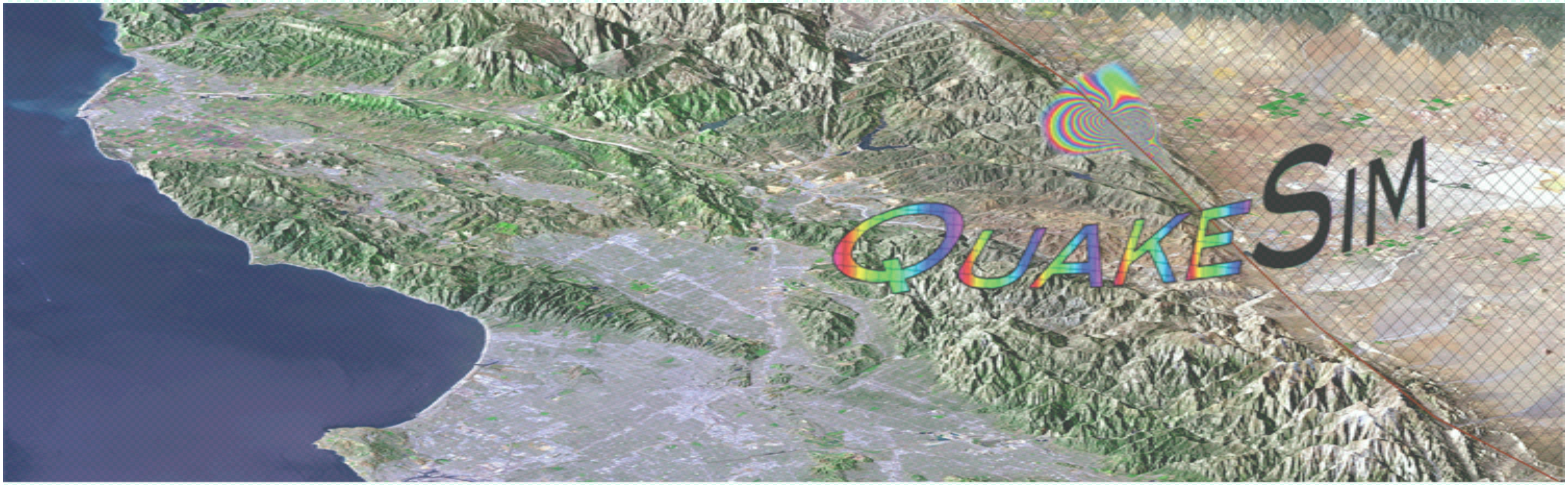
National Aeronautics and Space Administration

Introduction to GeoFEST



Jay Parker

Geodynamics & Space Geodesy Group

Jet Propulsion Laboratory/California Institute of Technology

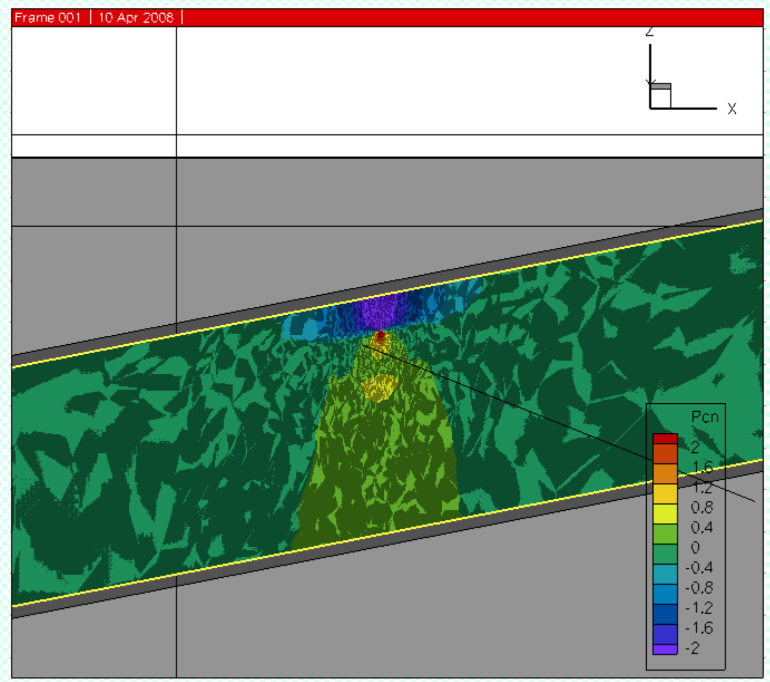
Topics

- QuakeSim Resources, California Faults
- Why use finite elements in geodesy
- What GeoFEST computes
- Parallel operation, refinement, accuracy
- Steps to creating your simulation
- California deformation simulations

QuakeSim is . . .

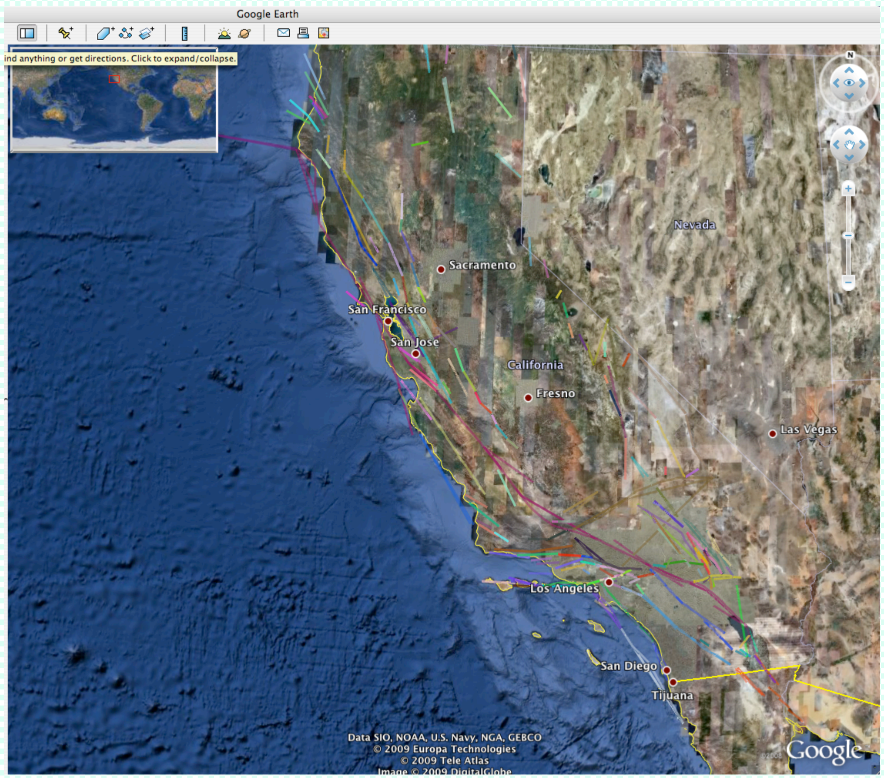
- . . .developing a solid Earth science framework
  - for modeling earthquake and tectonic processes.

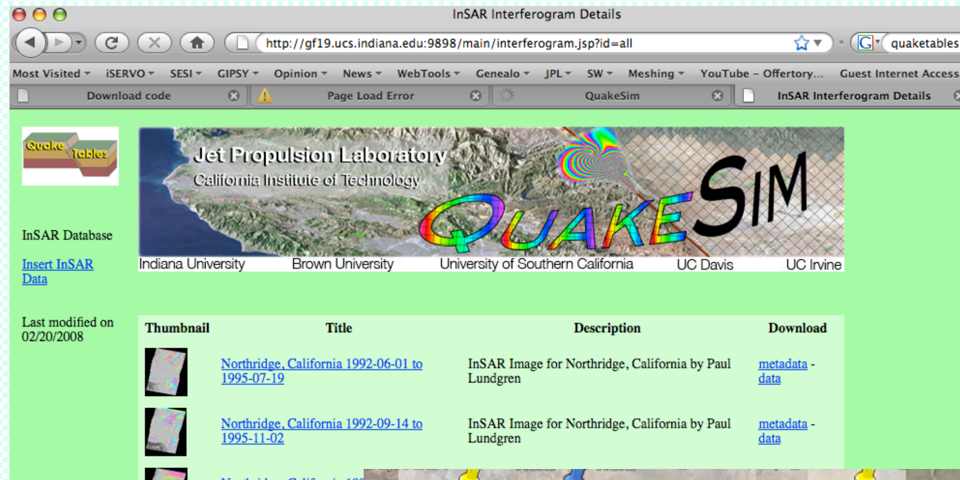
- . . . sponsored by the NASA Earth Science Technology Office (ESTO)
- . . . with core developers at
  - *Brown University*
  - *Indiana University*
  - *NASA Ames Research Center*
  - *NASA Jet Propulsion Laboratory*
  - *University of California Davis*
  - *University of California Irvine*
  - *University of Southern California*
- . . . and the participation of
  - *California State University Northridge*
  - *Harvey Mudd College*
  - *Los Alamos National Laboratory*

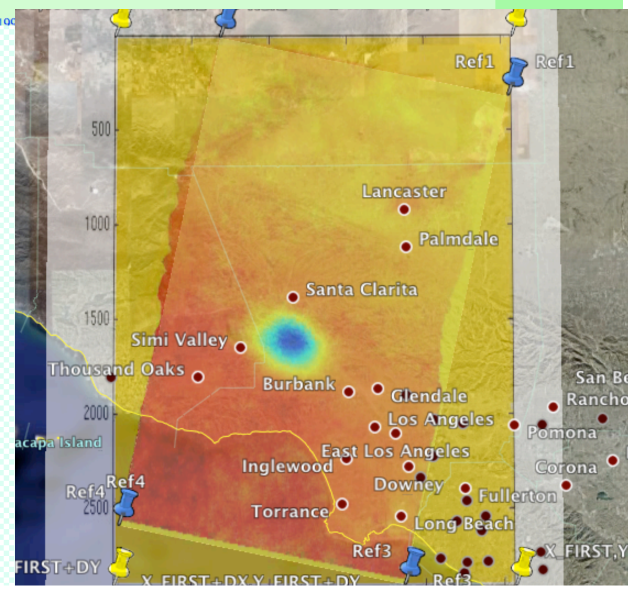


QuakeSim Resources: QuakeTables

- QuakeTables: federated database of faults, data.

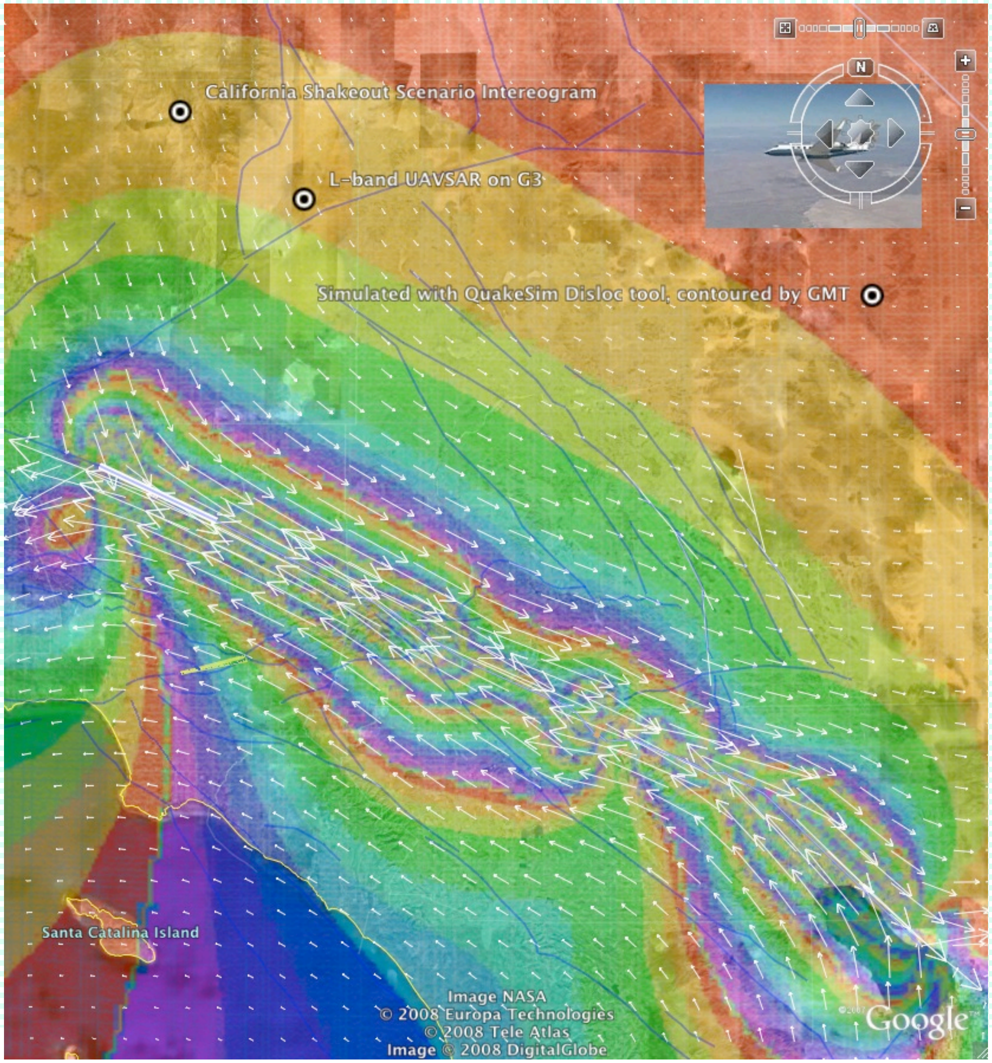






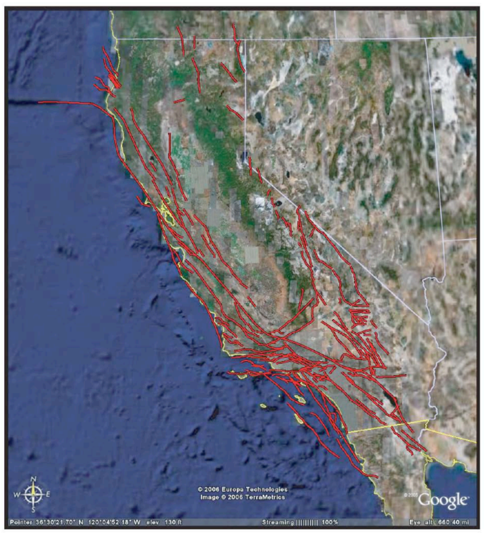
Disloc Tool, Interferograms

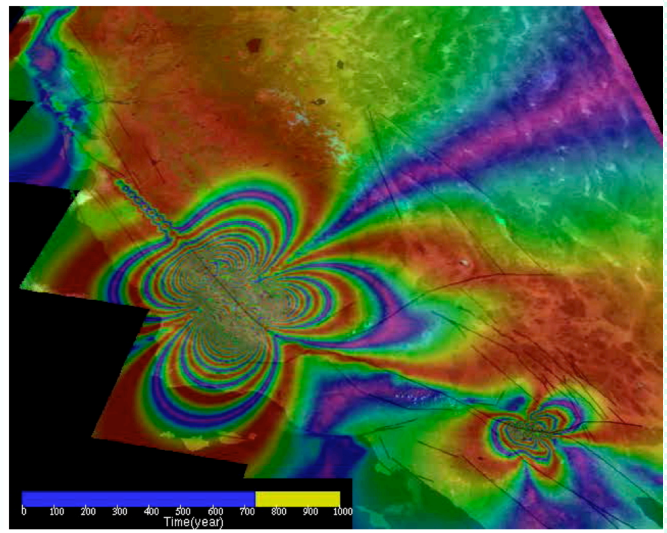
- Great California Shakeout simulated interferogram



QuakeSim Resources: VirtualCalifornia

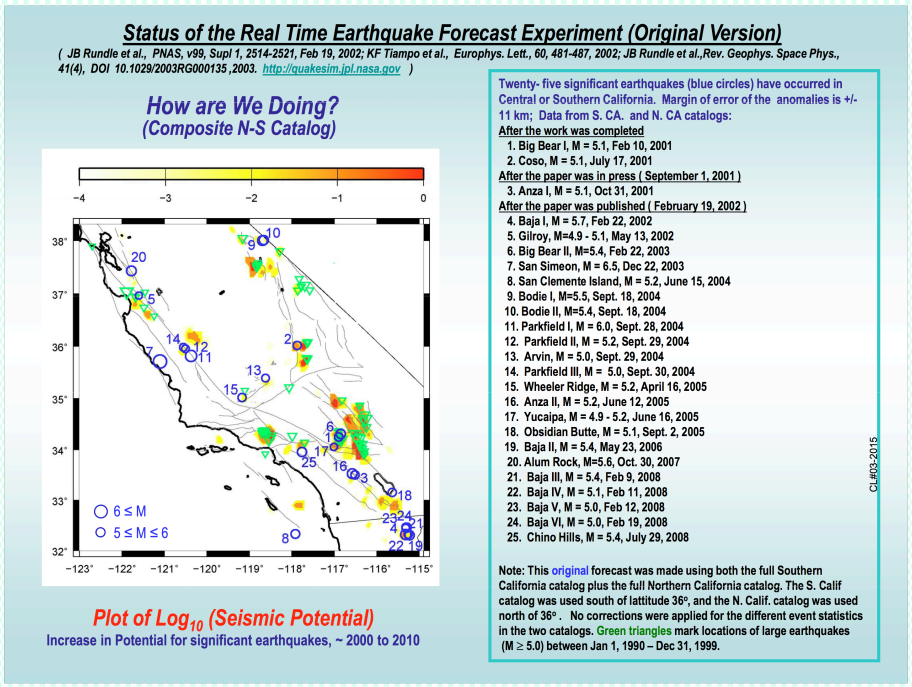
- Network of fault elements covering California
- Slip,stress,failure are fully coupled
- Space-time history diagrams, directional correlation

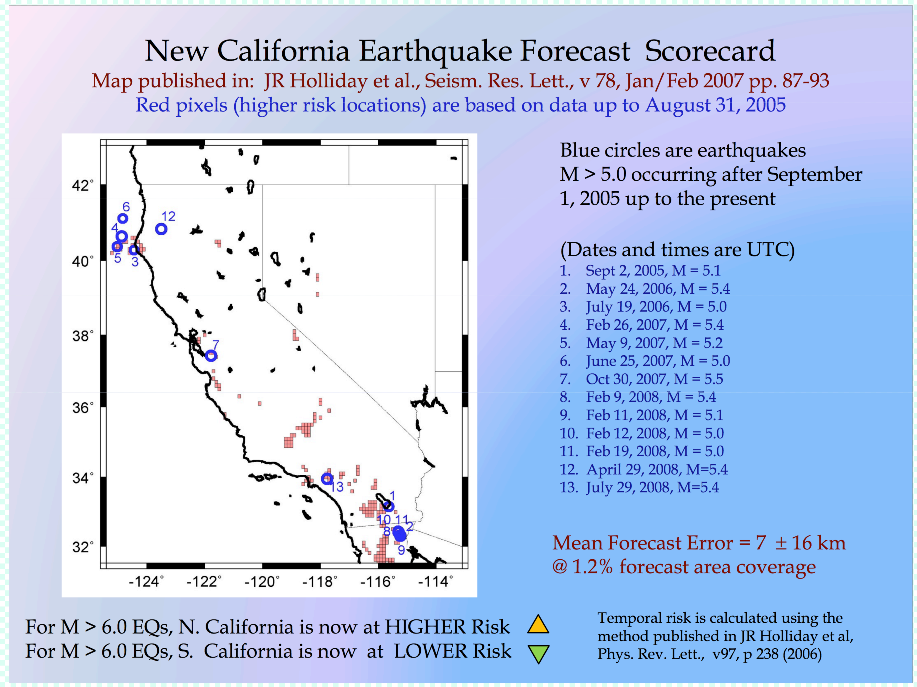




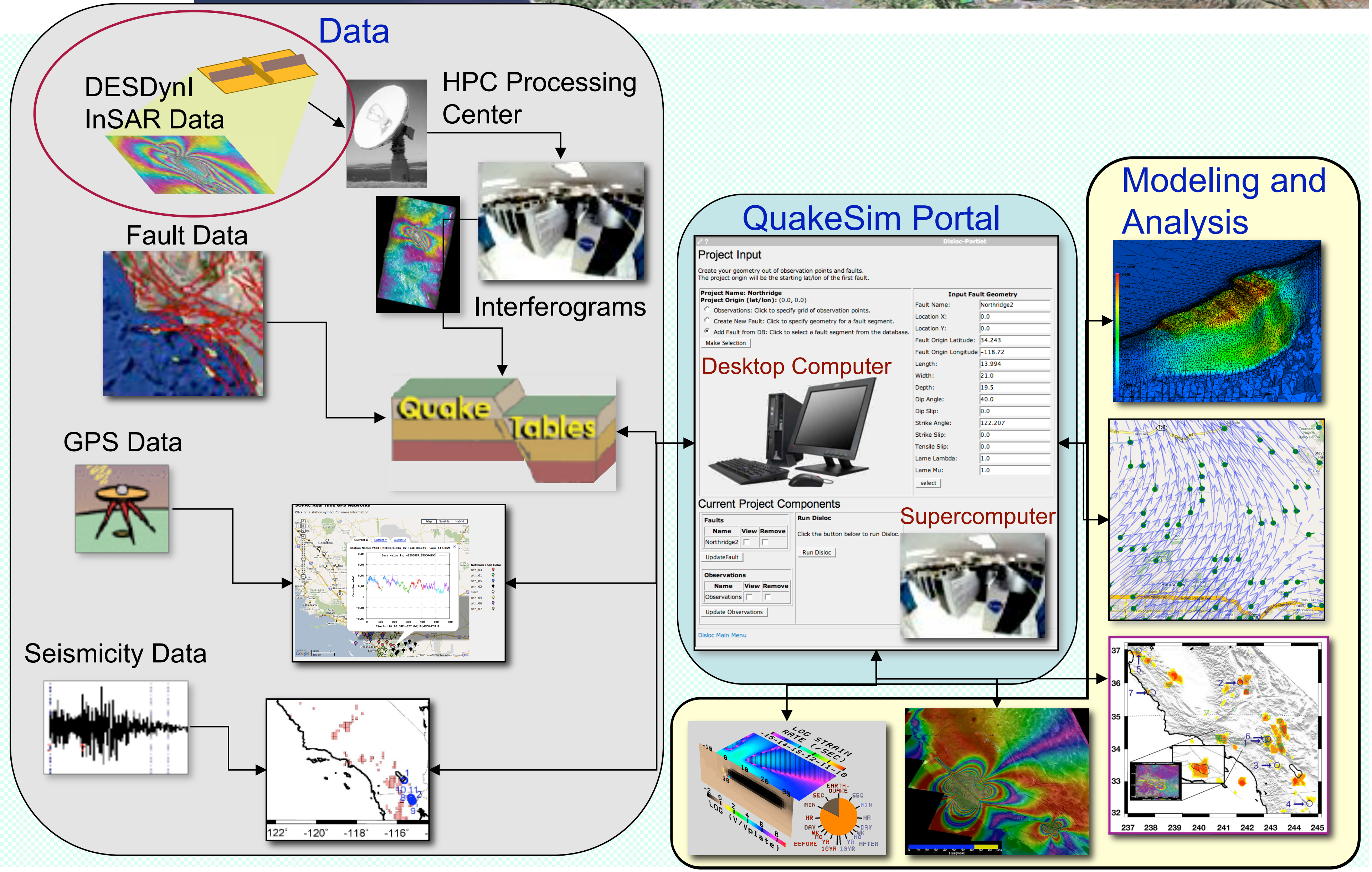
QuakeSim Resources: Forecast Scorecards

- PI method (Rundle)
- RIPI (Holiday)



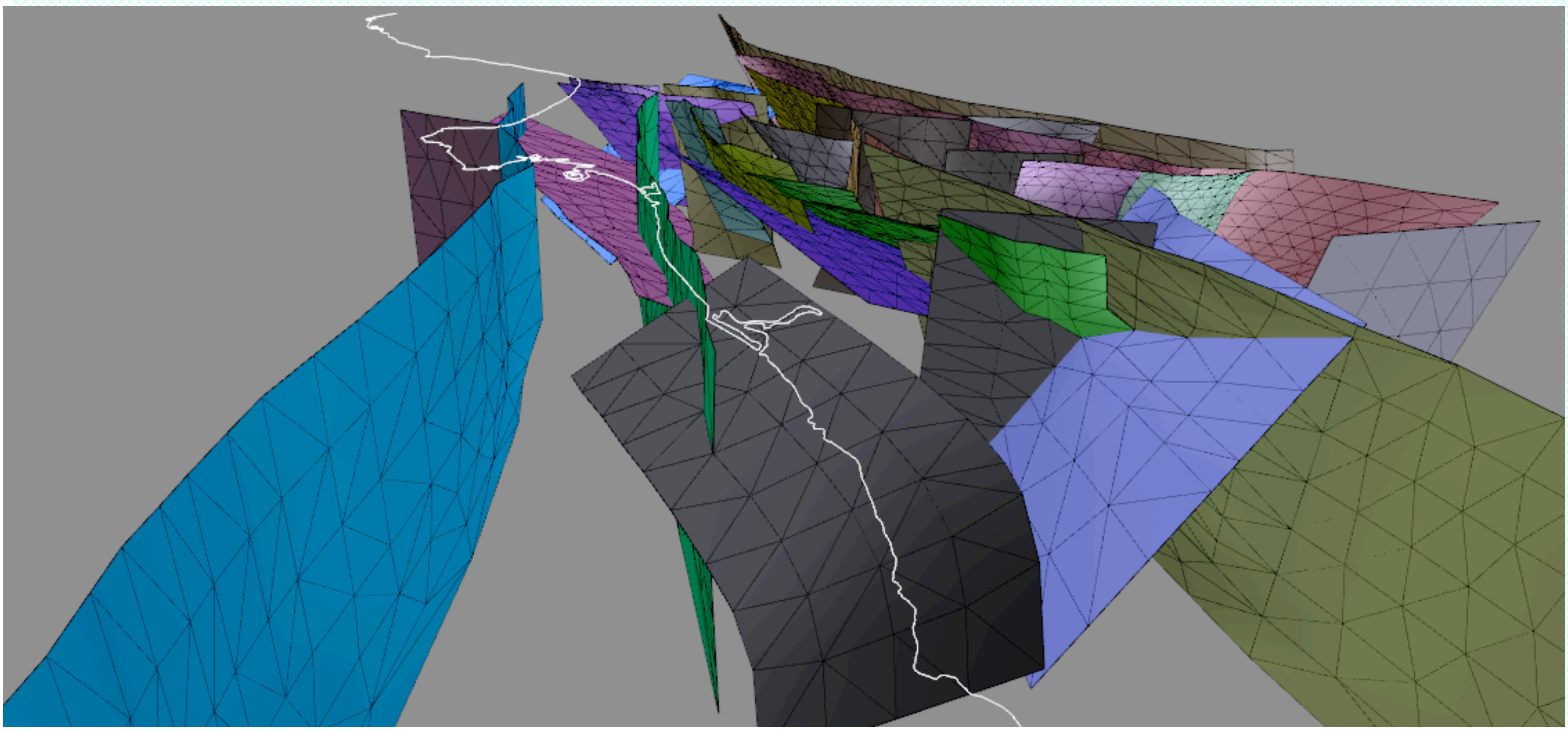


End-to-End Flow:
DESDynI to Models and Forecasts



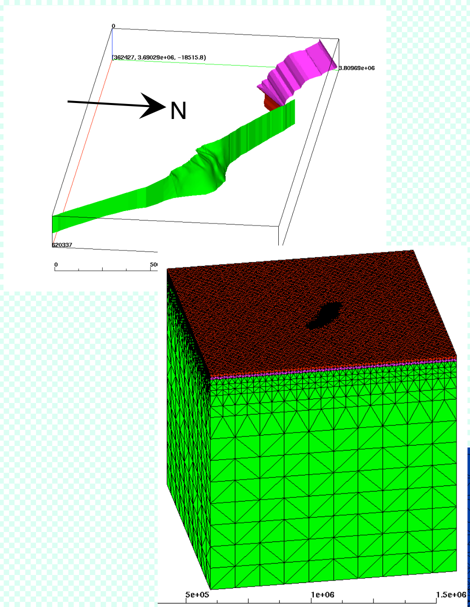
Why use finite elements in geodesy?

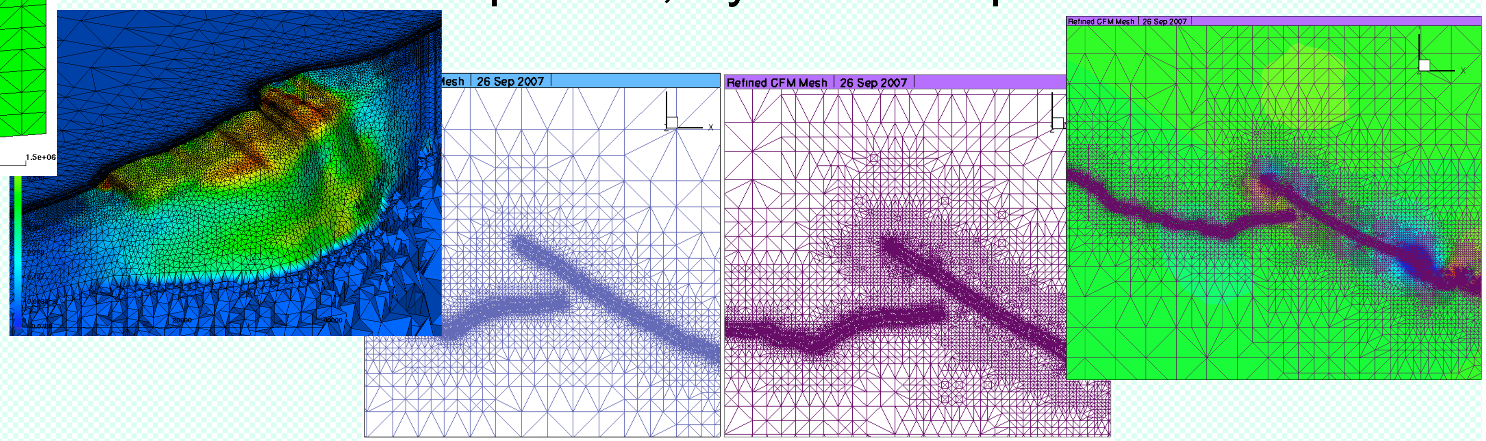
• Geometry of Los Angeles is faulted, complicated!
(Credit Scott Marshall, Appalacian State University)



GeoFEST is . . .

- *<u>GEO</u>*physical *<u>F</u>*inite *<u>E</u>*lement *<u>S</u>*imulation *<u>T</u>*ool
- 3D Linear Tetrahedra (and 2D Linear Quads/Tris)
- Evolution of displacements and stress,
- Elastic domain with faults, viscoelastic relaxation
- ~15000 lines of C source (plus Pyramid F90 library)
- Source at OpenChannel (easy to obtain, modify)
- 3D mode: MPI parallel, Pyramid adaptive mesh features





Contributors: Charles Norton, Gregory Lyzenga, Margaret Glasscoe, Carl Gable (LANL)
Users: Paul Lundgren, Gilles Peltzer, students at Purdue, UC Davis, University of Oregon. . .

What GeoFEST computes

Elastic equilibrium $$\sigma_{ij,j} + f_i = 0,$$

Viscoelastic relaxation $$\frac{\partial \sigma_{ij}}{\partial t} = c_{ijkl}\left(\frac{\varepsilon_{kl}}{\partial t} - \frac{\varepsilon_{kl}^{vp}}{\partial t} \right),$$

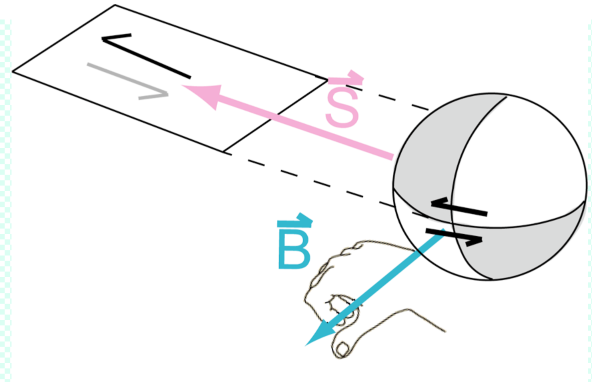
Isotropic material $$c_{ijkl} = \mu(x)\left(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk}\right) + \lambda(x)\delta_{ij}\delta_{kl},$$

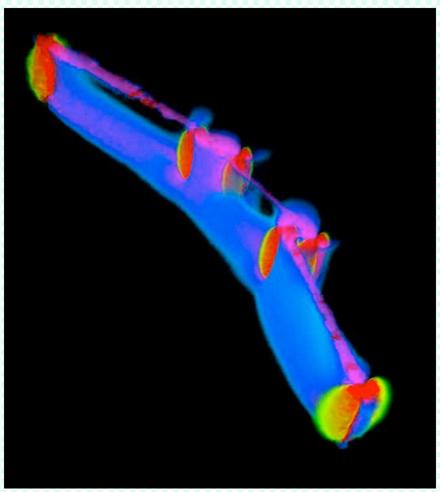
Viscoplastic strain rate $$\frac{\partial \varepsilon_{ij}^{vp}}{\partial t} = \beta_{ij}\left(\sigma_{ij}\right),$$

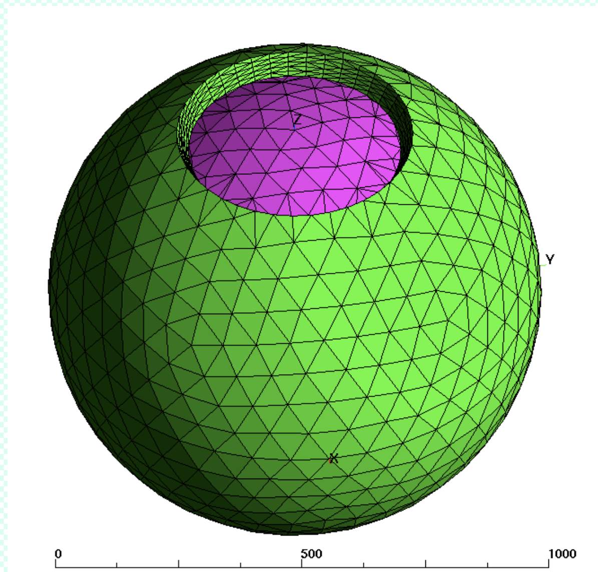
. . . so materials have lame parameters, viscosity, and body force

What GeoFEST computes (2)

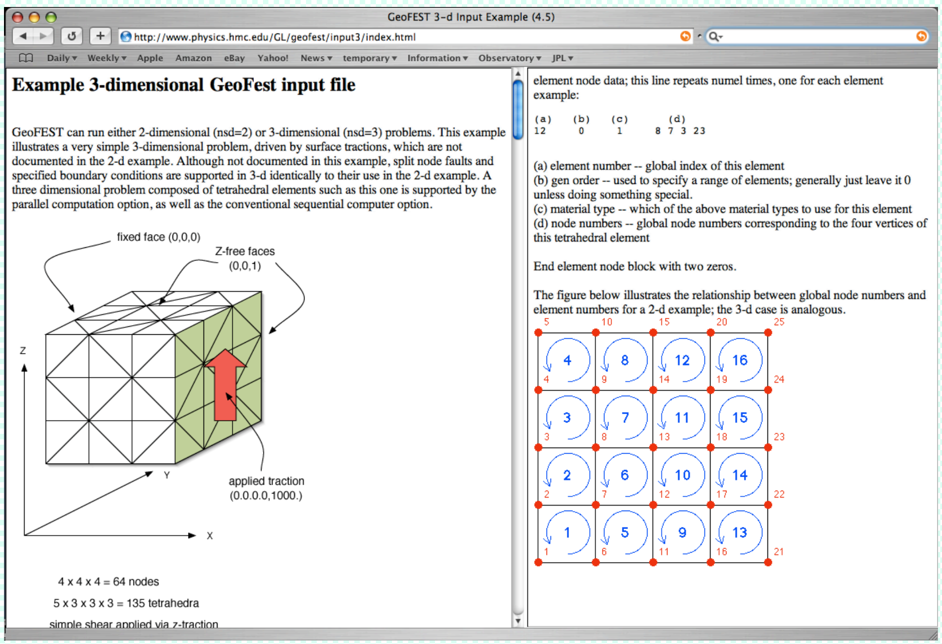
- Imposed fault slip
- Buoyant response
- Strain Energy

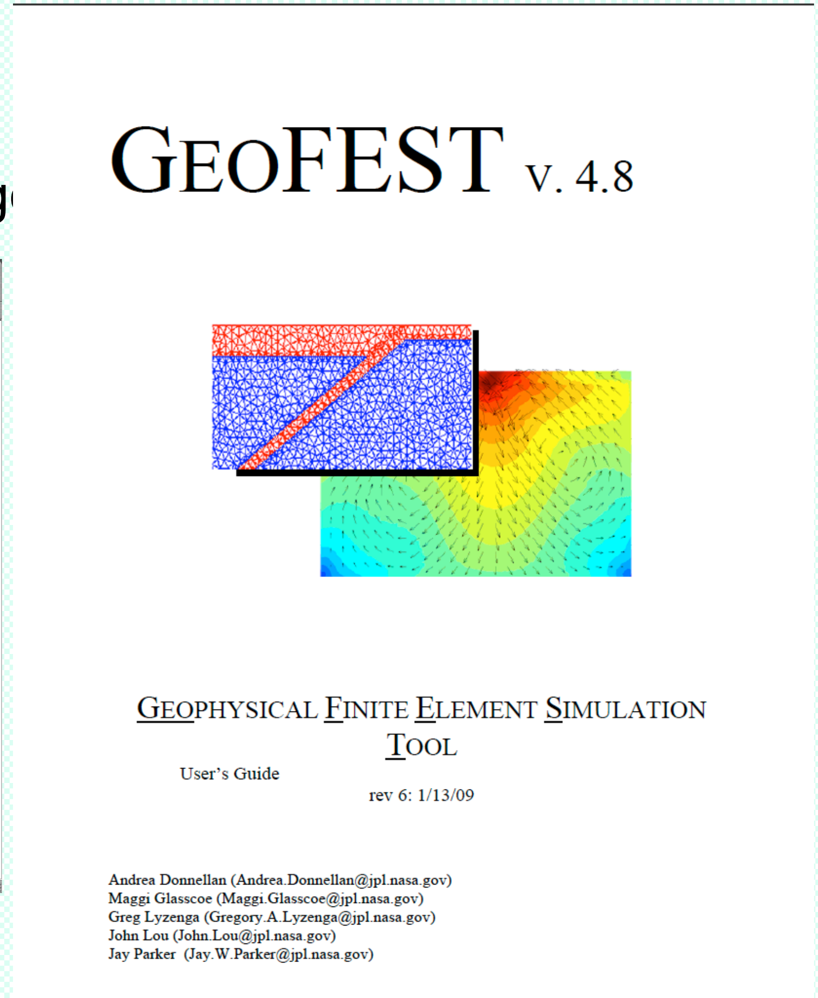




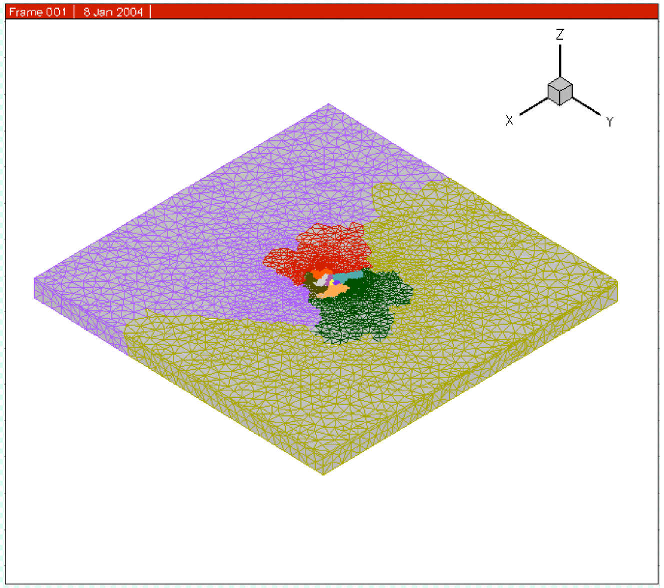


- GeoFEST Documentation and Learning Materials
  - GeoFEST User's Guide
  - GeoFEST Introductory web page





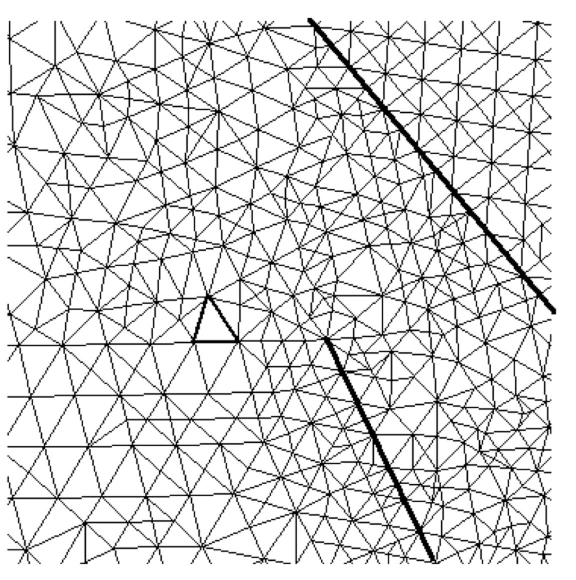
Parallelizing FEM

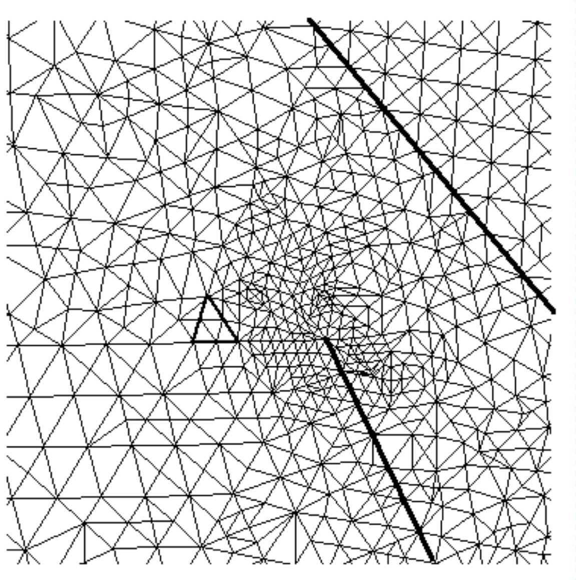


- Decompose domain into contiguous blocks of elements (nodes on edges)
- Balance #of elements; minimize (but don't balance) communication
- Use *message passing* to globally update dot products, matrix products, etc.
- 3-D mesh design and partitioning not trivial: use PYRAMID

GeoFEST/PYRAMID

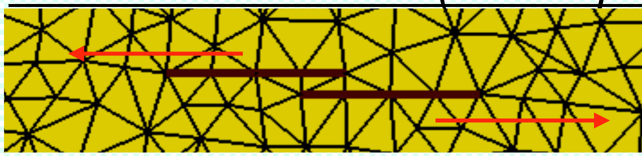
Refinement near Landers step



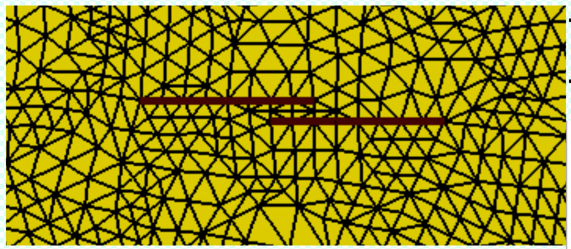


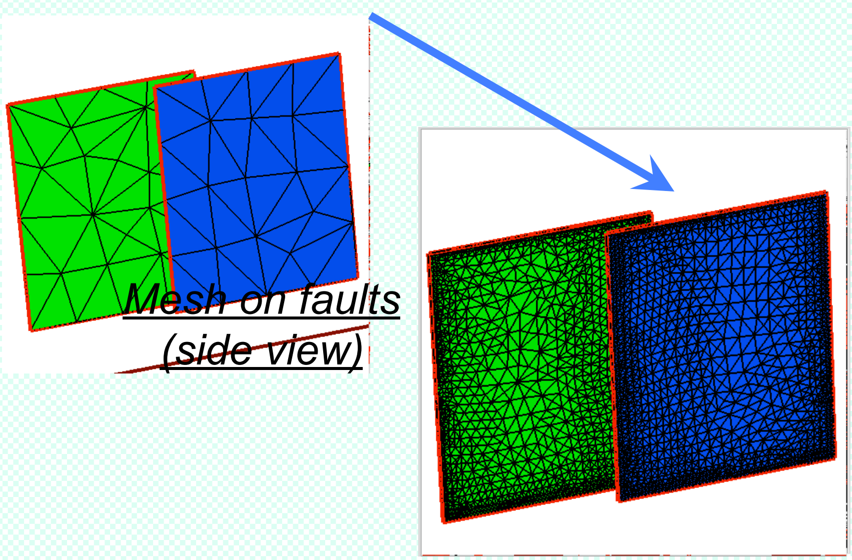
Adaptive Meshing

Initial surface mesh (center portion):



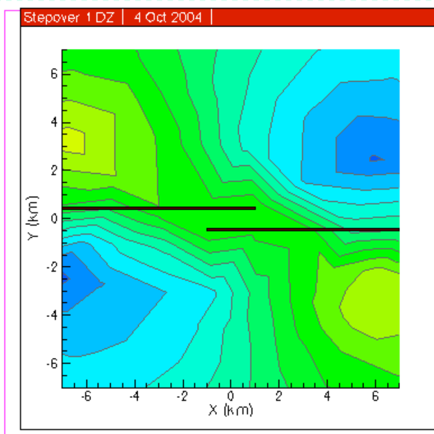
Obtain elastic solution
Strain energy,
Refine



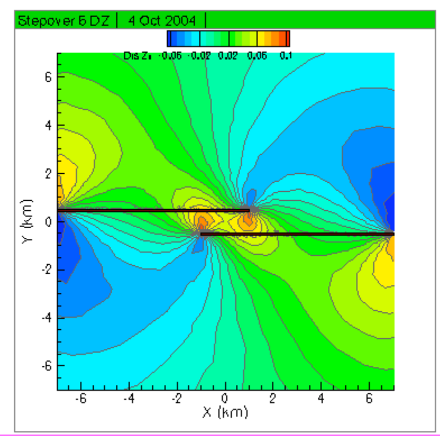


Mesh on faults (side view)

- guiVISCO method (preprocess)
- PYRAMID parallel library
  (NASA ESTO CT Project)
  – Changes mesh after import to cluster
  – Strain energy guides 3D refinement

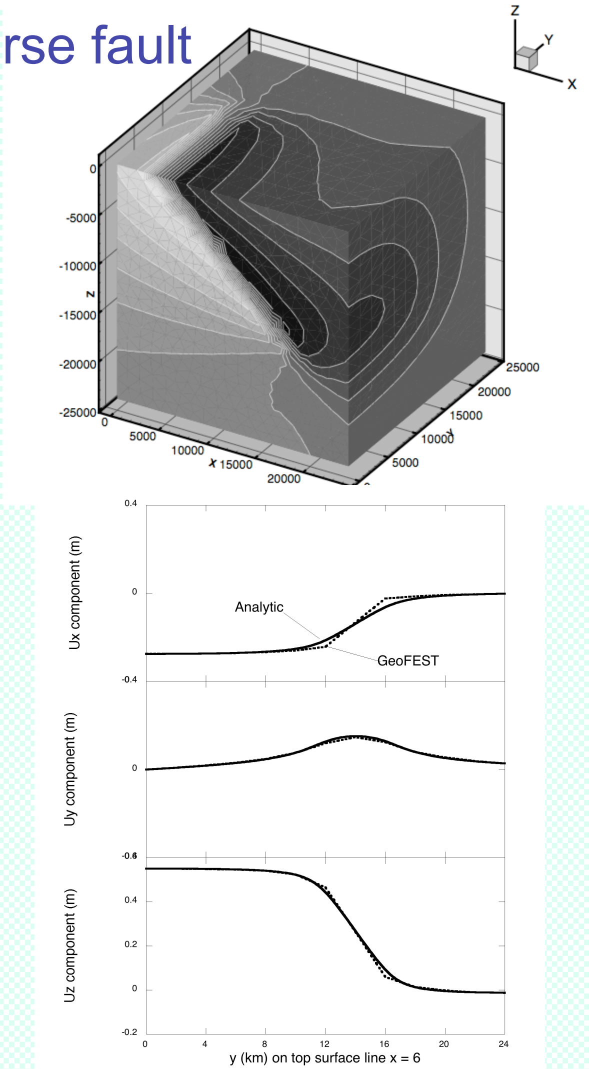


Z component at surface
Refinement cycles 1 and 6

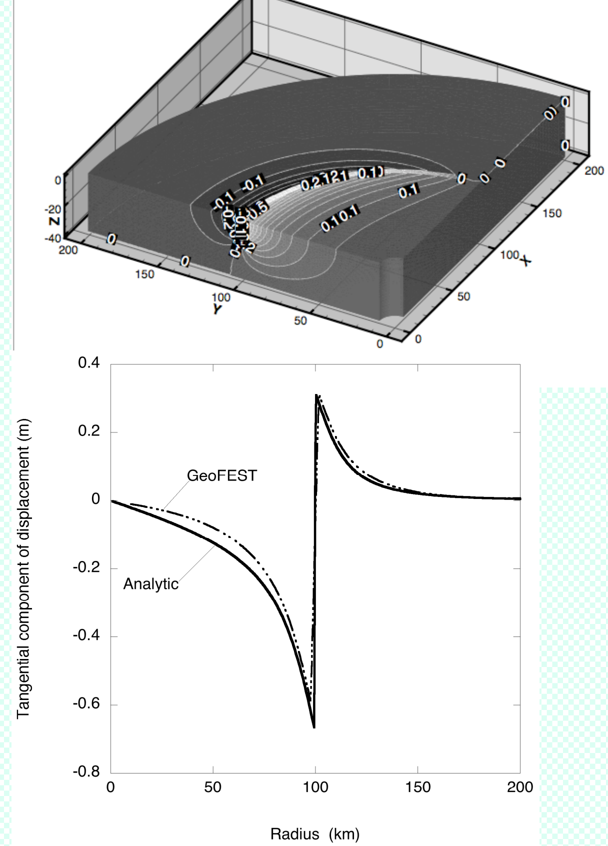


CFEM Workshop Cases

Reverse fault



Circular fault



--Workshop on Community Finite Element Models for Fault Systems and Tectonic Studies

LaGriT creates sophisticated meshes

LaGriT Meshing for Geological Applications | Home

http://meshing.lanl.gov/

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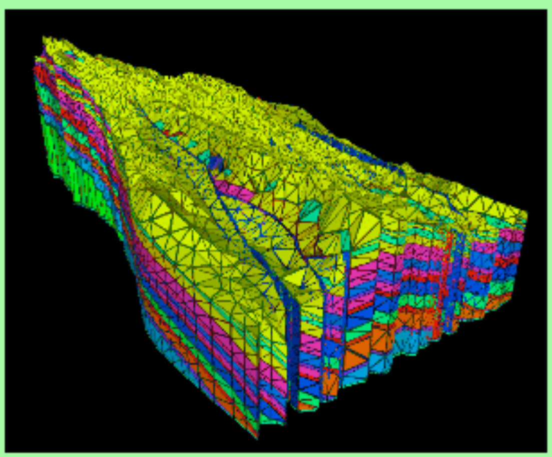
LaGriT:Meshing for Geological Applications

EES6 Home | Grid Projects | LaGriT | Gridder | GMV | Demos

Tetrahedral Grid Yucca Mountain Unsaturated Zone



Geologic applications for grids produced with LaGriT are modeling subsurface porous flow and reactive chemical transport by finite element (FEHMN code developed at LANL) and finite difference methods. LaGriT is also used as the first step in quality analysis and manipulation of geometric data.

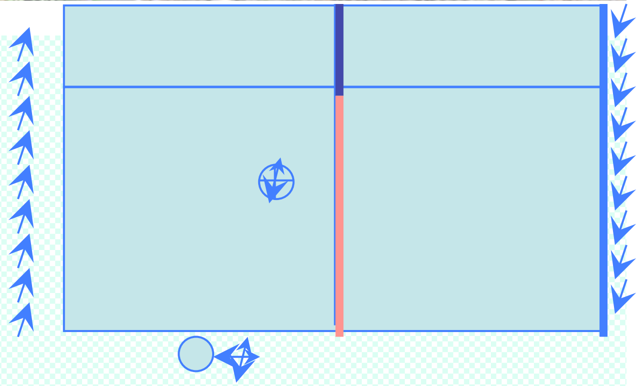
Projects in which LaGriT is utilized include:

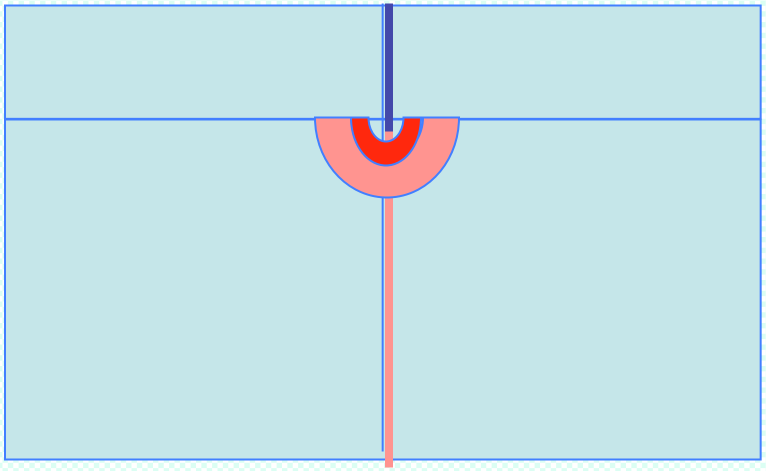
- Yucca Mountain Site Characterization Project (YMP)
- Nevada Test Site Underground Test Area Flow and Transport Modeling
- Southern California Earthquake Center (SCEC) meshing of California Fault Systems
- Environmental Restoration at Los Alamos and Savannah River
- Oil and Gas Reservoir Modeling
- Semiconductor Design Modeling
- High Speed Hydrodynamics

There are a wide variety of geological applications where accurate representation of complex engineering systems and geologic structure and stratigraphy is critical to producing accurate numerical models of fluid flow and mass transport. Oil and gas reservoir production, groundwater resource development and waste disposal in a geologic repository are examples of the areas where modeling is used to predict the long term behavior of a system. In all the systems, grid generation is a key link between the geoscientific information systems and numerical models. Grids must capture complex geometry and insure the computationals are optimized to produce accurate and stable solutions. LaGriT is a toolbox library with functions to produce 2D and 3D grids of elements that are tetrahedral, triangular, hexahedral and quadrilaterals. A 3D model of a computational mesh created from the 3D model is shown. 2D grids with arbitrary orientation or 3D grids with complex boundaries can be extracted from the geologic framework model. For more details refer to the Geo Meshing Overview (PDF).

Simple San Andreas - new issues

- Two strands, schedules (v4.6beta)
- Concentrated RHS source
- Requires high convergence
- Requires spin-up (5 cycles?)
- Post-event surface velocity
  - Sample of rapid decay
  - Reaching new equilibrium





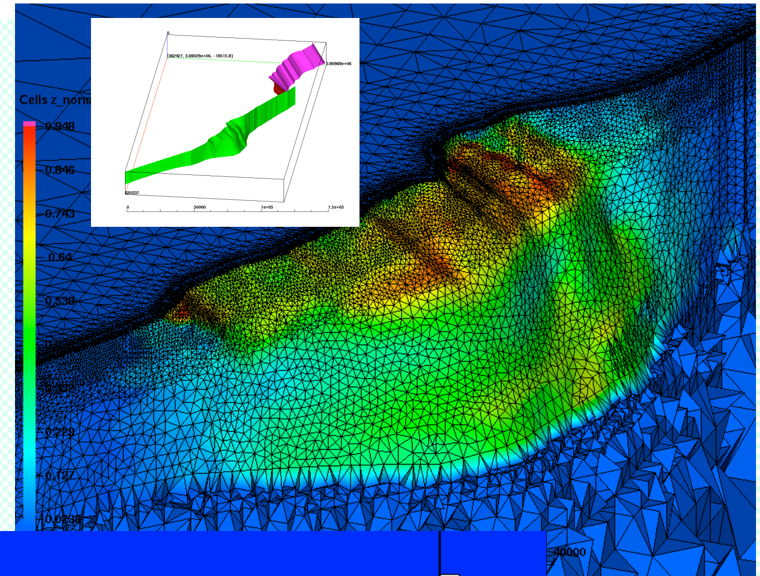
New Wrinkle: CFM/LaGriT San Andreas Fault

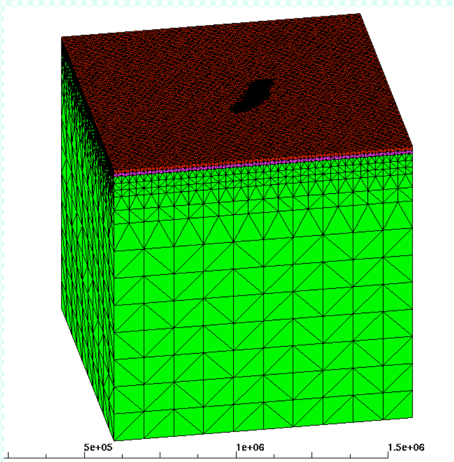
•Community Fault Model: High fidelity representation of known features of Southern California fault network (triangle facets)

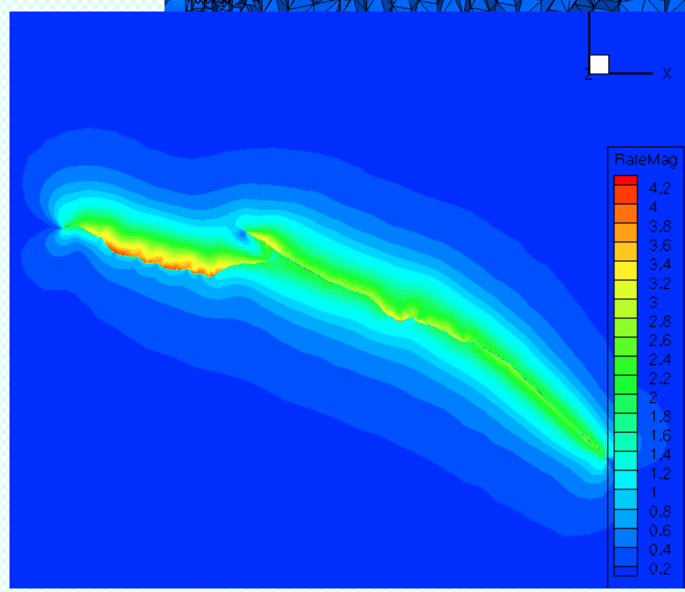
•LaGriT: Carl W. Gable (LANL) meshing package - he supplied the initial tetrahedral mesh

•Translating to GeoFEST: variant of “geotrans” JPL perl script

•Objective: model stress transfer (San Andreas is driver fault, Cucamonga and Sierra Madre are receivers of altered Coulomb stress). Also, demonstrate AMR on nonflat faults.

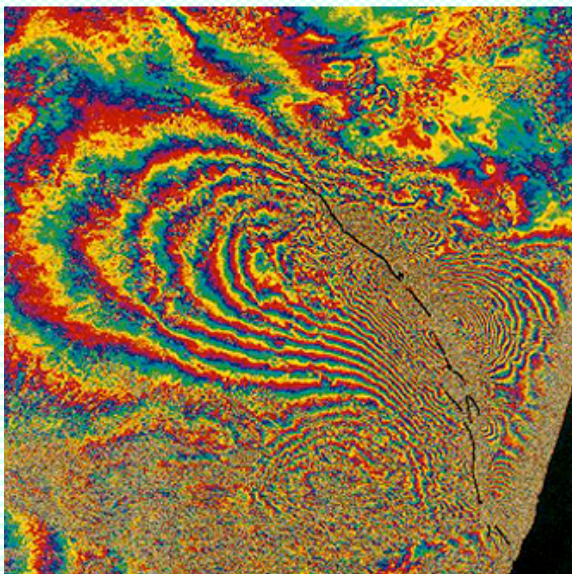




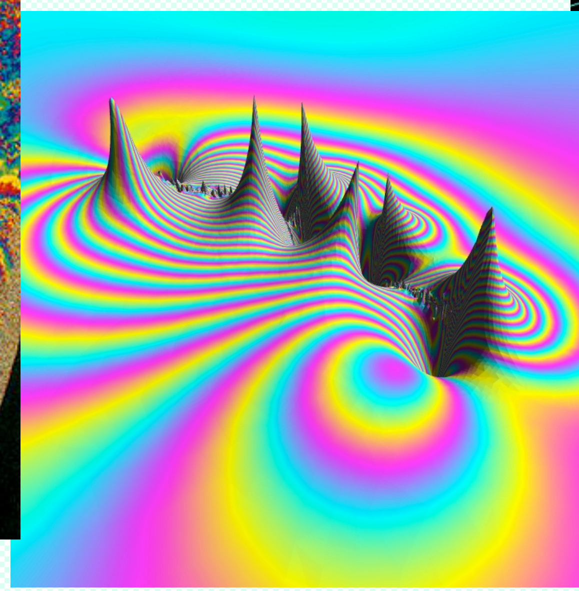


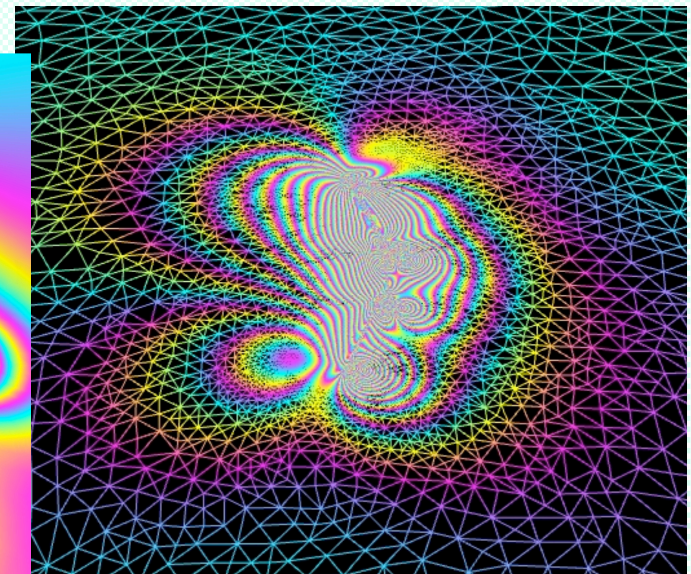
Simulated ERS-1 InSAR fringe

- GeoFEST surface displacements coded as InSAR fringes
- Satellite look angle, wavelength used correctly
- GeoFEST-simulated Landers coseismic pattern generally matches ERS-1



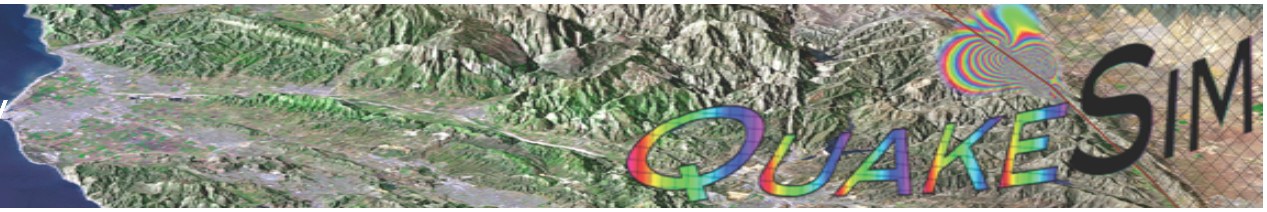
Landers ERS-1 Interferogram
Massonnet et al, Nature 1993





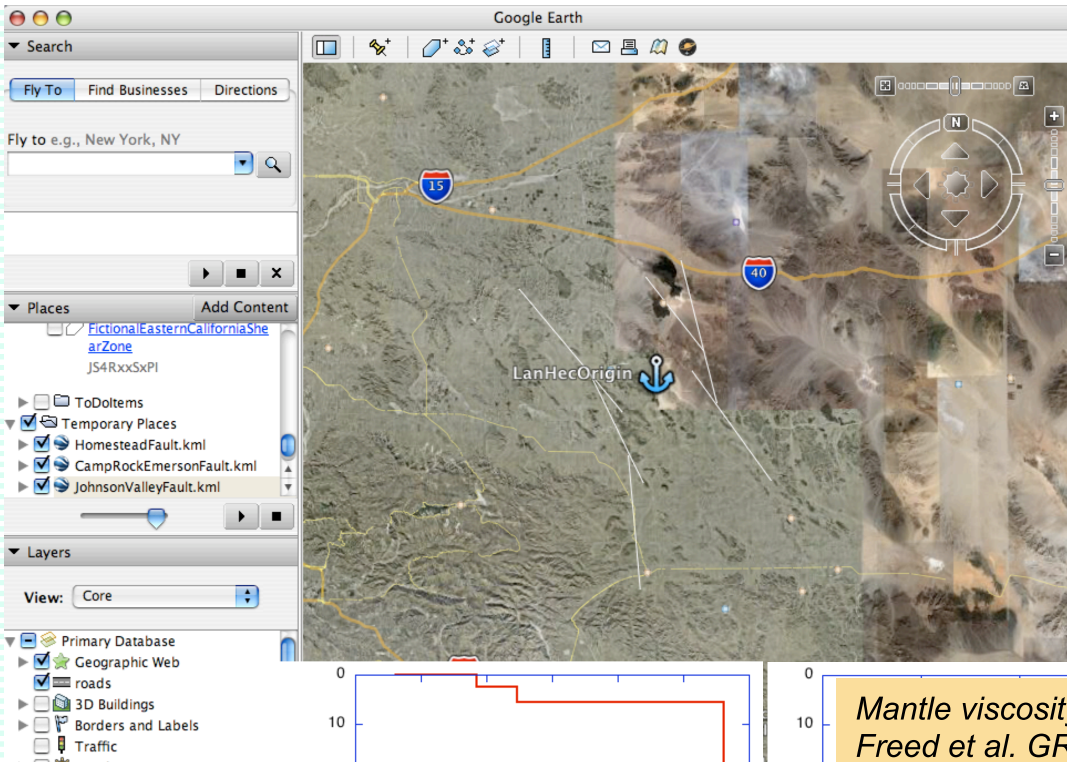
Work with Chris Henze, NASA Ames Research Laboratory

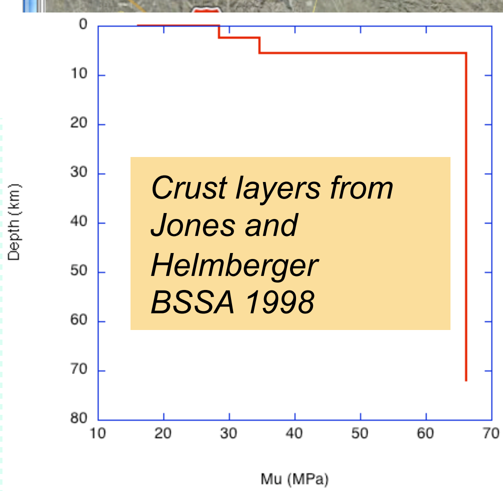
Mojave study

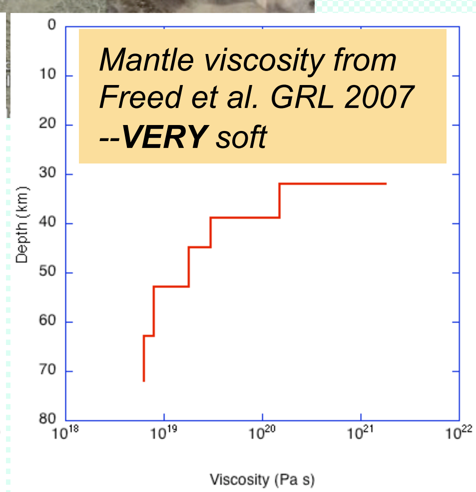


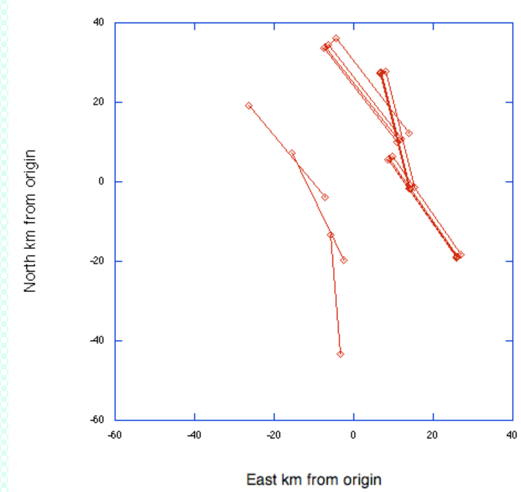
In progress:
Impose slip model for Landers 1992
Followed by Hector Mine 1999
Compare relaxation to GPS, InSAR

In conjunction with:
Validation of VE, refinement
Initial nonlinear VE study

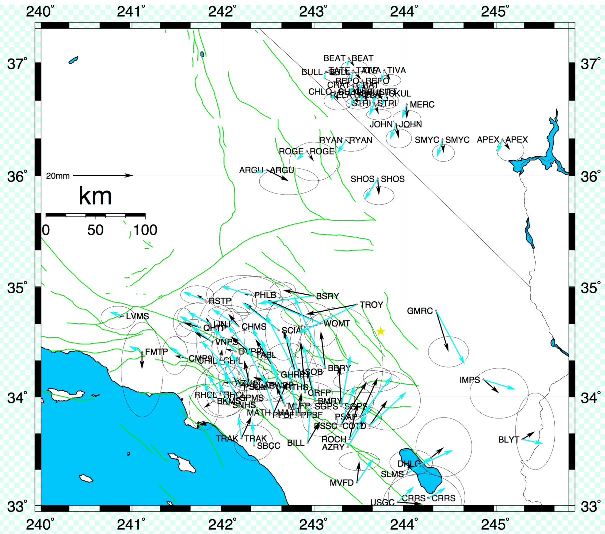






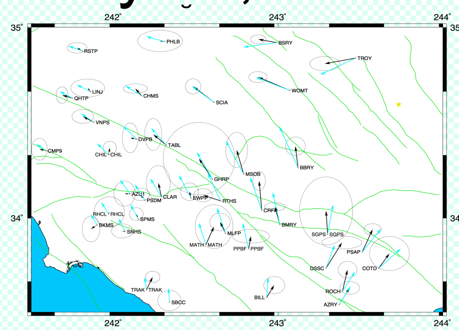


Hector Transient: Deep flow or deep slip?

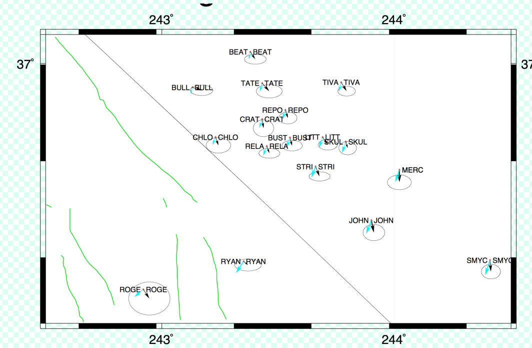


2008 Sep 24 16:30:43 Mojave GeoFEST model

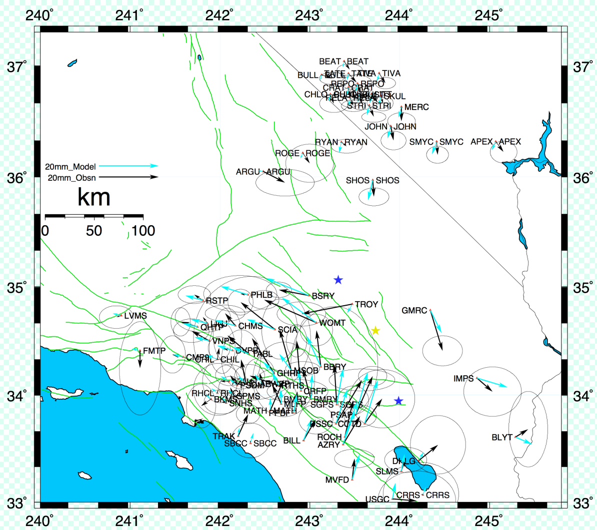
GeoFEST Model (10 layers, 6 faults)



2008 Sep 24 16:38:49 Mojave GeoFEST model



2008 Sep 24 16:36:22 Mojave GeoFEST model

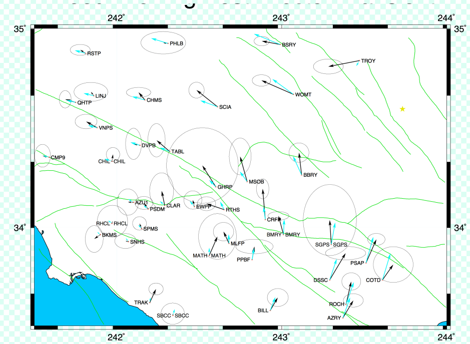


2008 Sep 25 18:04:45 Simplex ph5a: Deep Afterslip

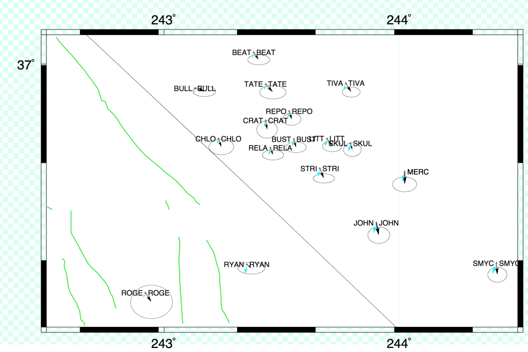
Elastic Half-space Model

1m slip from 17 to 80 km deep

140 km long fault under Hector mine



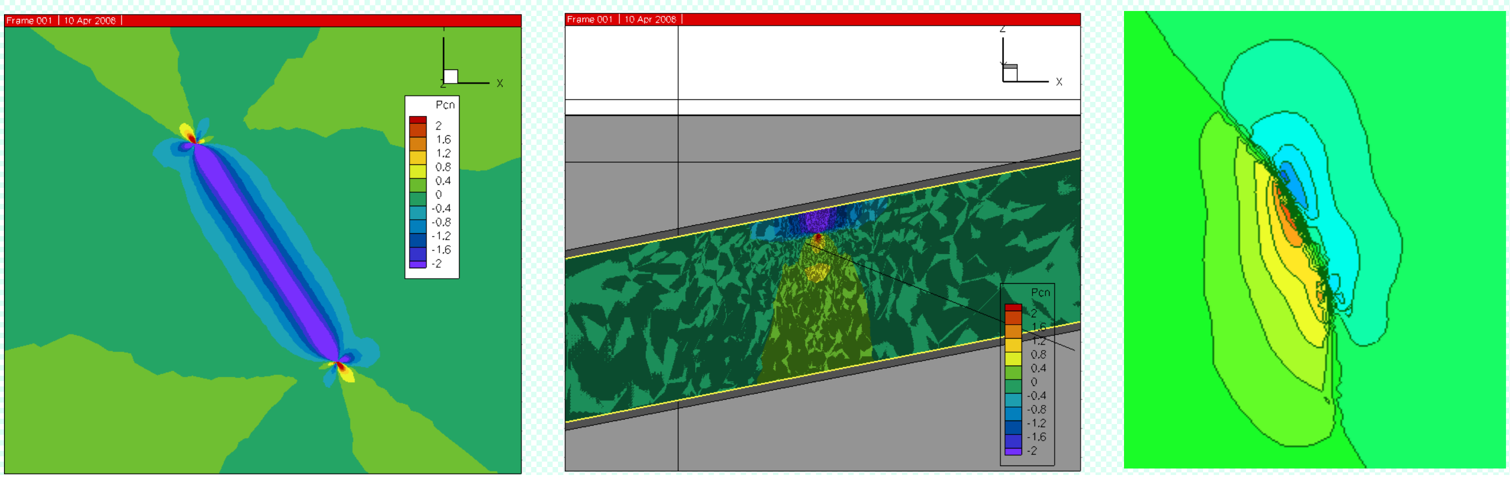
2008 Sep 25 18:03:36 Simplex ph5a: Deep Afterslip



2008 Sep 25 18:03:32 Simplex ph5a: Deep Afterslip

Summary

- GeoFEST now handles wrinkled faults, complicated layering
- Workflow for LaGriT meshes is becoming more routine
- Freely available source code: **Open Channel Foundation, GeoFEST v4.8**
- Scales well to very large problems, parallel supercomputers
- More robust features coming soon (nonlinear rheology, heat-dependent rheology, refinement options, stress-fail faults)
- Ideal for validation of fault geometry and rheology, stress transfer, anomaly detection and characterization



Left to right:Coulomb stress from uniform San Andreas model, top surface; same, at depth; Landers coseismic model, north displacement