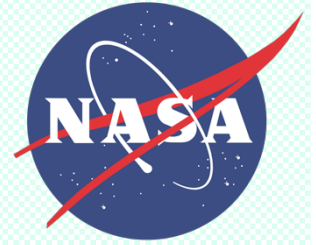
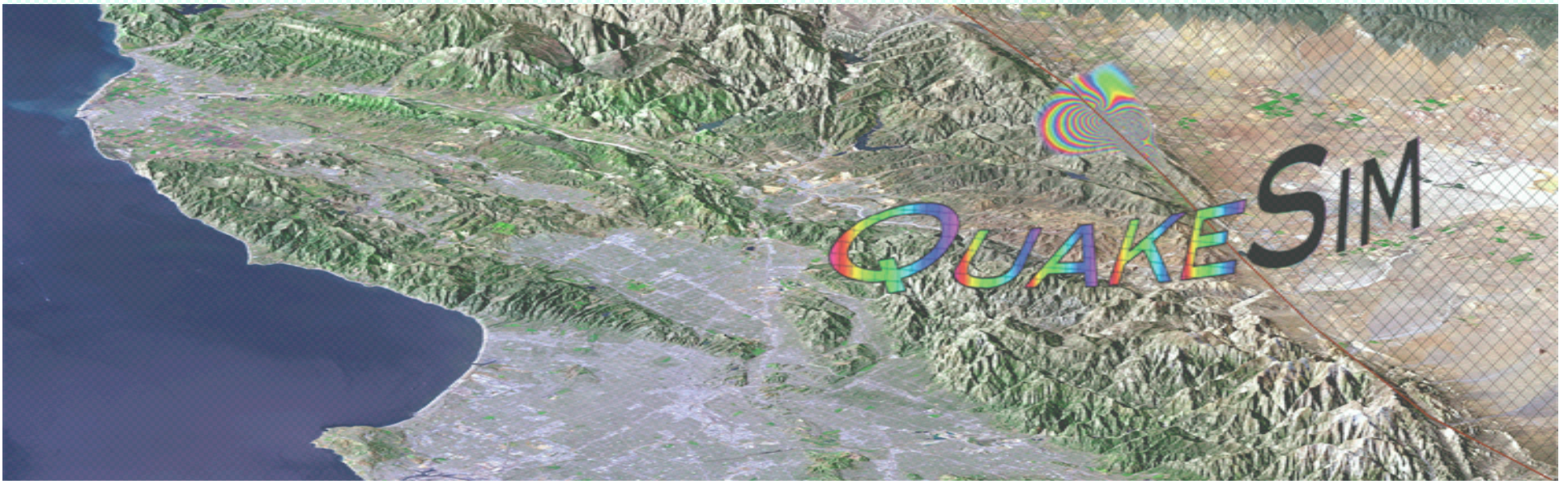


National Aeronautics and Space Administration



# Introduction to GeoFEST



Jay Parker

Geodynamics & Space Geodesy Group

Jet Propulsion Laboratory/California Institute of Technology



## Topics



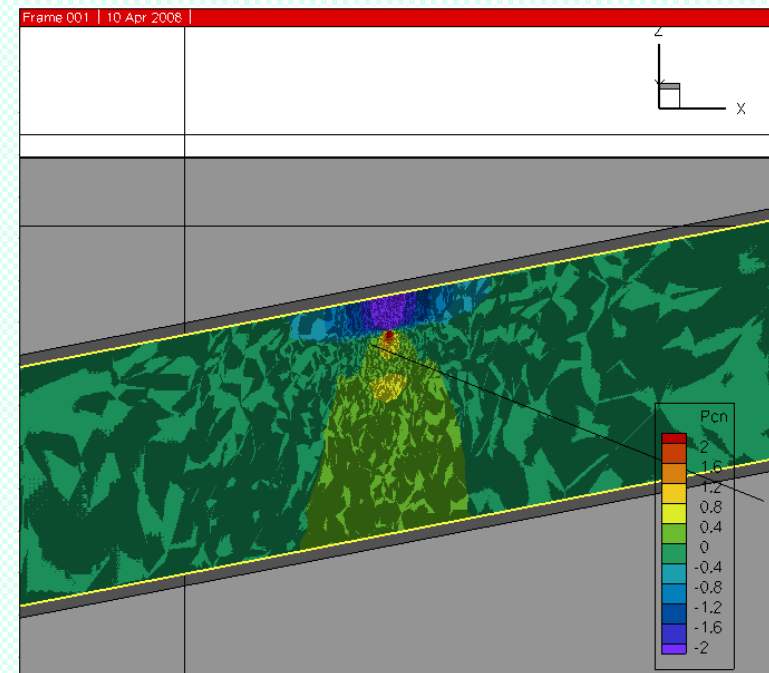
- QuakeSim Resources, California Faults
- Why use finite elements in geodesy
- What GeoFEST computes
- Parallel operation, refinement, accuracy
- Steps to creating your simulation
- California deformation simulations



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*



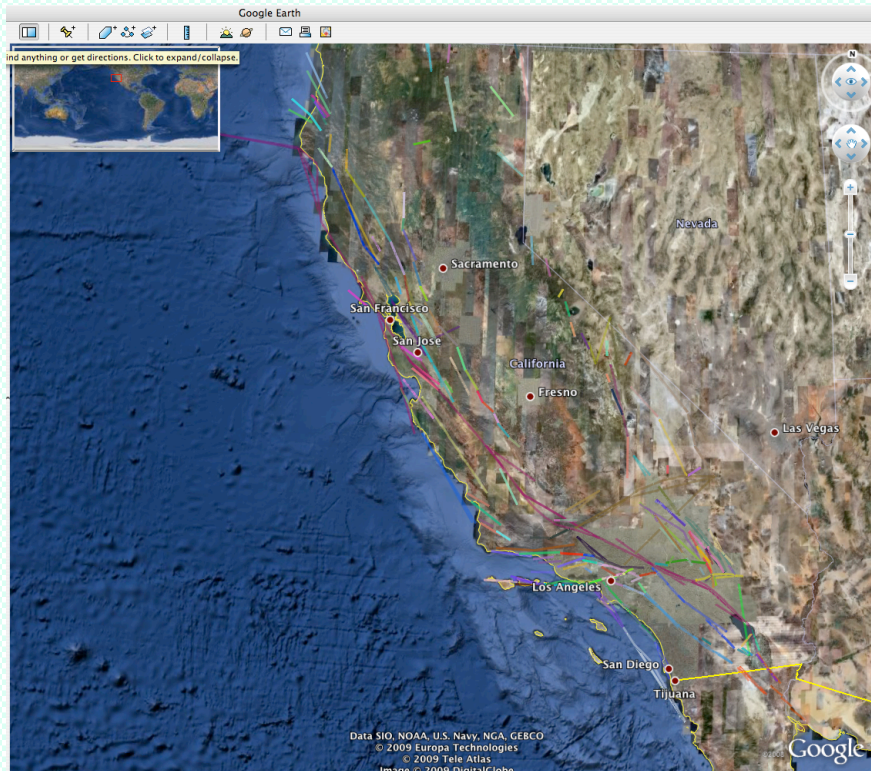




# QuakeSim Resources: QuakeTables



- QuakeTables: federated database of faults, data.



InSAR Interferogram Details

<http://gf19.ucs.indiana.edu:9898/main/interferogram.jsp?id=all>

Most Visited | ISERVO | SESI | GIPSY | Opinion | News | WebTools | Genealo | JPL | SW | Meshing | YouTube | Offortory... | Guest Internet Access

Download code | Page Load Error | QuakeSim | InSAR Interferogram Details

**QuakeTables**

Jet Propulsion Laboratory  
California Institute of Technology

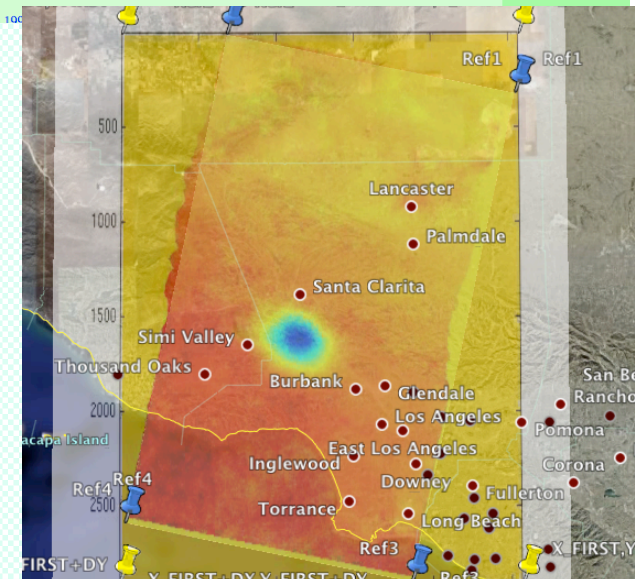
**QUAKE SIM**

Indiana University | Brown University | University of Southern California | UC Davis | UC Irvine

InSAR Database  
[Insert InSAR Data](#)

Last modified on 02/20/2008

Thumbnail	Title	Description	Download
	<a href="#">Northridge, California 1992-06-01 to 1995-07-19</a>	InSAR Image for Northridge, California by Paul Lundgren	<a href="#">metadata - data</a>
	<a href="#">Northridge, California 1992-09-14 to 1995-11-02</a>	InSAR Image for Northridge, California by Paul Lundgren	<a href="#">metadata - data</a>
	<a href="#">Northridge, California 100</a>		



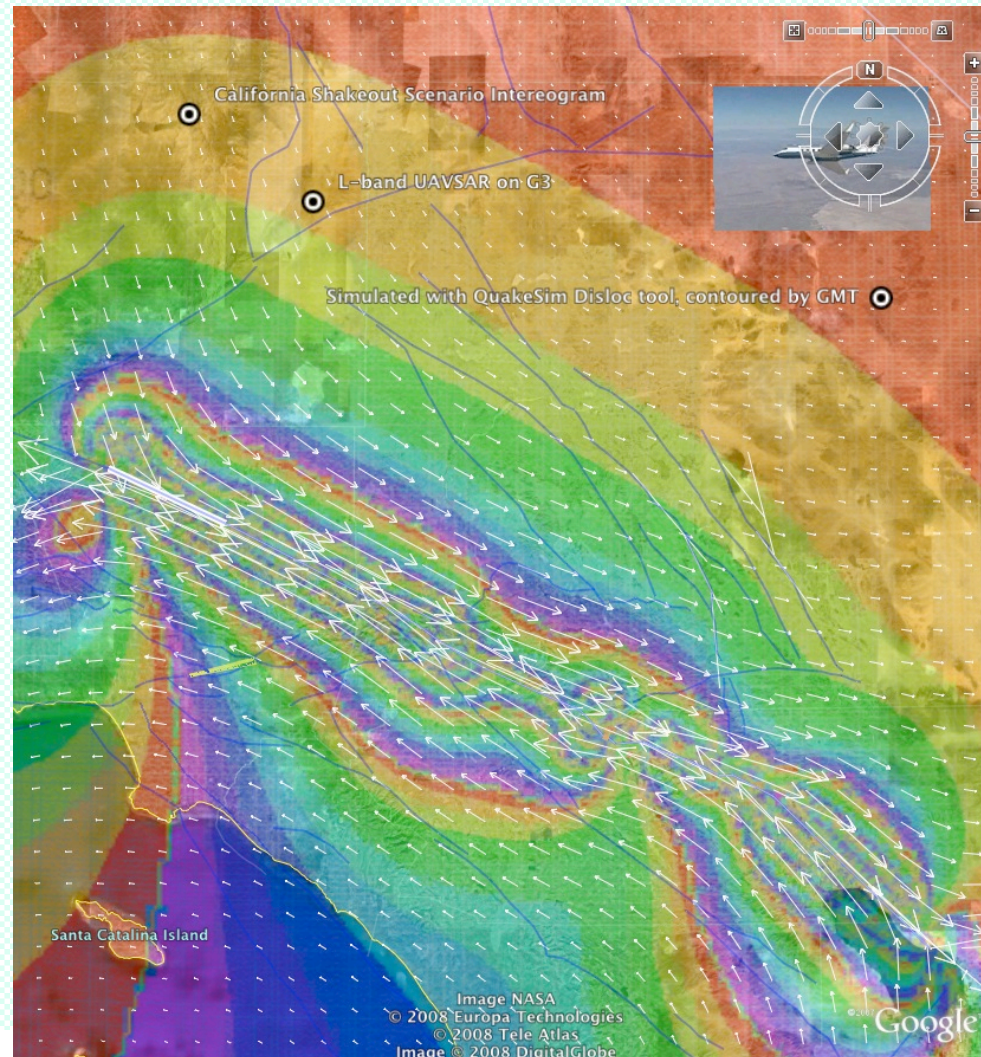




## Disloc Tool, Interferograms



- Great California Shakeout simulated interferogram

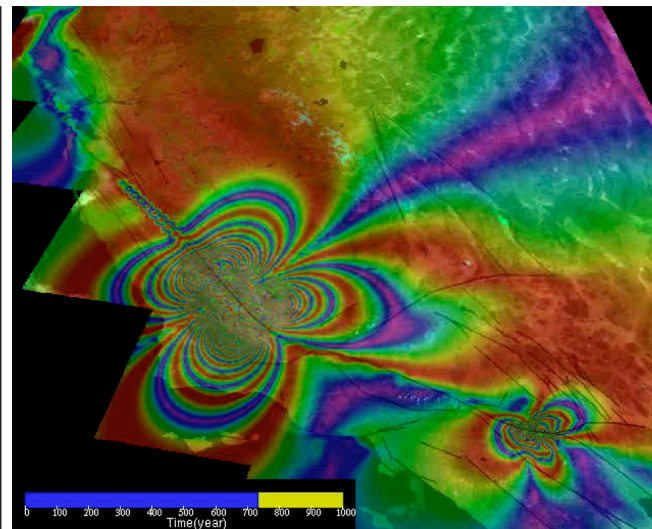
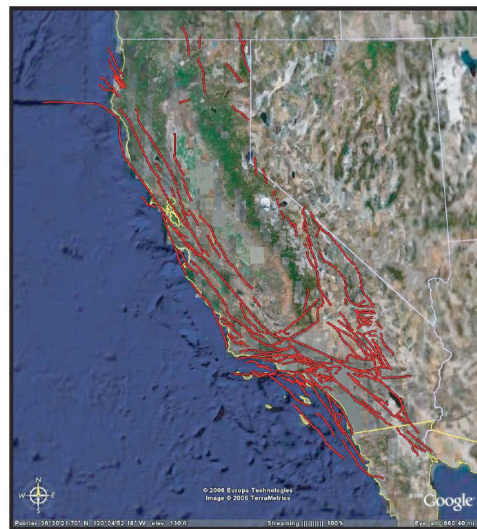




## QuakeSim Resources: VirtualCalifornia



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







# QuakeSim Resources: Forecast Scorecards

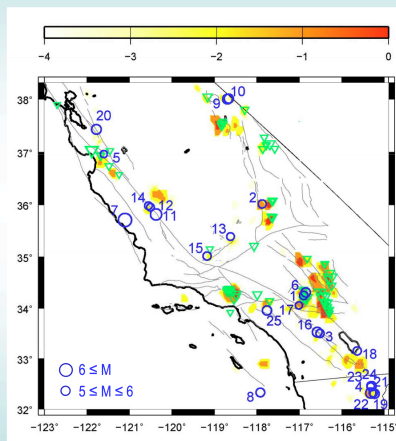


- PI method (Rundle)
- RIPI (Holiday)

## Status of the Real Time Earthquake Forecast Experiment (Original Version)

( JB Rundle et al., PNAS, v99, Supl 1, 2514-2521, Feb 19, 2002; KF Tiampo et al., Europhys. Lett., 60, 481-487, 2002; JB Rundle et al., Rev. Geophys. Space Phys., 41(4), DOI 10.1029/2003RG000135, 2003. <http://quakesim.jpl.nasa.gov> )

### How are We Doing? (Composite N-S Catalog)



### Plot of $\log_{10}$ (Seismic Potential)

Increase in Potential for significant earthquakes, ~ 2000 to 2010

Twenty-five significant earthquakes (blue circles) have occurred in Central or Southern California. Margin of error of the anomalies is  $\pm 11$  km; Data from S. CA. and N. CA catalogs:

After the work was completed

1. Big Bear I, M = 5.1, Feb 10, 2001

2. Coso, M = 5.1, July 17, 2001

After the paper was in press (September 1, 2001)

3. Anza I, M = 5.1, Oct 31, 2001

After the paper was published (February 19, 2002)

4. Baja I, M = 5.7, Feb 22, 2002

5. Gilroy, M=4.9 - 5.1, May 13, 2002

6. Big Bear II, M=5.4, Feb 22, 2003

7. San Simeon, M = 6.5, Dec 22, 2003

8. San Clemente Island, M = 5.2, June 15, 2004

9. Bodie I, M=5.5, Sept. 18, 2004

10. Bodie II, M=5.4, Sept. 18, 2004

11. Parkfield I, M = 6.0, Sept. 28, 2004

12. Parkfield II, M = 5.2, Sept. 29, 2004

13. Arvin, M = 5.0, Sept. 29, 2004

14. Parkfield III, M = 5.0, Sept. 30, 2004

15. Wheeler Ridge, M = 5.2, April 16, 2005

16. Anza II, M = 5.2, June 12, 2005

17. Yucaipa, M = 4.9 - 5.2, June 16, 2005

18. Obsidian Butte, M = 5.1, Sept. 2, 2005

19. Baja II, M = 5.4, May 23, 2006

20. Alum Rock, M=5.6, Oct. 30, 2007

21. Baja III, M = 5.4, Feb 9, 2008

22. Baja IV, M = 5.1, Feb 11, 2008

23. Baja V, M = 5.0, Feb 12, 2008

24. Baja VI, M = 5.0, Feb 19, 2008

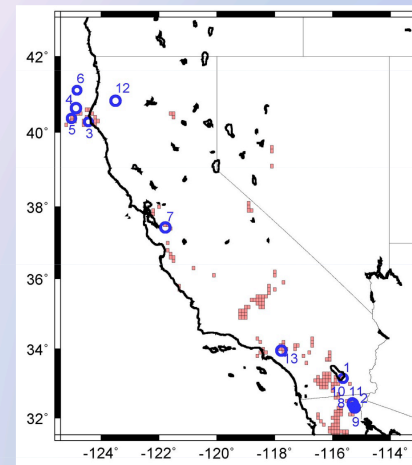
25. Chino Hills, M = 5.4, July 29, 2008

Note: This original forecast was made using both the full Southern California catalog plus the full Northern California catalog. The S. Calif catalog was used south of latitude 36°, and the N. Calif. catalog was used north of 36°. No corrections were applied for the different event statistics in the two catalogs. Green triangles mark locations of large earthquakes ( $M \geq 5.0$ ) between Jan 1, 1990 - Dec 31, 1999.

## New California Earthquake Forecast Scorecard

Map published in: JR Holliday et al., Seism. Res. Lett., v 78, Jan/Feb 2007 pp. 87-93

Red pixels (higher risk locations) are based on data up to August 31, 2005



Blue circles are earthquakes  $M > 5.0$  occurring after September 1, 2005 up to the present

(Dates and times are UTC)

1. Sept 2, 2005, M = 5.1
2. May 24, 2006, M = 5.4
3. July 19, 2006, M = 5.0
4. Feb 26, 2007, M = 5.4
5. May 9, 2007, M = 5.2
6. June 25, 2007, M = 5.0
7. Oct 30, 2007, M = 5.5
8. Feb 9, 2008, M = 5.4
9. Feb 11, 2008, M = 5.1
10. Feb 12, 2008, M = 5.0
11. Feb 19, 2008, M = 5.0
12. April 29, 2008, M = 5.4
13. July 29, 2008, M = 5.4

Mean Forecast Error =  $7 \pm 16$  km  
@ 1.2% forecast area coverage

For  $M > 6.0$  EQs, N. California is now at HIGHER Risk  
For  $M > 6.0$  EQs, S. California is now at LOWER Risk

Temporal risk is calculated using the method published in JR Holliday et al, Phys. Rev. Lett., v97, p 238 (2006)



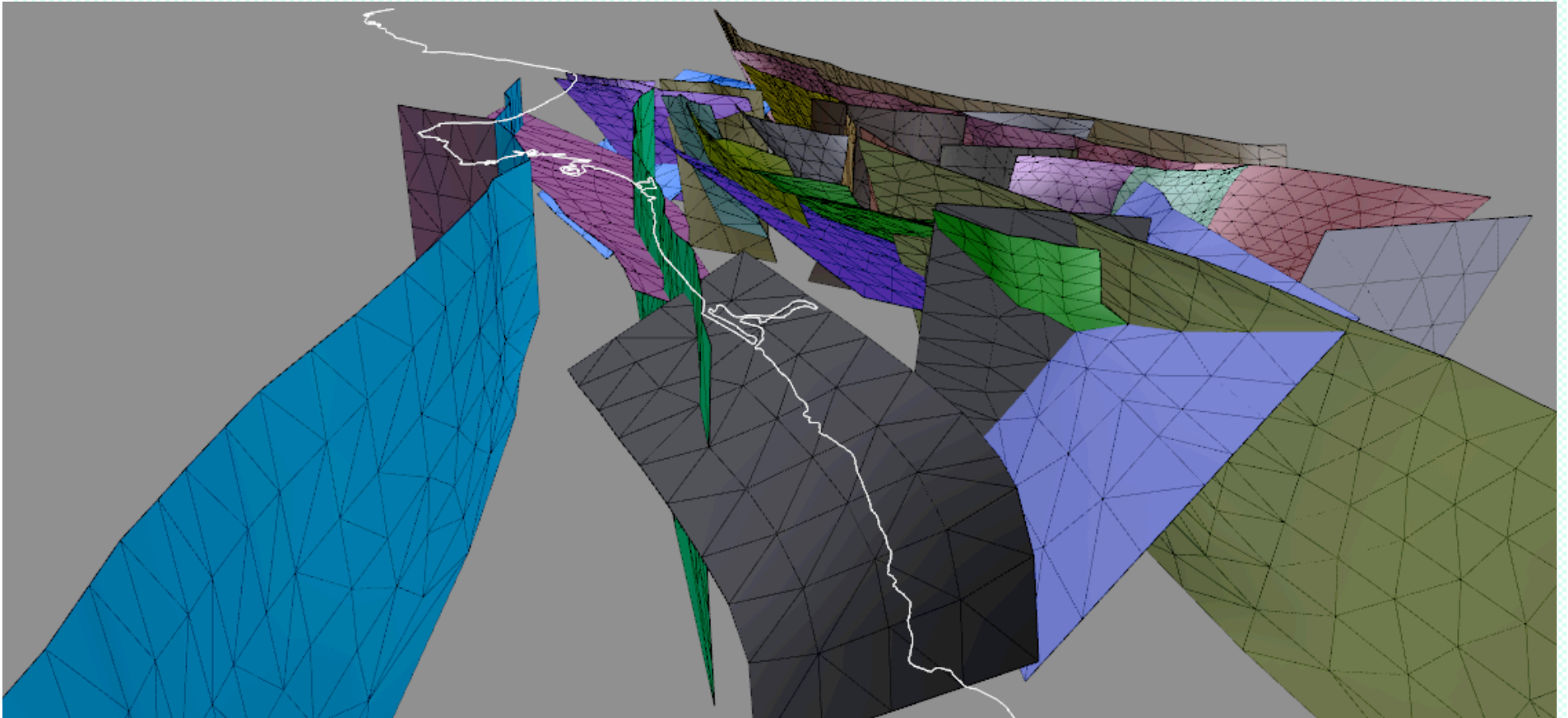




## Why use finite elements in geodesy?



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

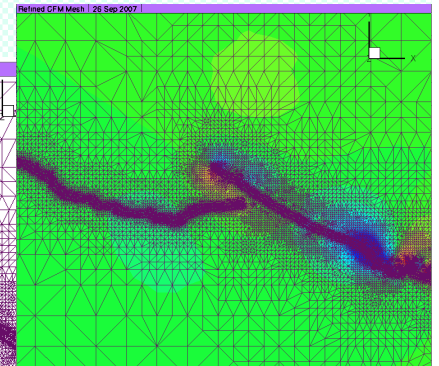
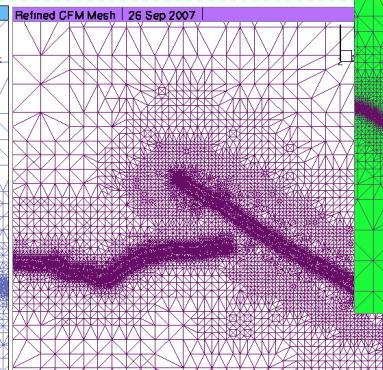
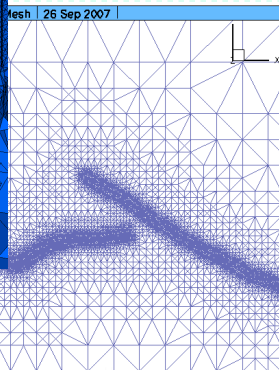
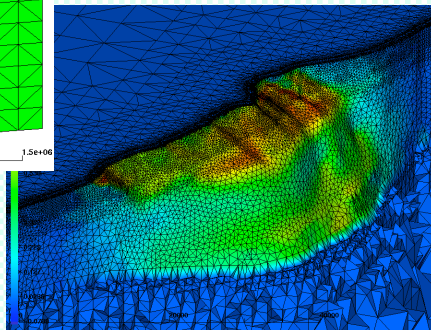
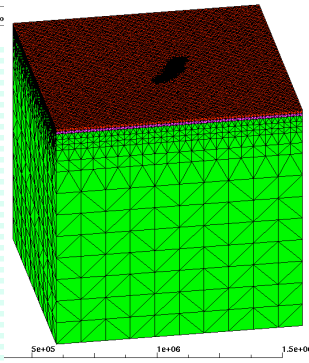
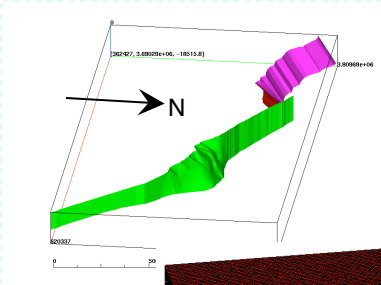




GeoFEST is . . .



- GEOphysical Finite Element Simulation Tool
- 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

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

Isotropic material

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

Viscoplastic strain rate

$$\frac{\partial \epsilon_{ij}^{vp}}{\partial t} = \beta_{ij}(\sigma_{ij}),$$

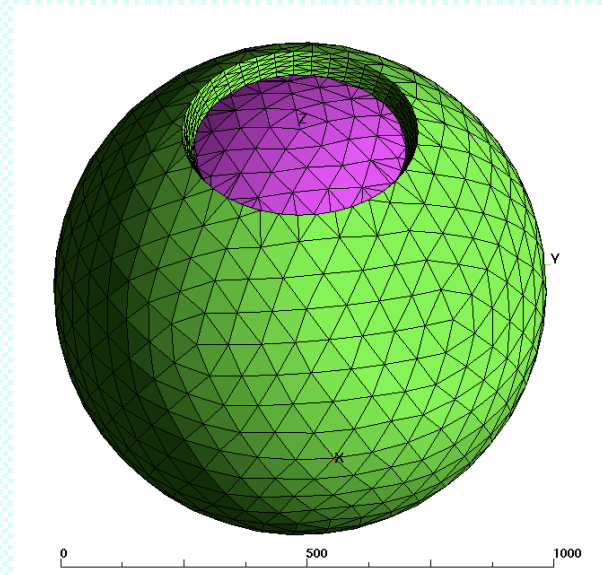
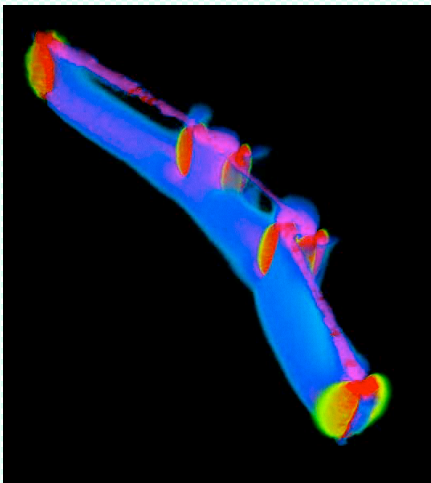
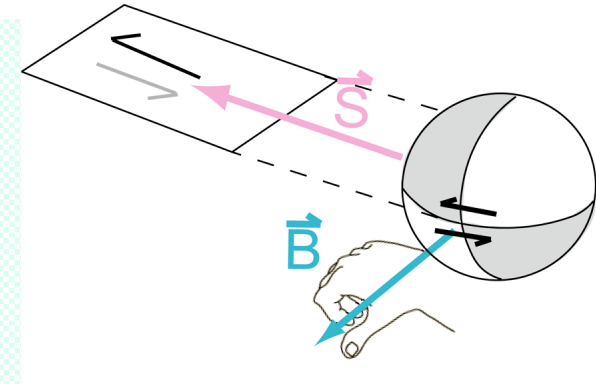
*... so materials have lame parameters, viscosity, and body force*



## What GeoFEST computes (2)



- Imposed fault slip
- Buoyant response
- Strain Energy





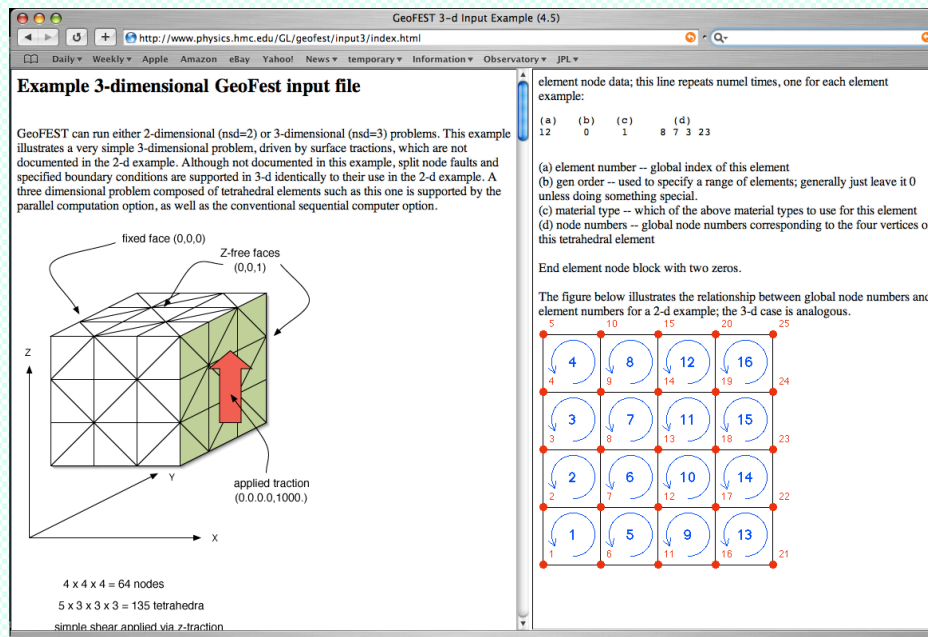


# GeoFEST learning materials



- 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

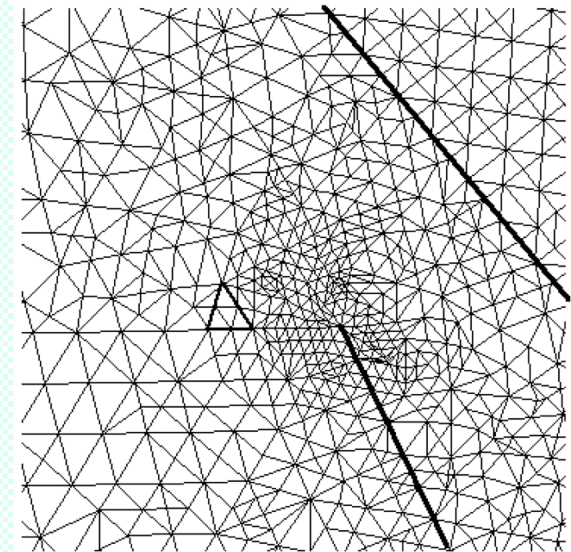
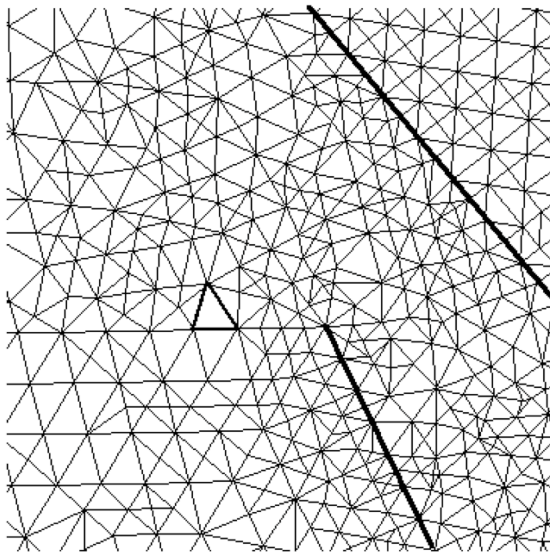






# GeoFEST/PYRAMID

## Refinement near Landers step

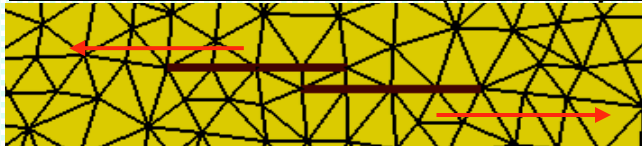




# Adaptive Meshing

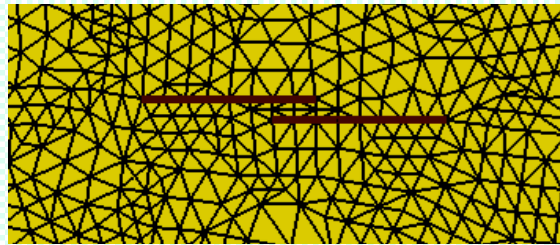


Initial surface mesh (center portion):

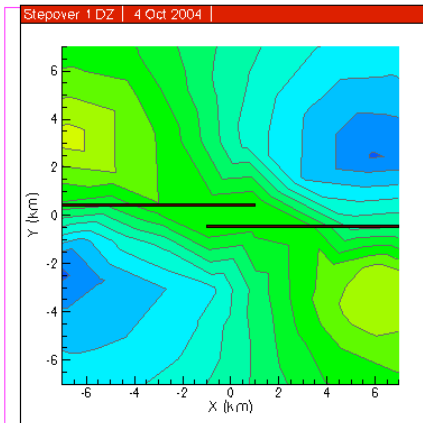
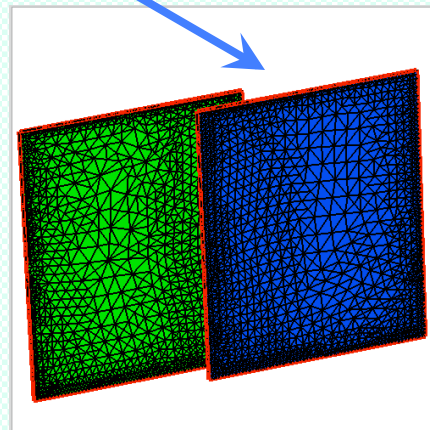
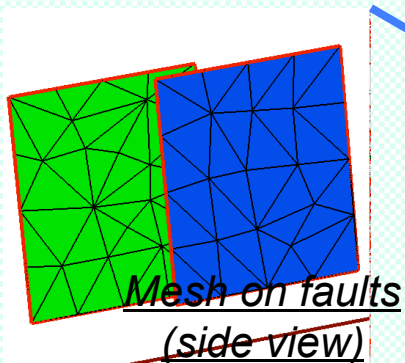


- guiVISCO method (preprocess)
- PYRAMID parallel library (NASA ESTO CT Project)

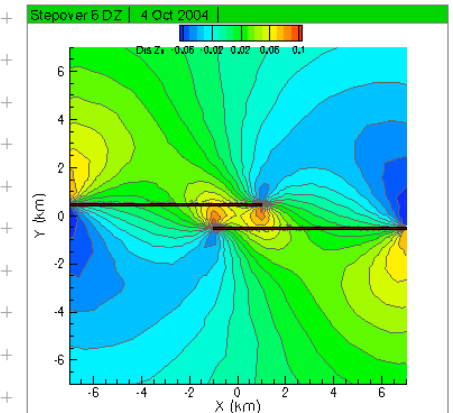
Obtain elastic solution  
Strain energy,  
Refine



- Changes mesh after import to cluster
- Strain energy guides 3D refinement



Z component at surface  
Refinement cycles 1 and 6



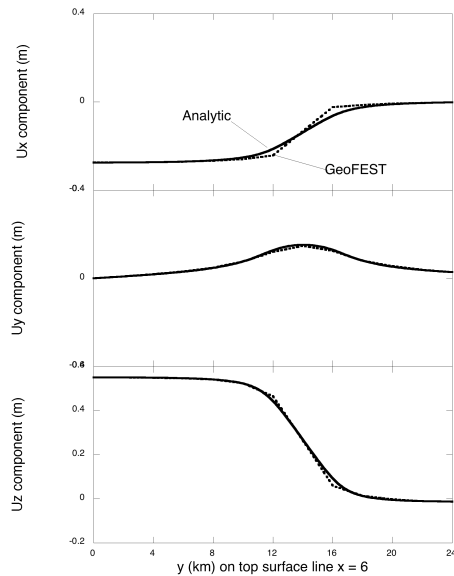
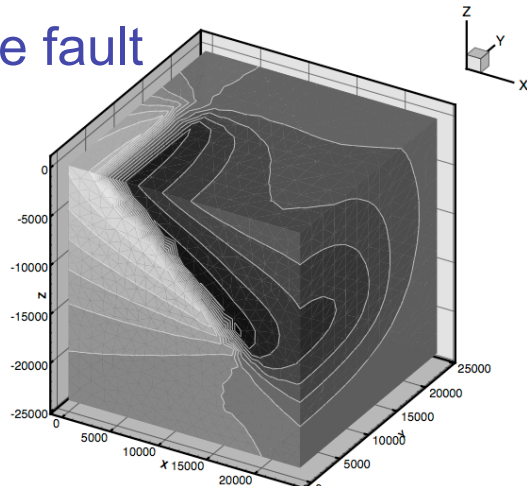




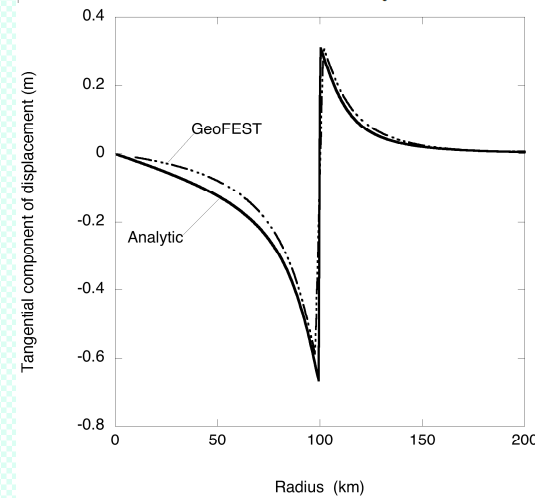
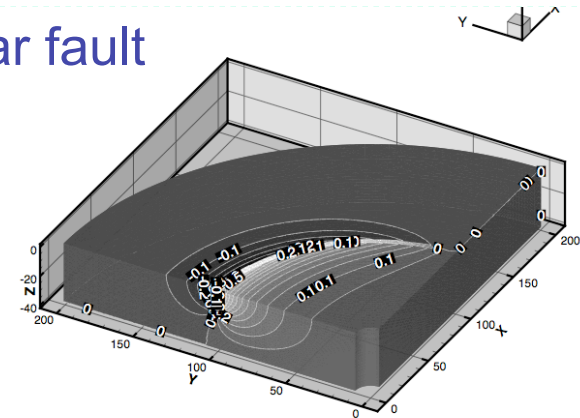
# CFEM Workshop Cases



## 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/

Most Visited | iSERVO | SESI | GIPSY | Opinion | News | WebTools | Genealo | JPL | SW | Meshing | YouTube - Offertory... | Guest Internet Access

Los Alamos National Laboratory

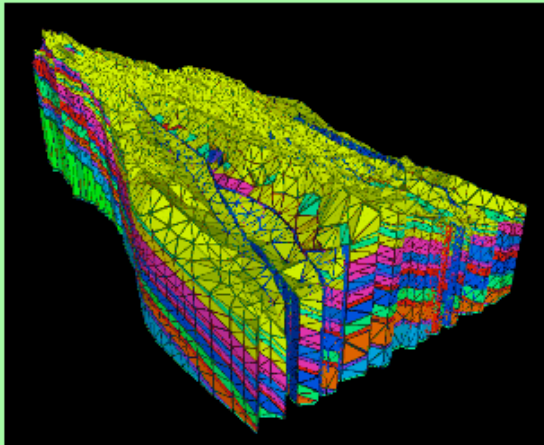
Lab Home | Phone | Search

# LaGriT: Meshing for Geological Applications

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

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

### Tetrahedral Grid Yucca Mountain Unsaturated Zone



[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 computations 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 \(PDF\)](#).

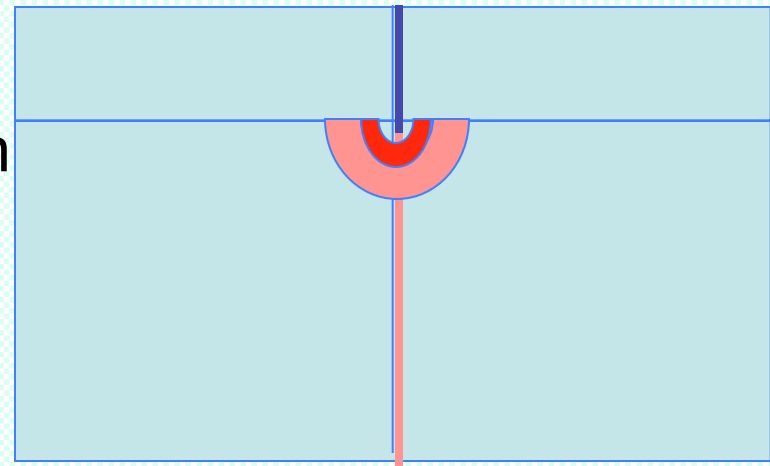
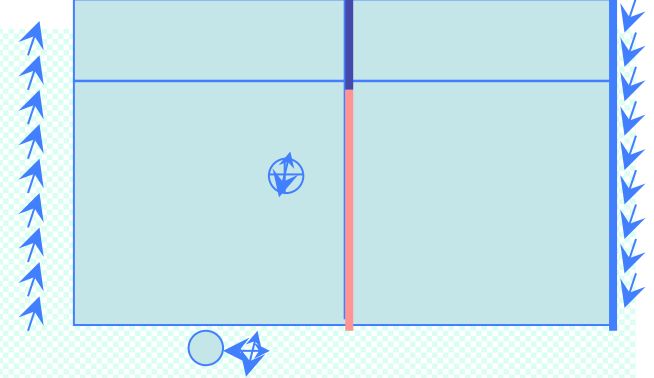




## Simple San Andreas - new issues



- 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

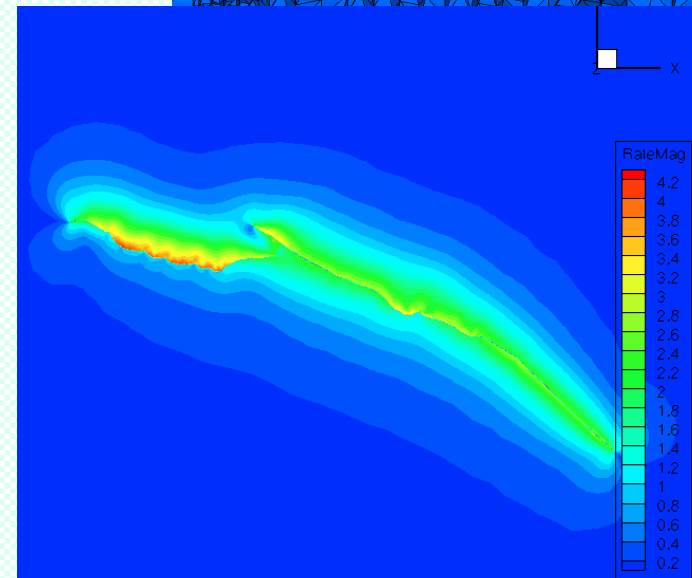
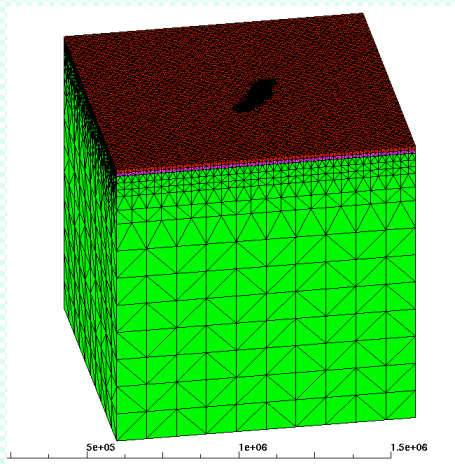
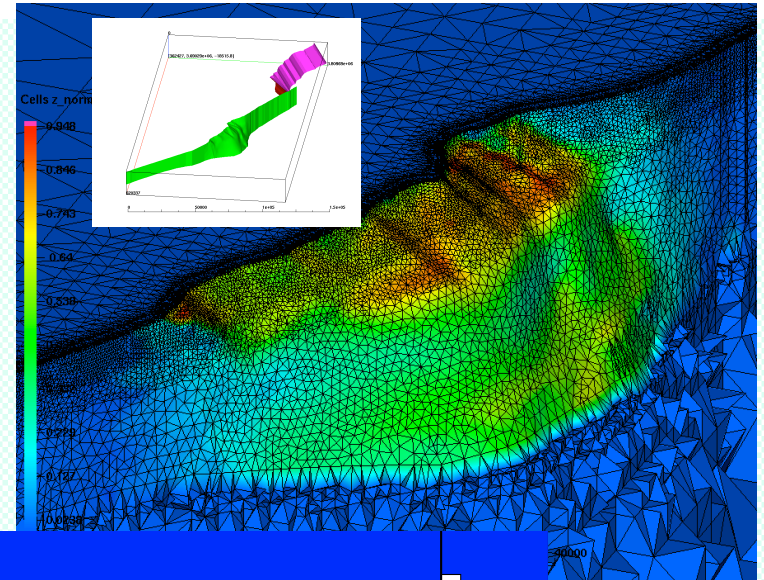




# New Wrinkle: CFM/LaGriT San Andreas Fault



- 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.



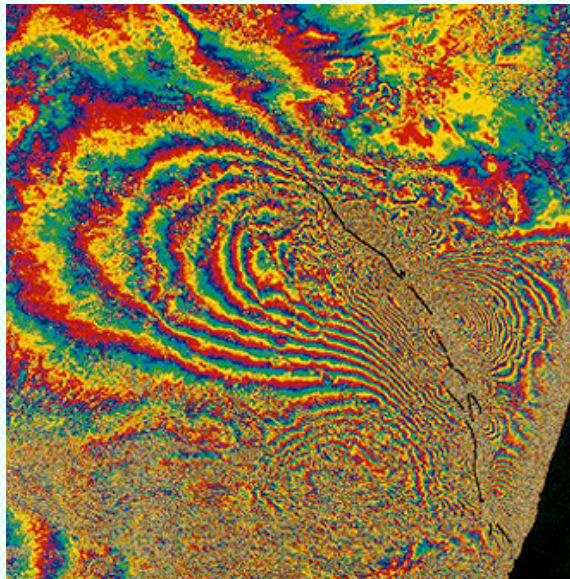




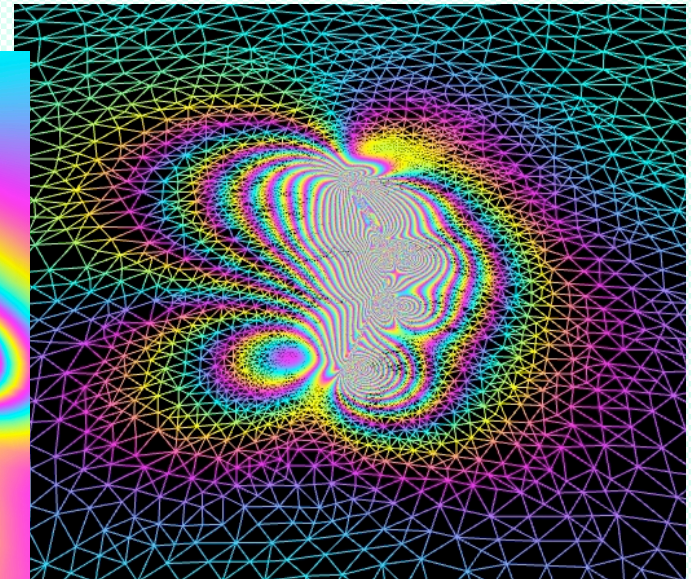
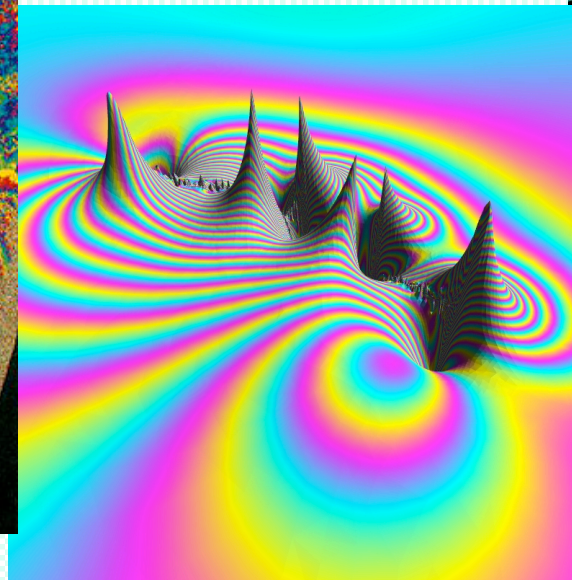
## Simulated ERS-1 InSAR fringe



- 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*

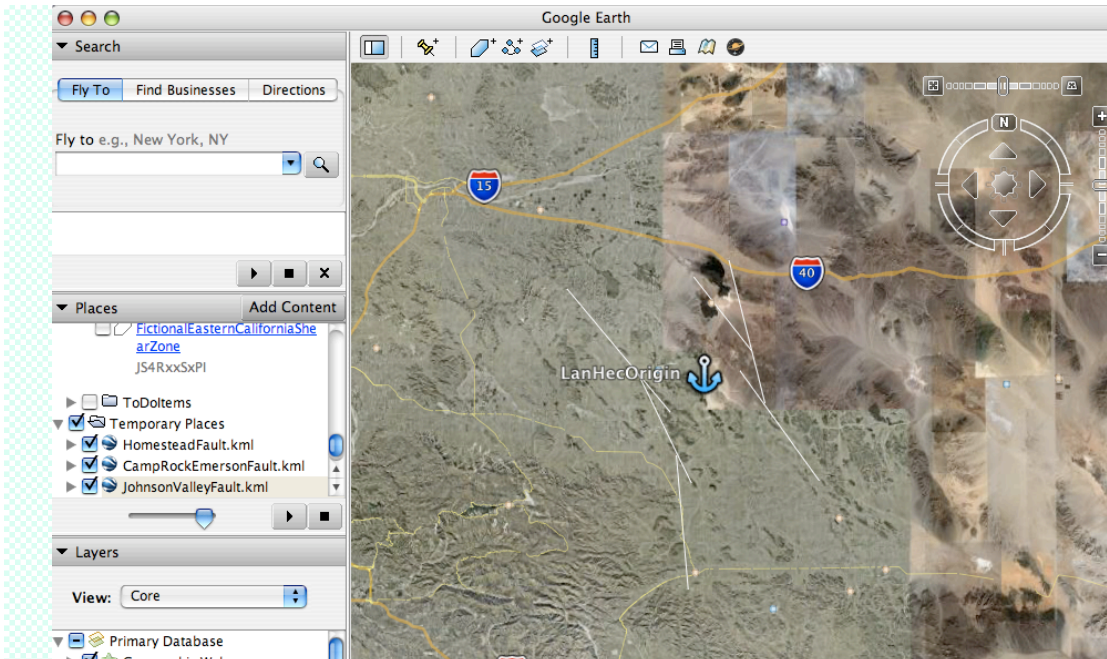


*Work with Chris Henze, NASA Ames Research Laboratory*





# Mojave study

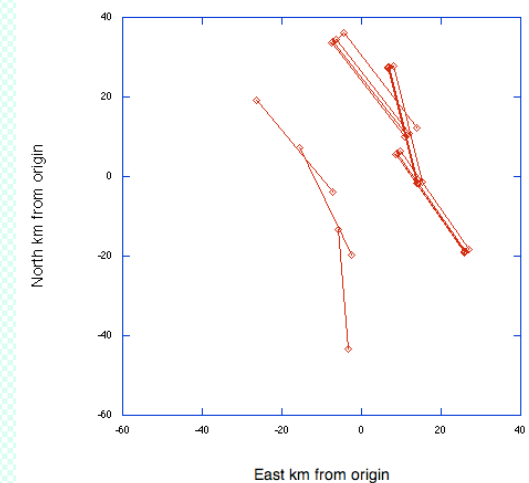
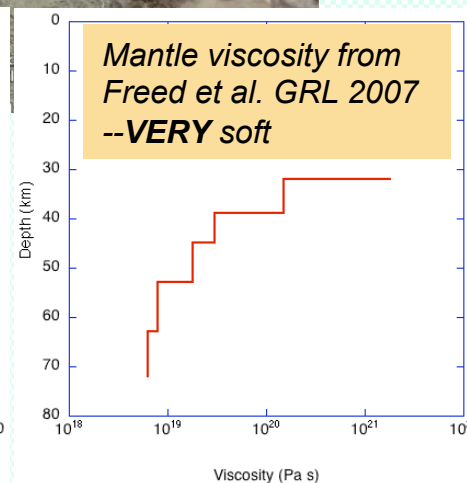
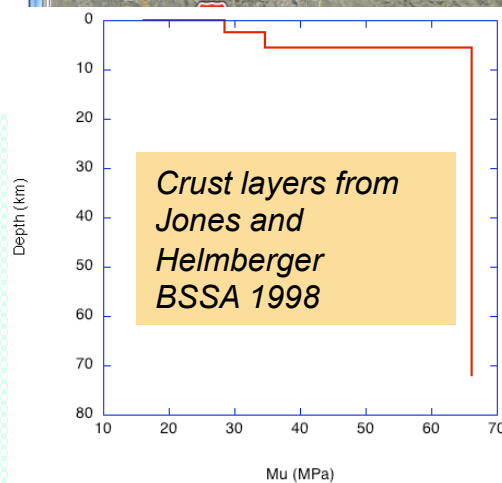


*In progress:*

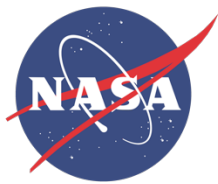
Impose slip model for Landers 1992  
Followed by Hector Mine 1999  
Compare relaxation to GPS, InSAR

*In conjunction with:*

Validation of VE, refinement  
Initial nonlinear VE study



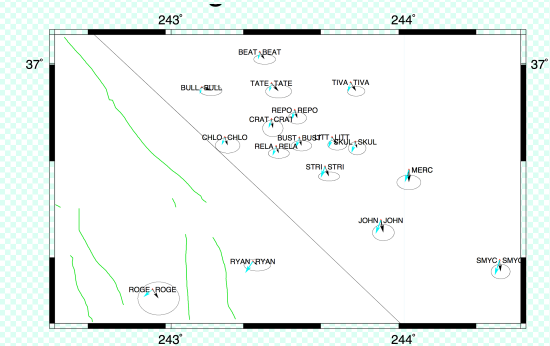
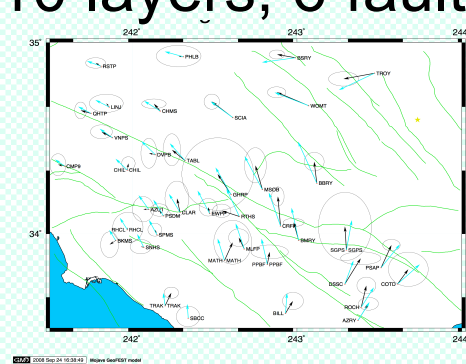
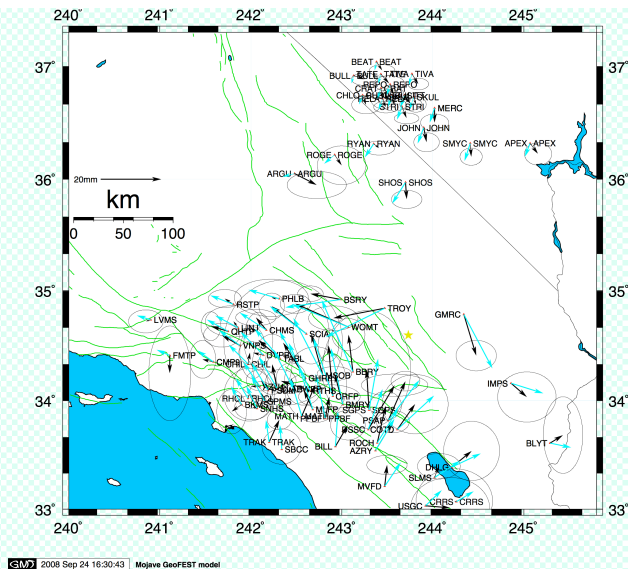




# Hector Transient: Deep flow or deep slip?



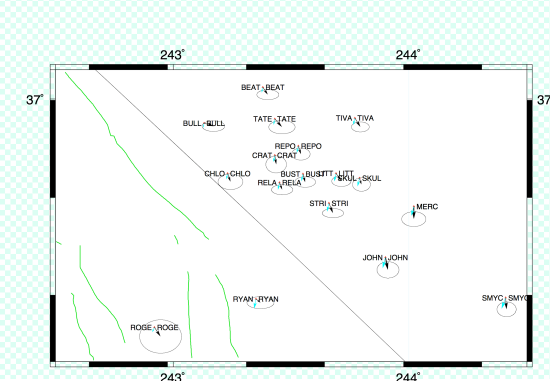
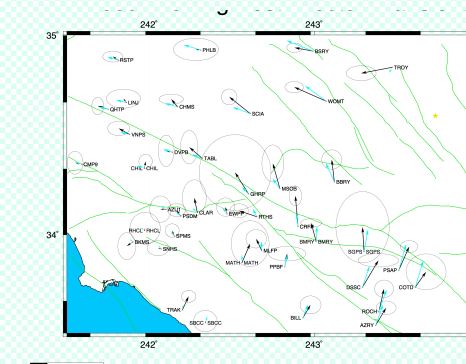
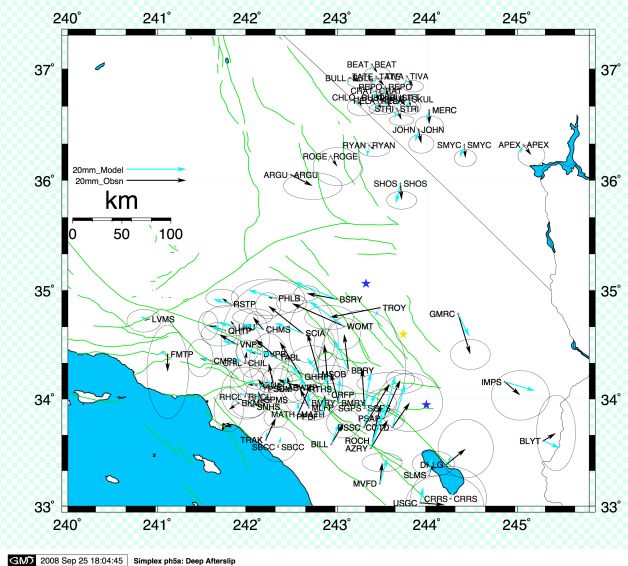
## GeoFEST Model (10 layers, 6 faults)



2008 Sep 24 16:30:43 Mojave GeoFEST model

2008 Sep 24 16:36:22 Mojave GeoFEST model

## Elastic Half-space Model 1m slip from 17 to 80 km deep 140 km long fault under Hector mine



2008 Sep 25 18:04:45 Simplex phis: Deep Alterity

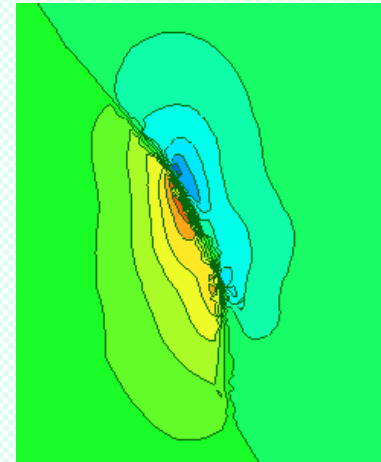
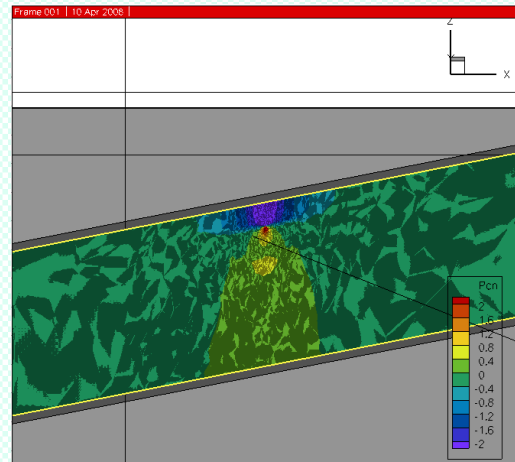
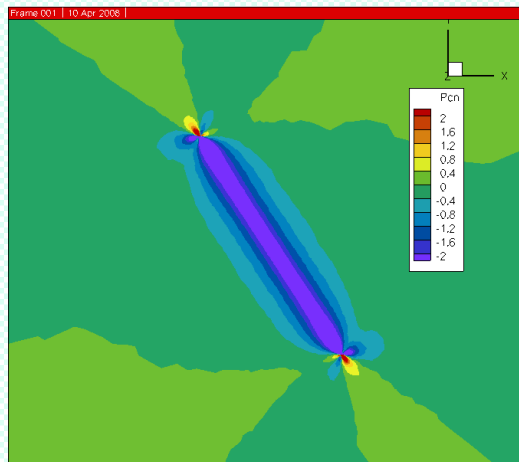
2008 Sep 25 18:03:32 Simplex phis: Deep Alterity



## 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