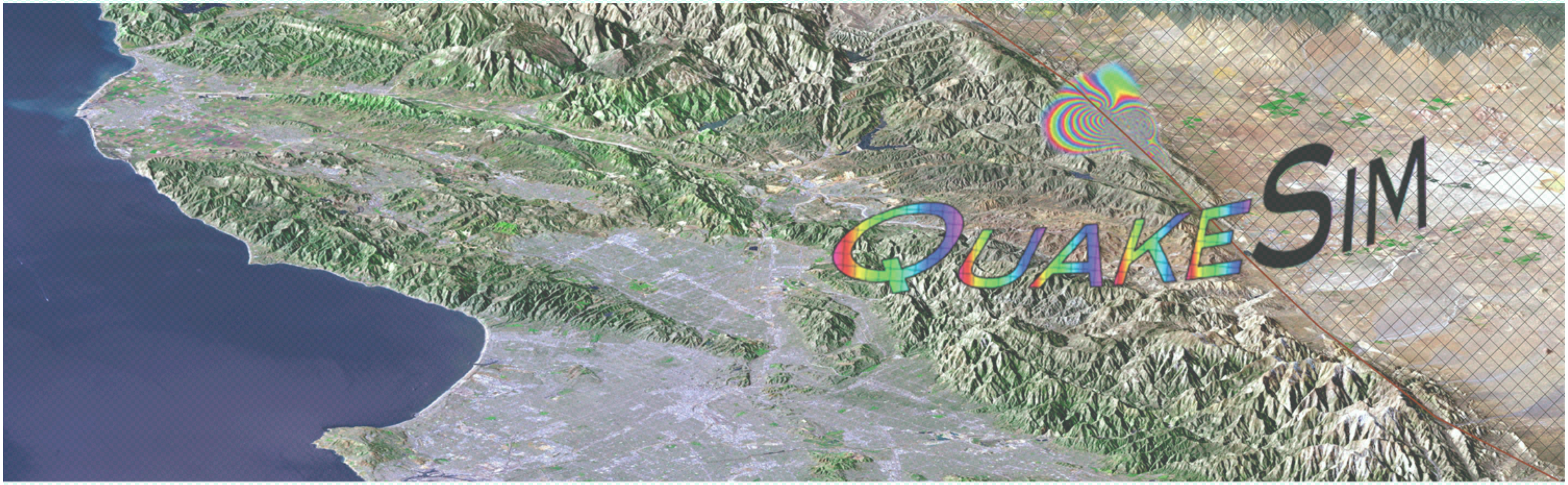
GeoFEST: Adaptive Meshing, Portal use



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(contributions from
Margaret Glasscoe, Andrea Donnellan)
Jet Propulsion Laboratory, California Institute of Technology

GeoFEST contributors

QuakeSIM

- Supported by the Computational Technologies Program of NASA's Earth Science Technology Office, http://ct-esto.jpl.nasa.gov/
- Project Principal Investigator -- *Andrea Donnellan*
- Management and Coordination -- *Michele Judd*
- guiVISCO object composer and mesher - *Jin-fa Lee (Ohio State)*
- PYRAMID, MPI Integration -- *Charles Norton, Edwin Tisdale*
- Validation -- *Cinzia Zuffada*
- Visualization -- *Peggy Li*
- Web Portal -- *Marlon Pierce (U. of Indiana)*

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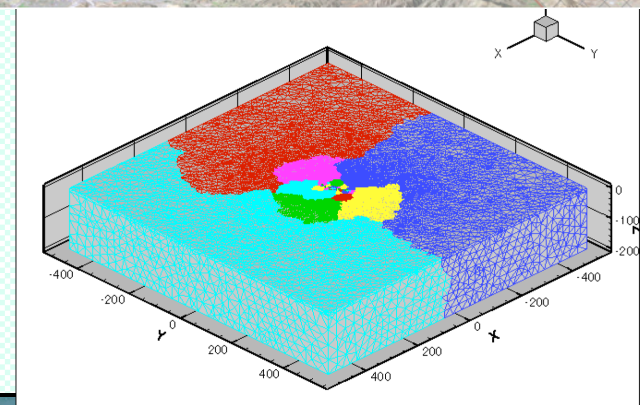
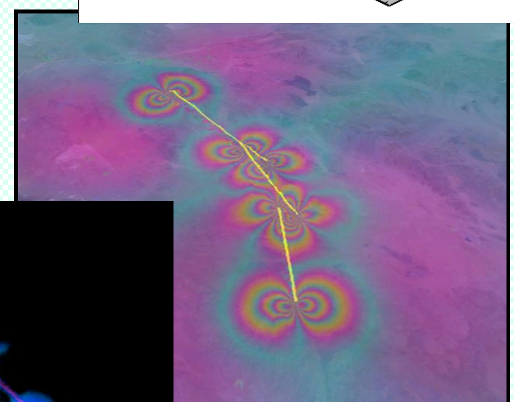
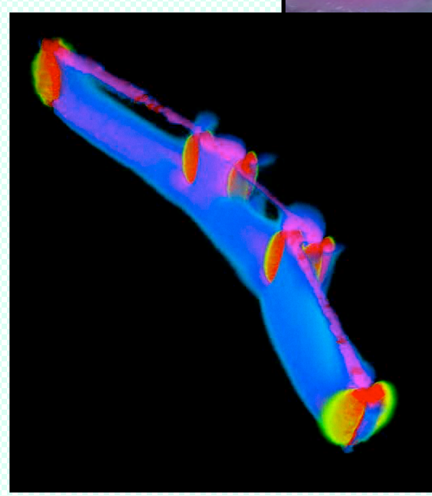
Why Mesh Refinement

- Why Stress/Strain, why Finite Elements
- Southern California settings, flexible meshing
- Parallel performance scaling for unstructured elements
- Cost of various mesh strategies
- Validation of fault stepover, refinement with strain energy





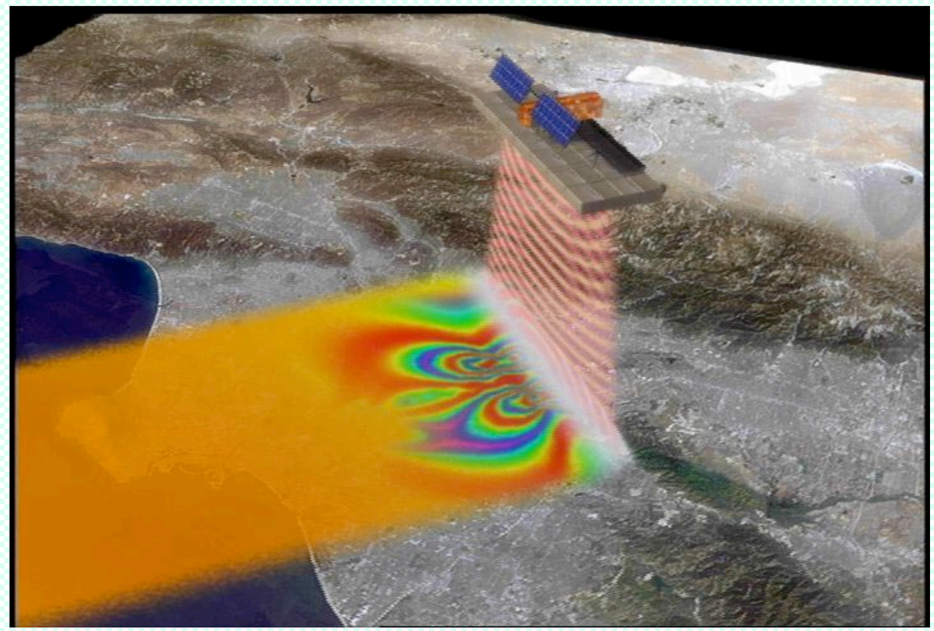


Why Stress/strain finite elements

- Earth Science is becoming pattern of *Monitor-Model-Assess-Predict*.
- New missions will generate 10 to 20 TB per week.

--Earth Science Enterprise Computational Technology Requirements Workshop, NASA, 2002

- Scales of earthquake sources span *eight* orders of magnitude (~fractal)
- Optimal use of data requires fit to a model
- Finite element mechanics fills key niche:
  - --couples to other methods (BE, . . .)
  - --approximate parameterizations (damage rheology, . . .)



Los Angeles Basin Compression

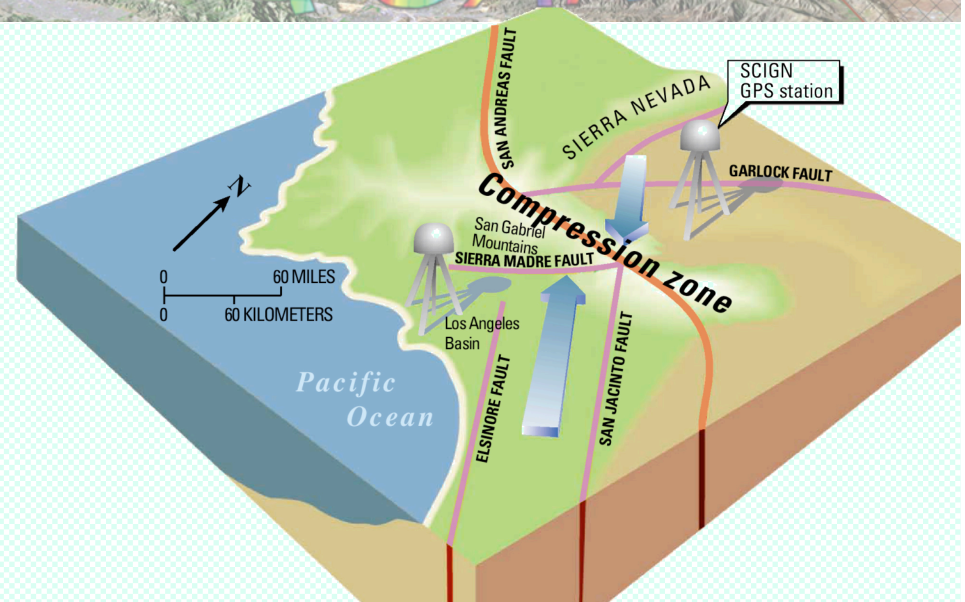
Demonstrate technology:

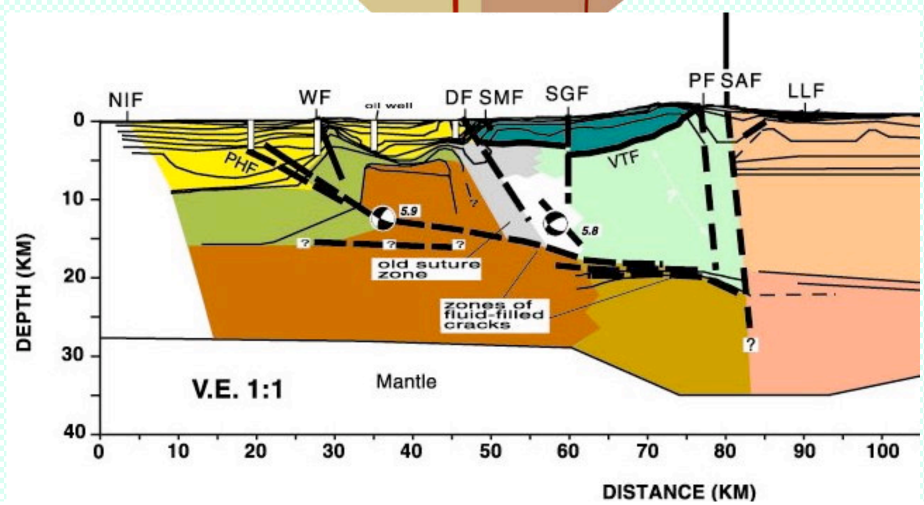
- Parallel AMR,
- >16 million finite elements,
- > 1000 time steps

Jointly match data:

- SCIGN velocity features
- Known fault rates
- Known mountain growth

--In progress.





Landers Event

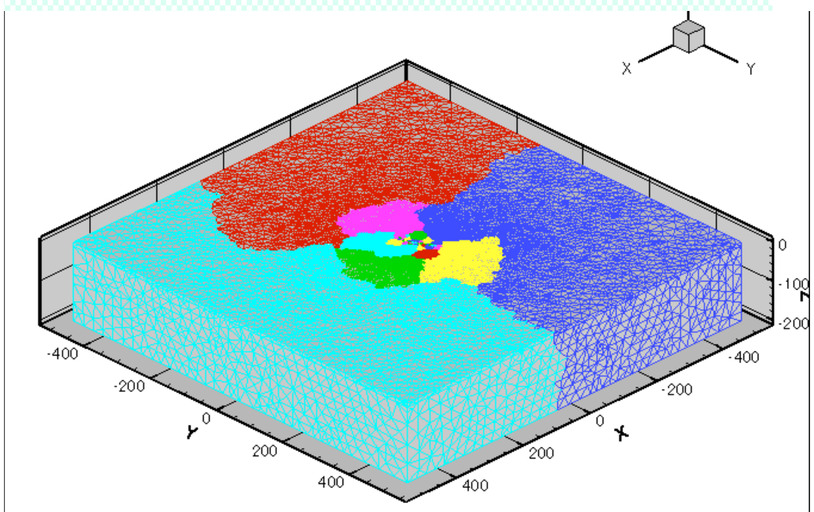
Vertical Faults, Finite Element Nodes

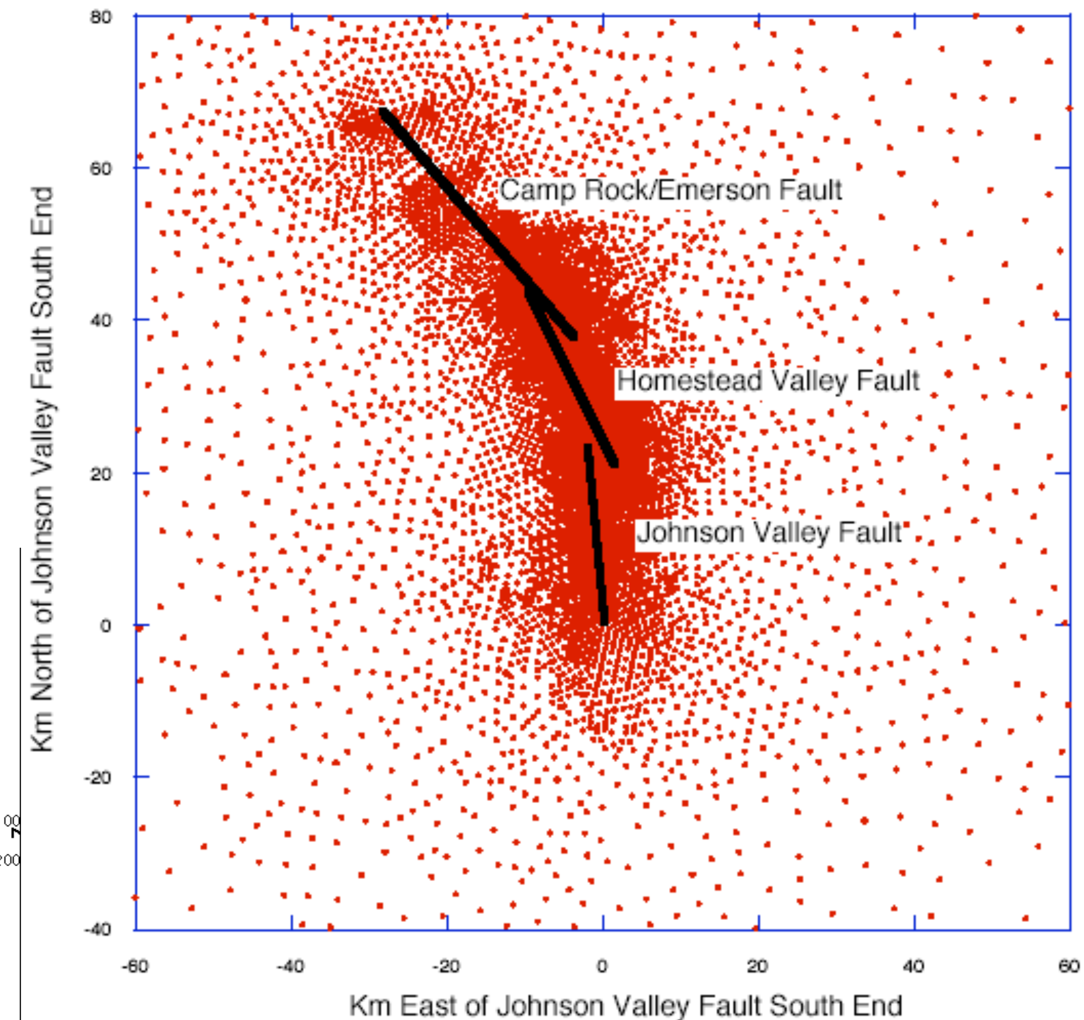
Demonstrate technology:

- Parallel AMR,
- >10 million finite elements,
- > 1000 time steps

Simulate event:

- Stress transfer
- Match GPS-observed regional relaxation





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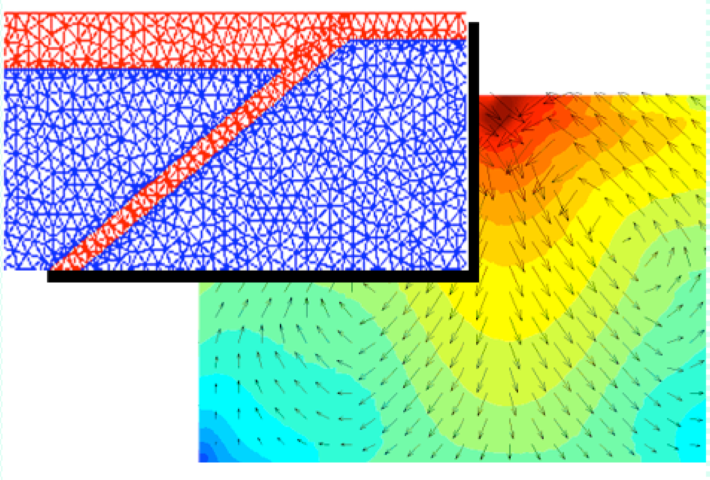
What is GeoFEST?

Geophysical Finite Element Simulation Tool

- Finite elements for elastic/viscoelastic stress, strain
- Unstructured 3-D meshes, material variations
- Fault dislocations and geophysical sources
  - *—stress-triggered fault slip*
  - *—non-Newtonian viscosity*
  - *—gravity, buoyancy*
- Support/development for
  - *—parallel computing*
  - *—adaptive mesh refinement*
  - *—visualization*
  - *—web computing*



GeoFEST Equations

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; Recently added buoyancy, surface tractions.

Two modes for using GeoFEST

QuakeSim

QuakeSim Web Portal

+ Can do full projects in browser
+ No code port required
+ Runs remote jobs simply

— Under development

OpenChannel Download

+ GeoFEST, Pyramid full source
+ Can debug at any level
+ Runs on many platforms

— Compiler required

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GeoFEST Problem Definition

Faults, Layers

Solid Geometry

Tetrahedral Mesh

Simulation Specification

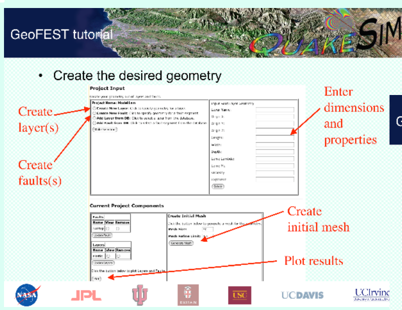
Material Properties

Boundary Conditions

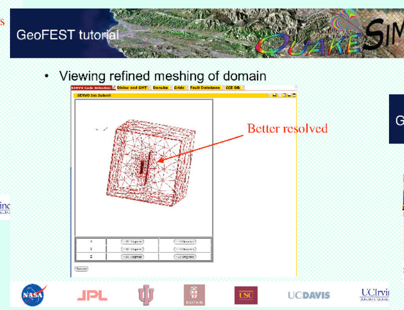
Input File

Run GeoFEST

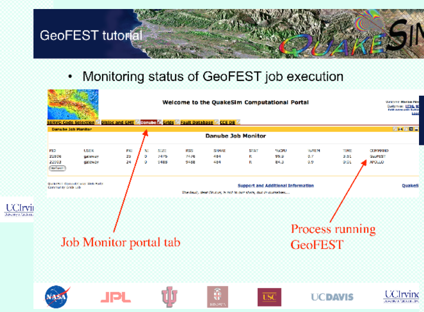
Visualization



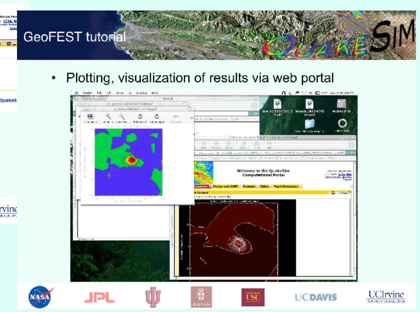
Setting geometry (QuakeTables fault database)



Mesh generation



GeoFEST simulation, job sumbission and control



Quick-view visualization

CT Project Milestones, Challenges

<u>*Baseline milestone (8/02):*</u>

- 50,000 elements, 1000 time steps
- Sequential execution in 13.8 hours

<u>*Parallel milestone (9/03):*</u>

- 1.25 million elements, 1000 time steps
- 64 processor Linux cluster in < 13.8 hours
  (attained 2.8 hours)

<u>*Final milestone (nominally 6/04):*</u>

- 16 million elements, 1000 time steps
- ~100's processor cluster in < 13.8 hours
- Demonstrate adaptive mesh refinement

<u>*The challenge: how costs scale*</u>

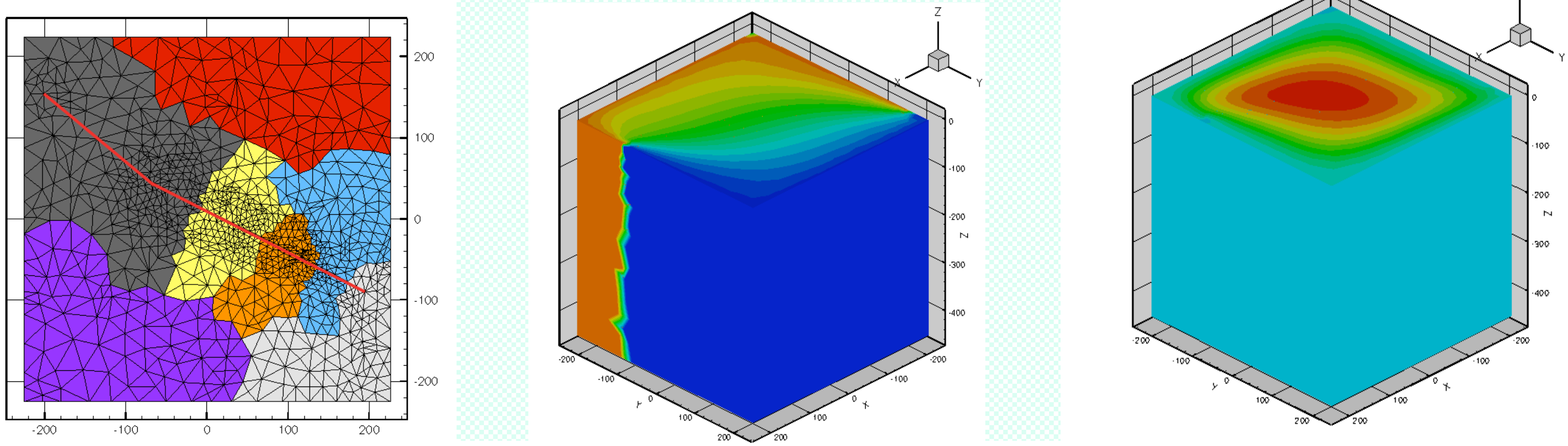
- File size: ~21 * Elements (compressed ASCII)
- Transfer time: ~3e-6 s * Elements (local network)
- Preprocessing: ~Elements
- Cluster memory: ~1e4 bytes*Elements
- Solve time: ~steps*$(\text{Elements})^{4/3}$/Processors

Pyramid Parallel Unstructured Adaptive Mesh Refinement Library

QUAKESIM

- A FORTRAN90-based software library
- For parallel unstructured adaptive mesh refinement
- Supports large-scale simulation applications with complex geometries.
- Manages partition of element domains on processors.
- With GeoFEST, solution-driven mesh improvement
- GeoFEST not using dynamic mesh modification

Los Angeles Basin: Mesh, Y, Z solutions



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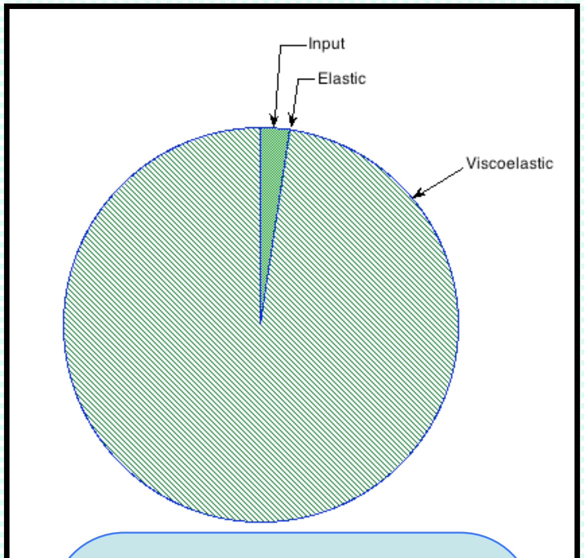
Parallel GeoFEST: Scaling

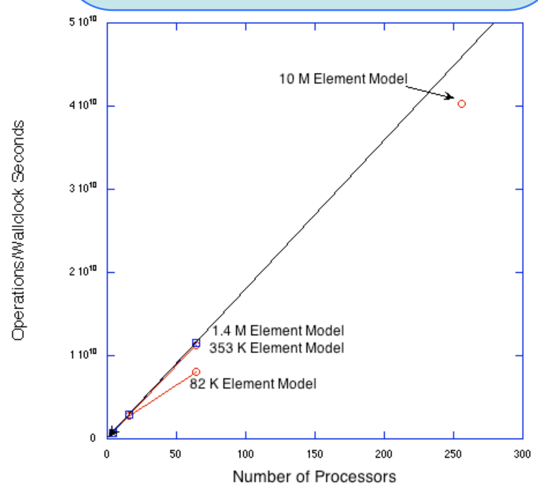


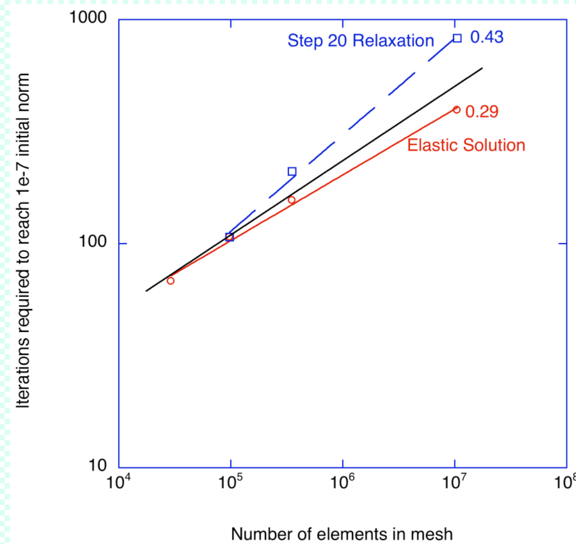
Landers, 1.4M elements
1000 time steps,
~200 iterations per step

=>Steps, iterations dominate time

Operations =
*Steps * Iterations **
*(~300)*Elements;*

=> Time ~ Ops/Procs



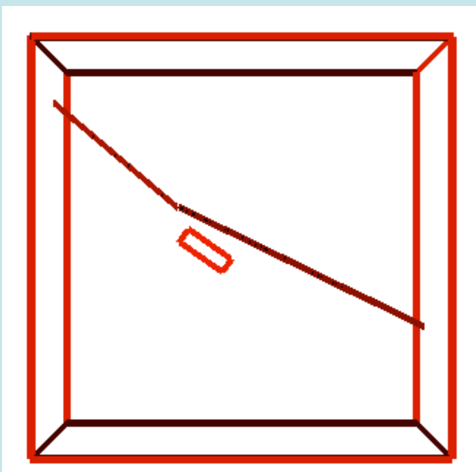


Iterations ~ Elements $^{(1/3)}$

=> Ops ~ Elts $^{(4/3)}$

How many elements?

Consider a L=500 (cube) domain, with a fault edge (finest feature l = 1km)



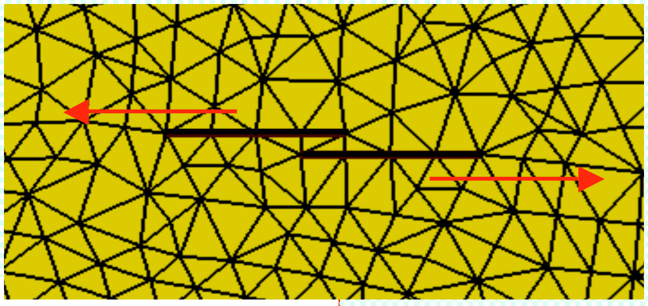
(motivated by LA Basin simulation geometry, shown here)

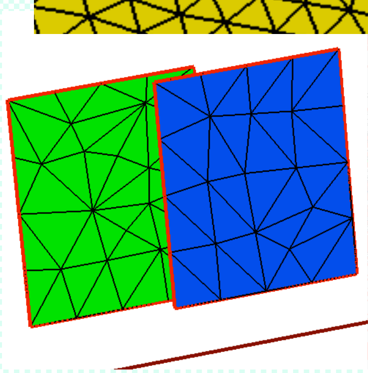
Some possible approaches:

- **Fine** density mesh everywhere:
  Elements = $5(L/l)^3$ = 725M.
- **Heuristic** *(roughly what we use today):*
  --elements grow by "*A*" with distance from line.
  Nearest edge, need ~20*(*L*/*l*)
  Next, (to *A* km) another ~20*(*L*/(*Al*))
  to 2*A*, another ~20*(*L*/(2*Al*))
  . . . **Geometric progression**, so (optimistically)
  Elements ~20(*L*/*l*)*A*/(*A*-1) ~ 30,000 (for *A*=1.5).
- Use **strain energy** from scratch solution to direct PAMR. Performance similar to heuristic, but *physics based*, *automatic*, *avoids errors*.

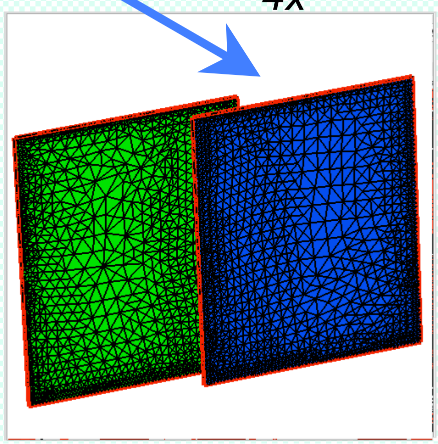
Adaptive Meshing (in progress)

Initial surface mesh (center portion):



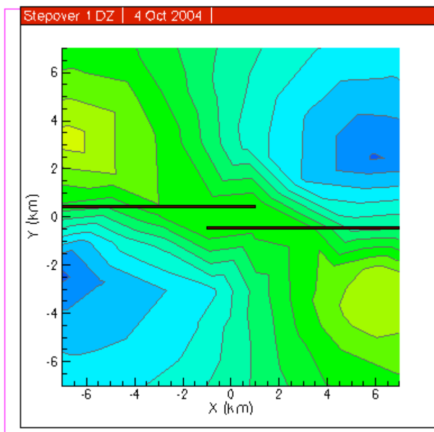


Obtain elastic solution
Strain energy
Refine
4x

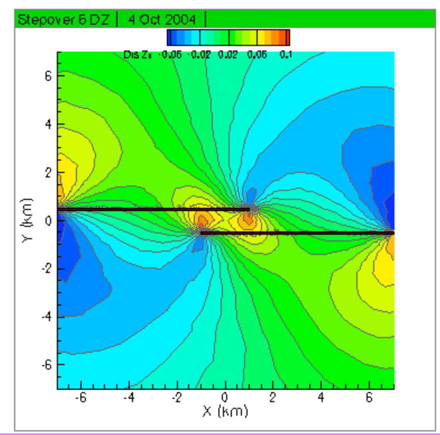


Mesh on faults (side view)

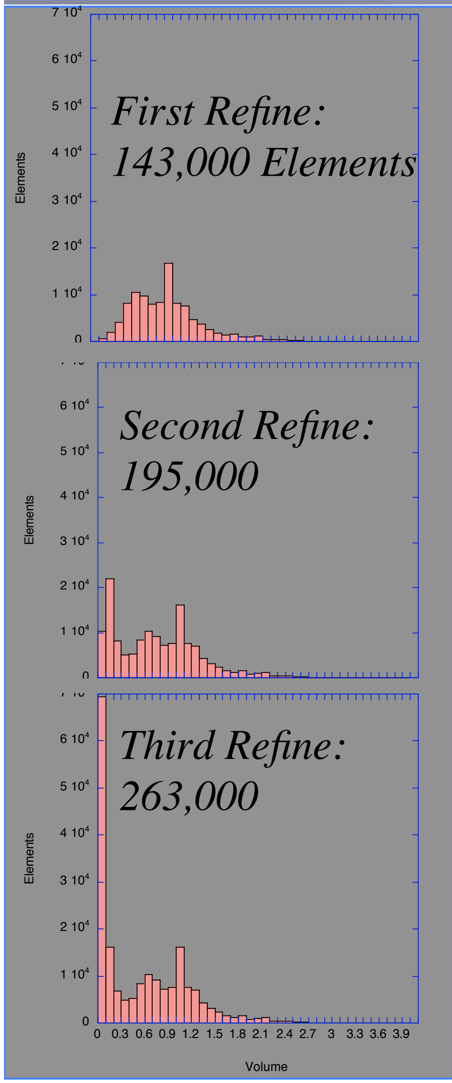
- Aim to use PYRAMID parallel library *(NASA ESTO CT Project)*
- Changes mesh after import to cluster
- Strain energy guides 3D refinement



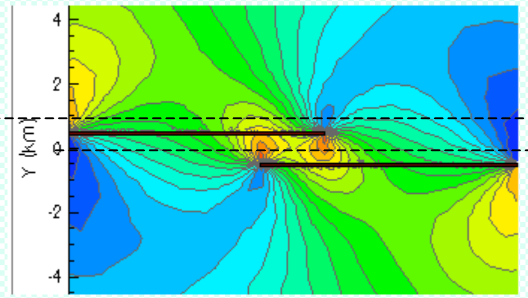
Z component at surface
Refinement cycles 1 and 6



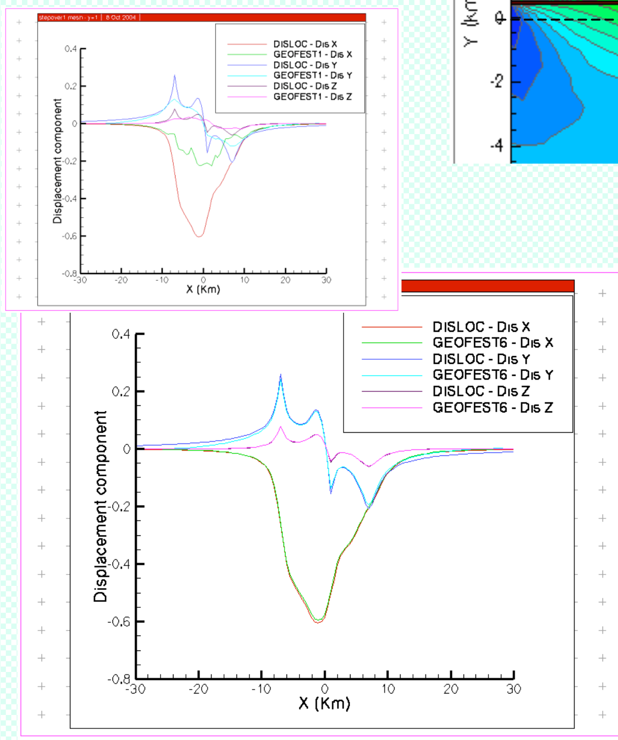
Detailed Validation
GeoFEST vs. Analytic Fault Stepover

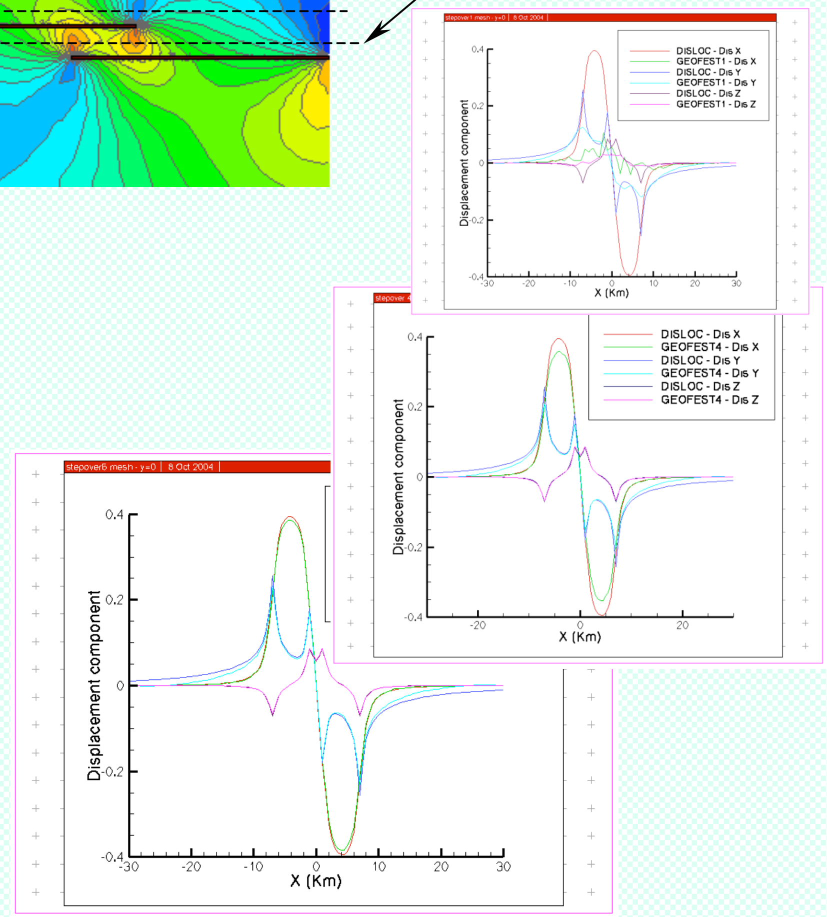


X,Y, Z components
Surface, horizontal line at y=1
Iteration 1 vs. 6



X,Y, Z components
Surface, horizontal line at y=0
Iterations1,4,6





GeoFEST Status

Summary

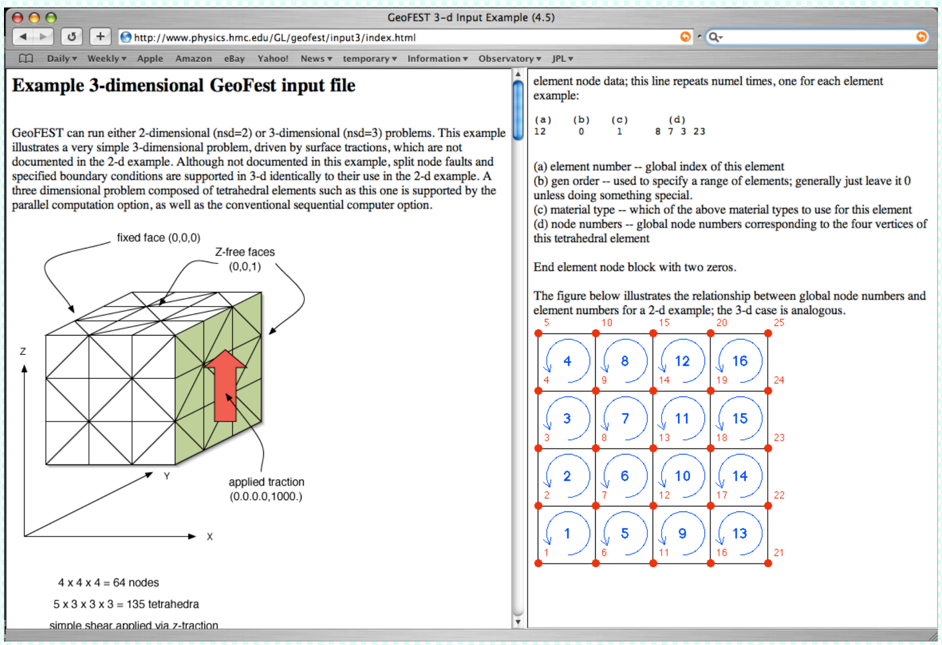
- Handles millions of elements in MPI code
- Heuristic mesher can vary density with high generality:
  High near fault edges, very low to extend to far boundaries
- PYRAMID integration works at first level (partition management) and generates quality refined meshes. Integration in progress.
- Strain Energy refinement converges to correct solution.
- Validation with known solutions indicates 1-2 iterations OK.
- Visit us at http://quakesim.jpl.nasa.gov

Background:
10M Element Landers coseismic uplift coded as radar phase,
256 Processors of SGI "Cosmos" system at JPL

- What is GeoFEST?
  - Geophysical Finite Element Simulation Tool
  - GeoFEST solves solid mechanics forward models with these characteristics:
    - 2-D or 3-D irregular domains
    - 1-D, 2-D or 3-D displacement fields
    - Static elastic or time-evolving viscoelastic problems
    - Driven by faults, boundary conditions or distributed loads
  - GeoFEST runs in a variety of computing environments:
    - UNIX workstations (including LINUX, Mac OS X, etc.)
    - Web portal environment
    - Parallel cluster/supercomputer environment

GeoFEST tutorial

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


GeoFEST 3-d Input Example (4.5)
http://www.physics.hmc.edu/GL/geofest/input3/index.html

Example 3-dimensional GeoFest input file

GeoFEST can run either 2-dimensional (nsd=2) or 3-dimensional (nsd=3) problems. This example illustrates a very simple 3-dimensional problem, driven by surface tractions, which are not documented in the 2-d example. Although not documented in this example, split node faults and specified boundary conditions are supported in 3-d identically to their use in the 2-d example. A three dimensional problem composed of tetrahedral elements such as this one is supported by the parallel computation option, as well as the conventional sequential computer option.

4 x 4 x 4 = 64 nodes
5 x 3 x 3 x 3 = 135 tetrahedra
simple shear applied via z-traction

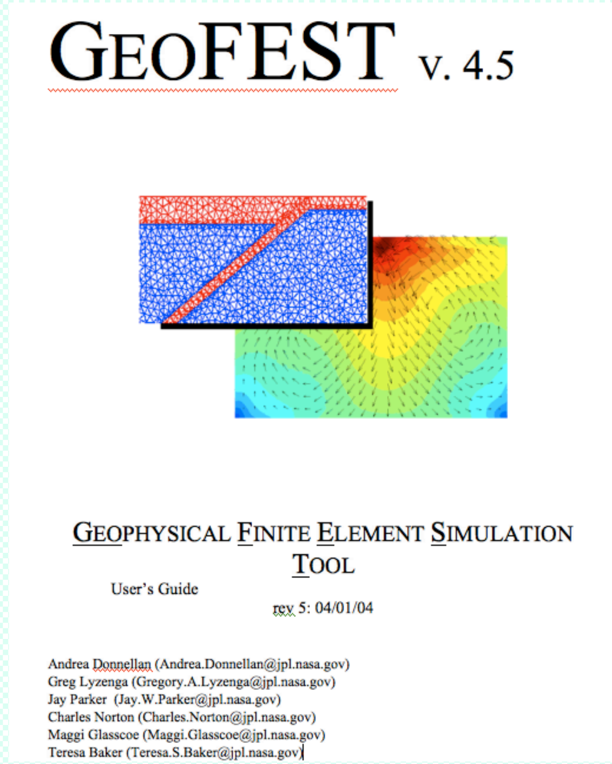
element node data; this line repeats numel times, one for each element
example:

```
(a)   (b)   (c)       (d)
12     0     1      8  7  3  23
```

(a) element number -- global index of this element
(b) gen order -- used to specify a range of elements; generally just leave it 0 unless doing something special.
(c) material type -- which of the above material types to use for this element
(d) node numbers -- global node numbers corresponding to the four vertices of this tetrahedral element

End element node block with two zeros.

The figure below illustrates the relationship between global node numbers and element numbers for a 2-d example; the 3-d case is analogous.


GeoFEST v. 4.5

Geophysical Finite Element Simulation Tool

User's Guide

rev 5: 04/01/04

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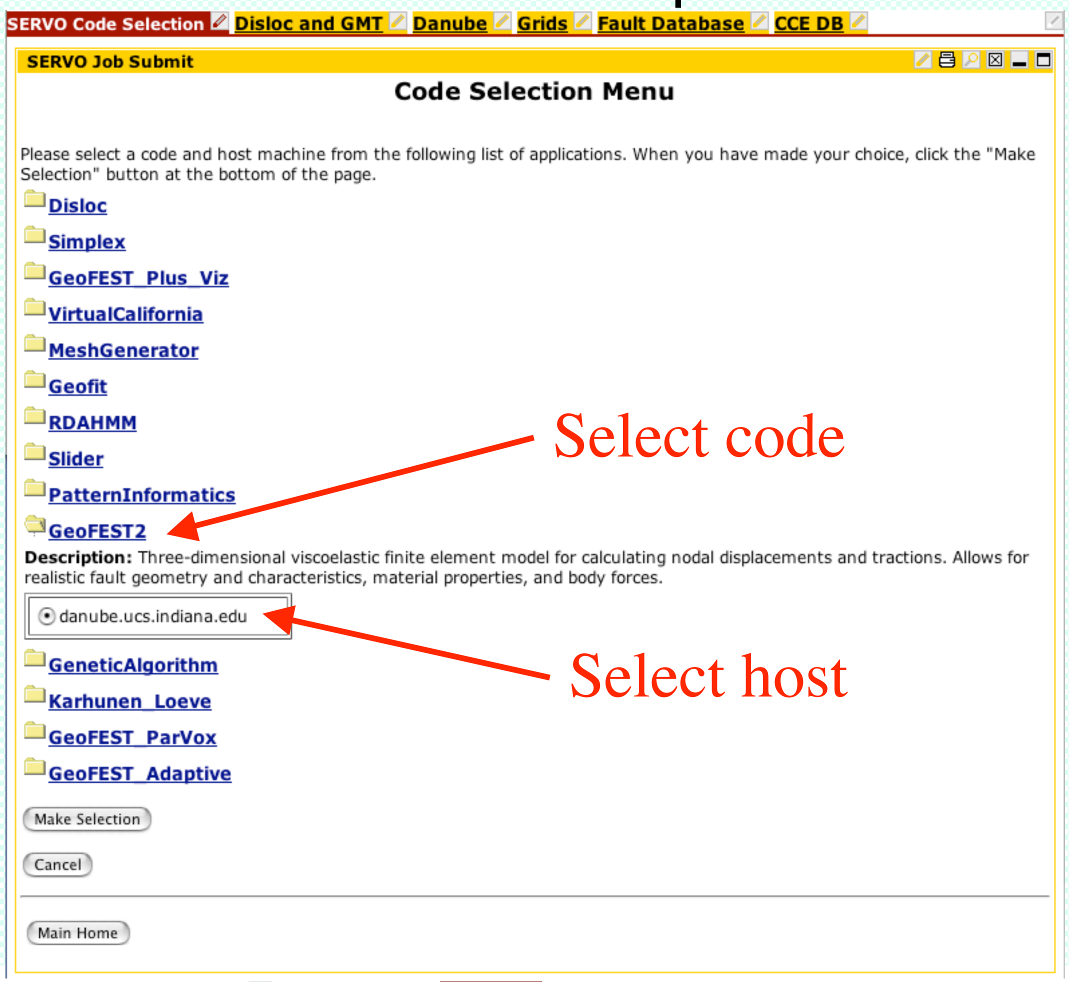
- Steps for running GeoFEST:
  - Create grid geometry
  - Enter boundary conditions, faults
  - Enter material properties, time stepping
  - Run problem
  - Plot, visualize results

GeoFEST tutorial

- Using the web portal environment to create and run a typical 3-dimensional model
  - Use web portal to draft domain layers and boundaries
  - Using portal, add fault(s) to domain
  - Generate grid points and elements with desired refinement
  - Provide supplemental information on boundary conditions, material properties, time stepping, etc.
  - Submit run to GeoFEST for execution
  - Examine and visualize results

GeoFEST tutorial

- Select the GeoFEST code in portal



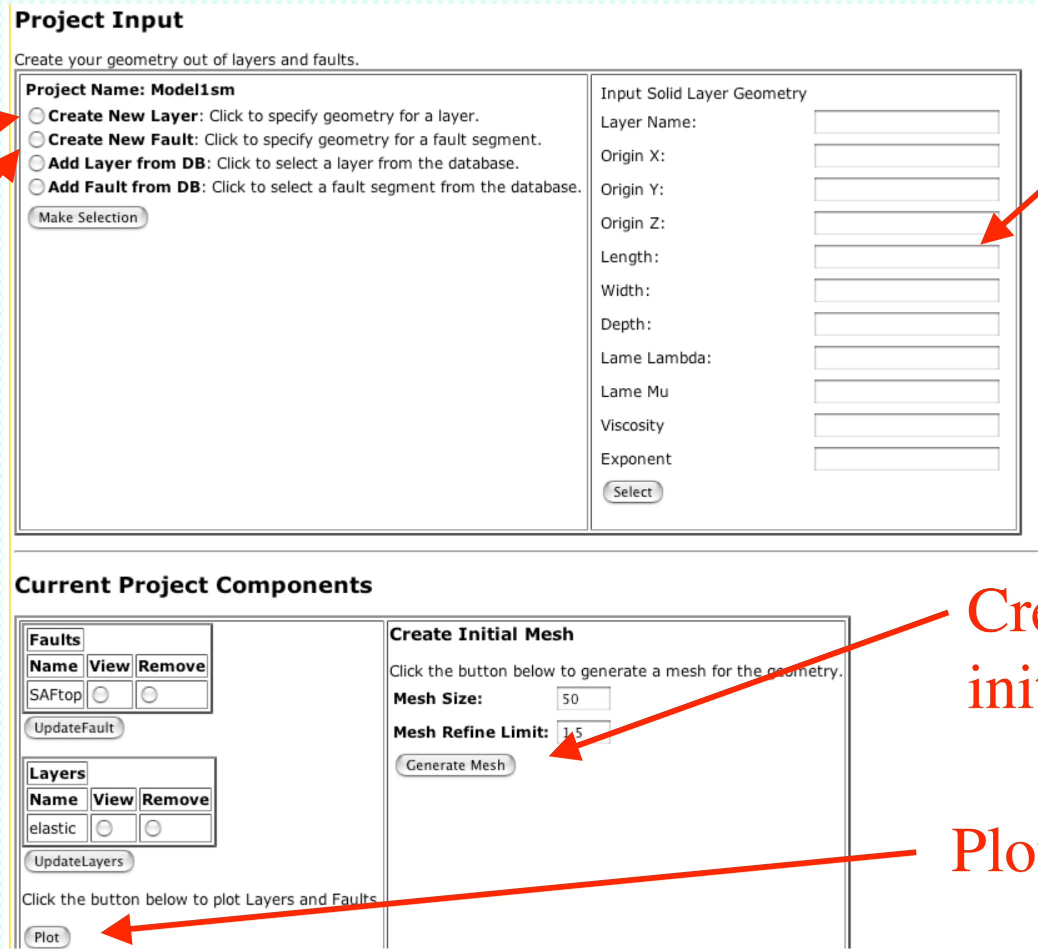
GeoFEST tutorial

QuakeSim

- Create the desired geometry

Create layer(s)

Create faults(s)



Enter dimensions and properties

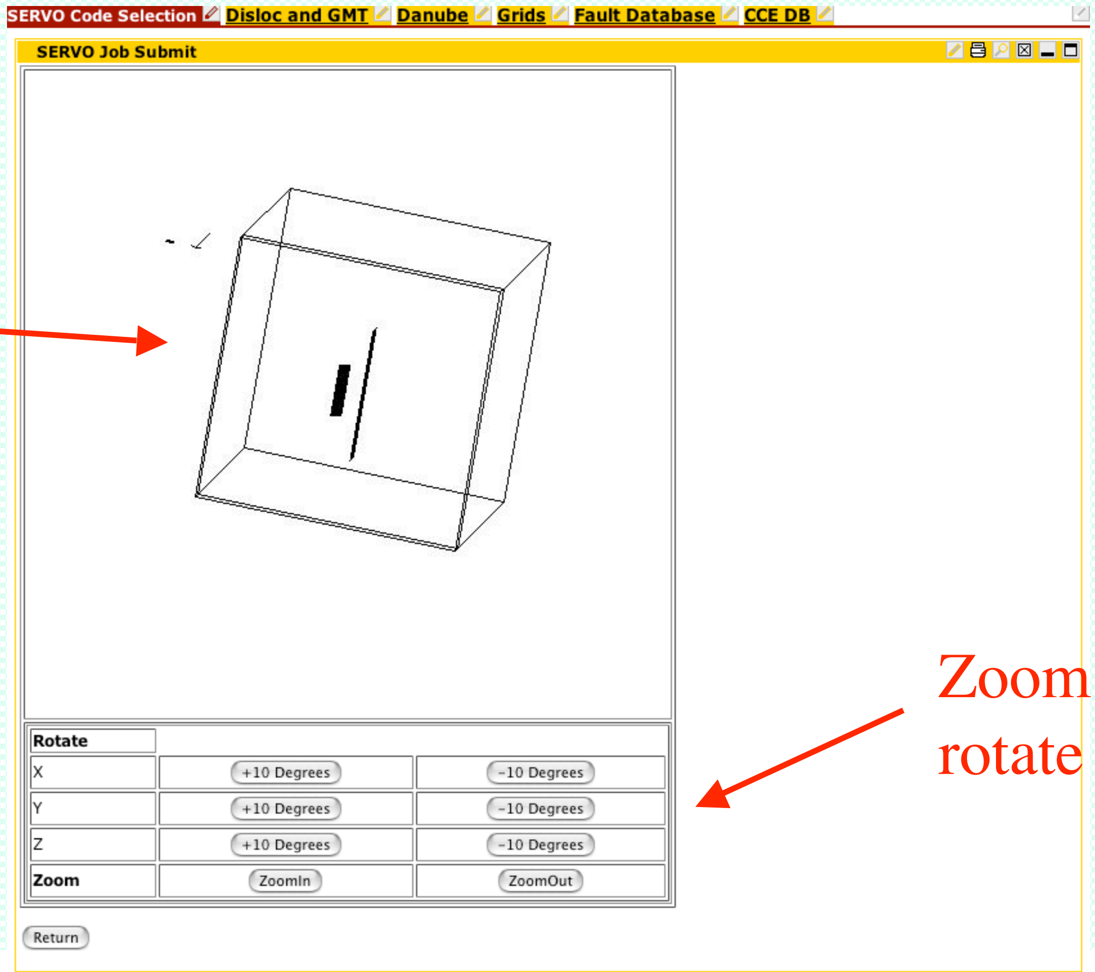
Create initial mesh

Plot results

GeoFEST tutorial

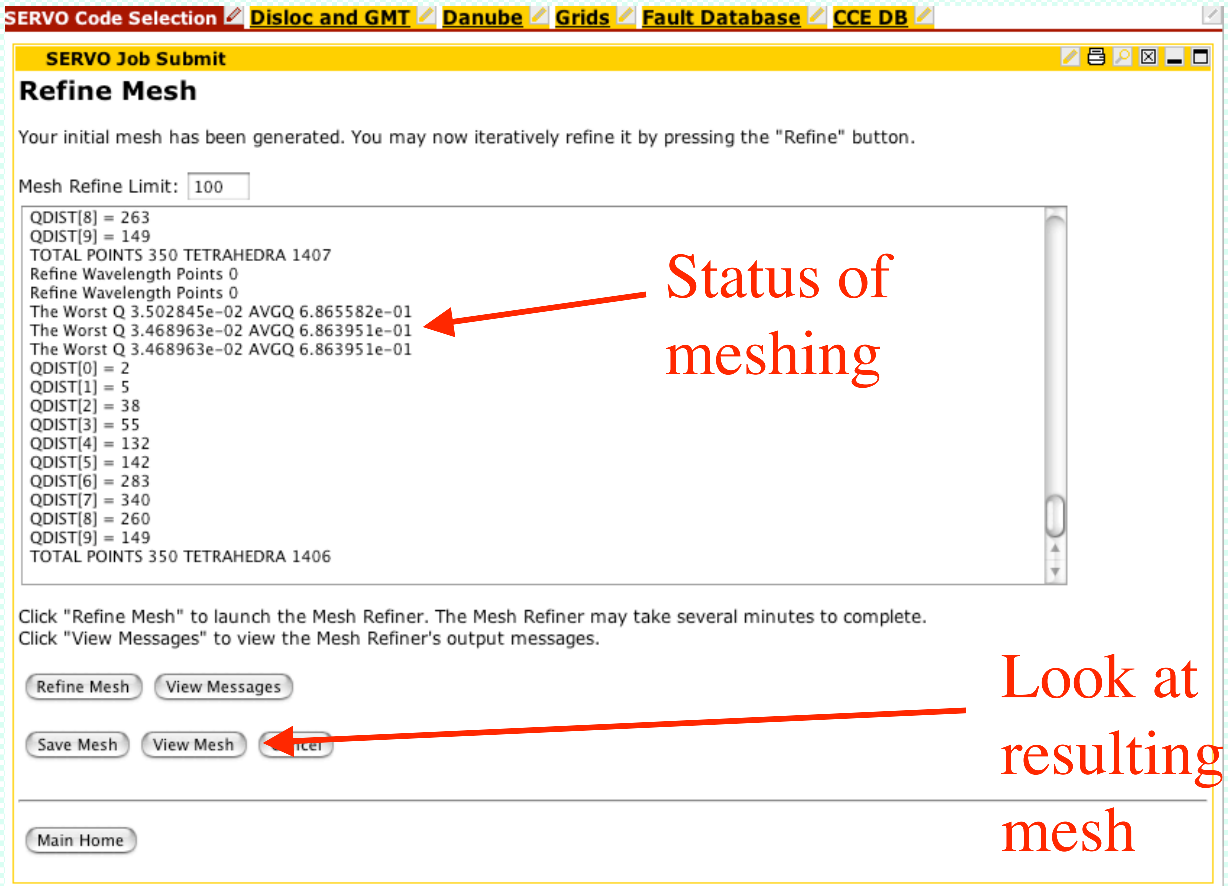
- Check the generated geometry

Pre-mesh view of layers and faults

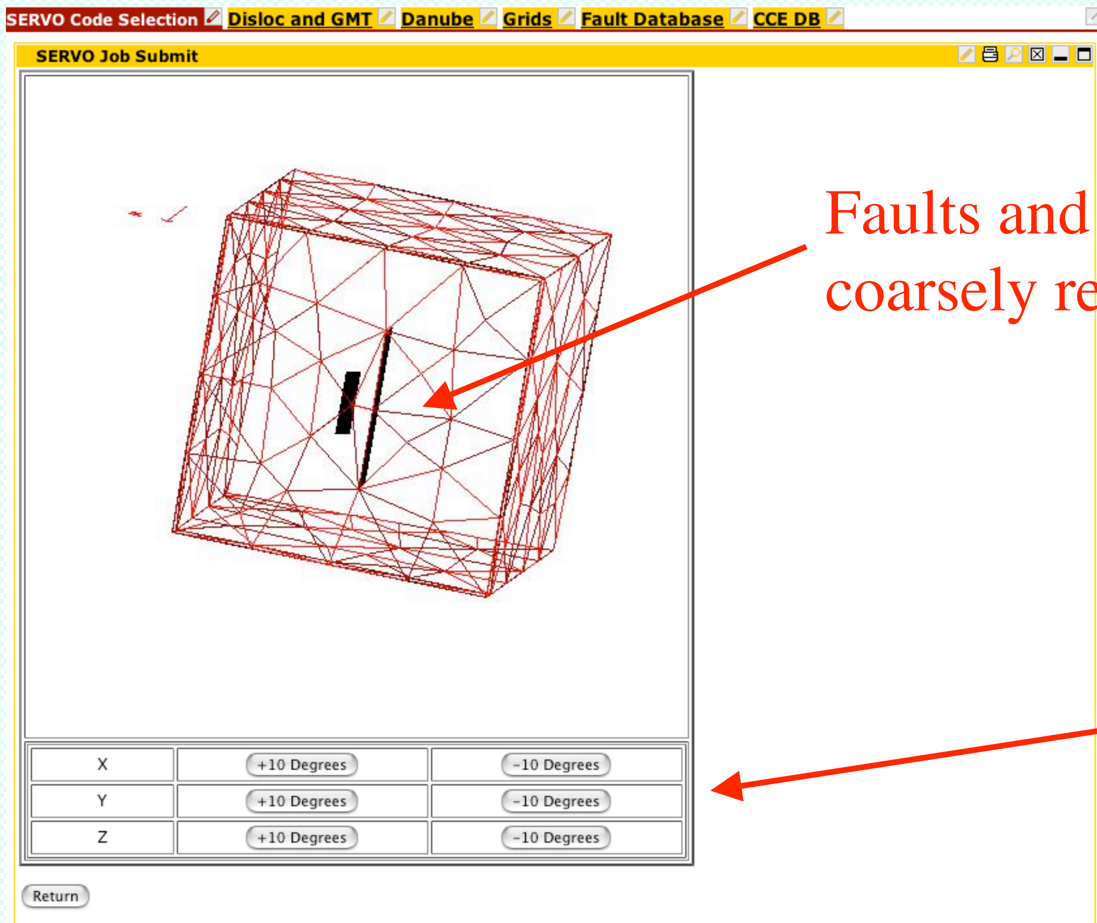


Zoom and rotate view

- After performing initial meshing of domain



- Viewing initial meshing of domain



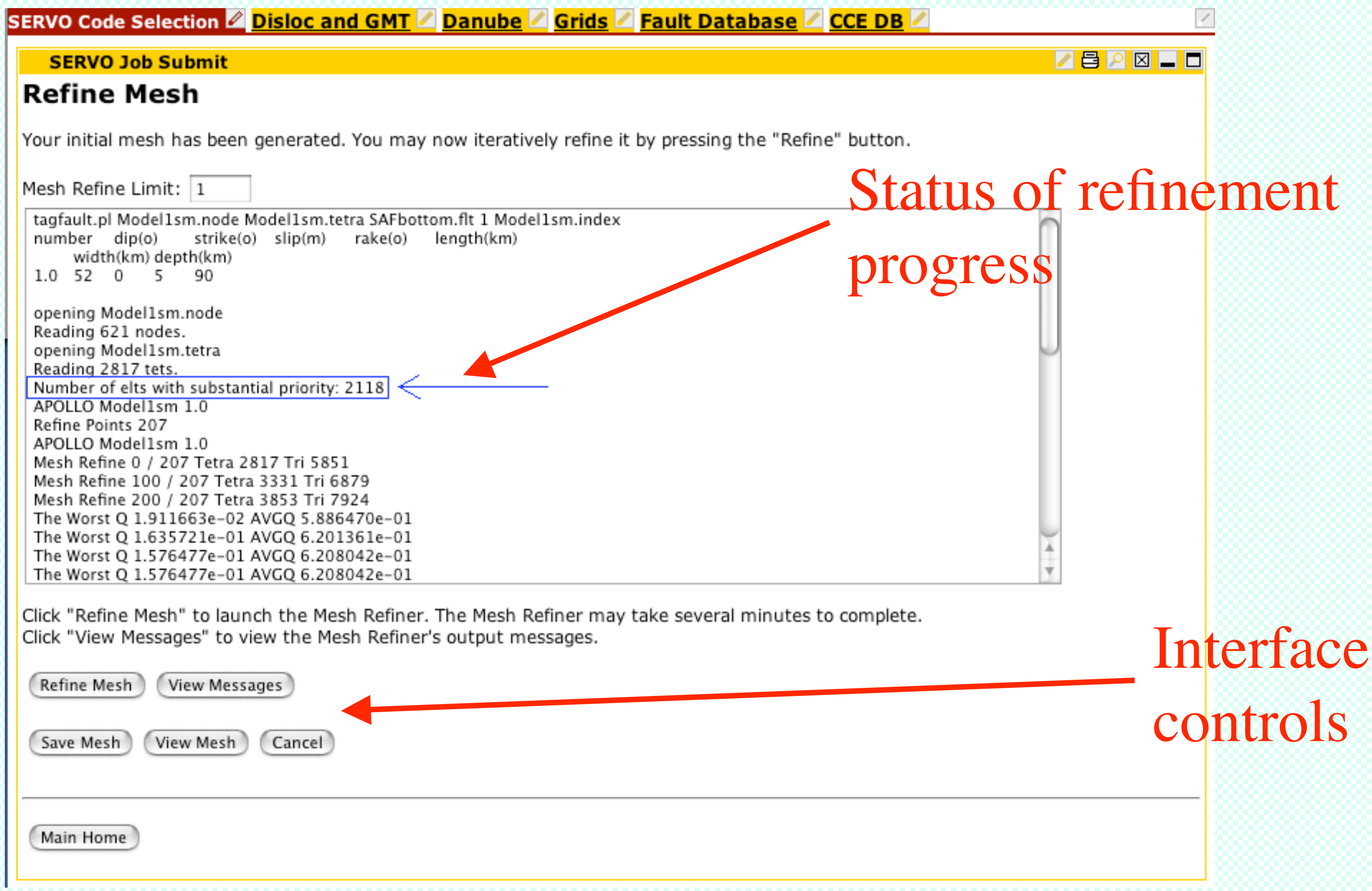
Faults and volumes coarsely resolved

Rotate views

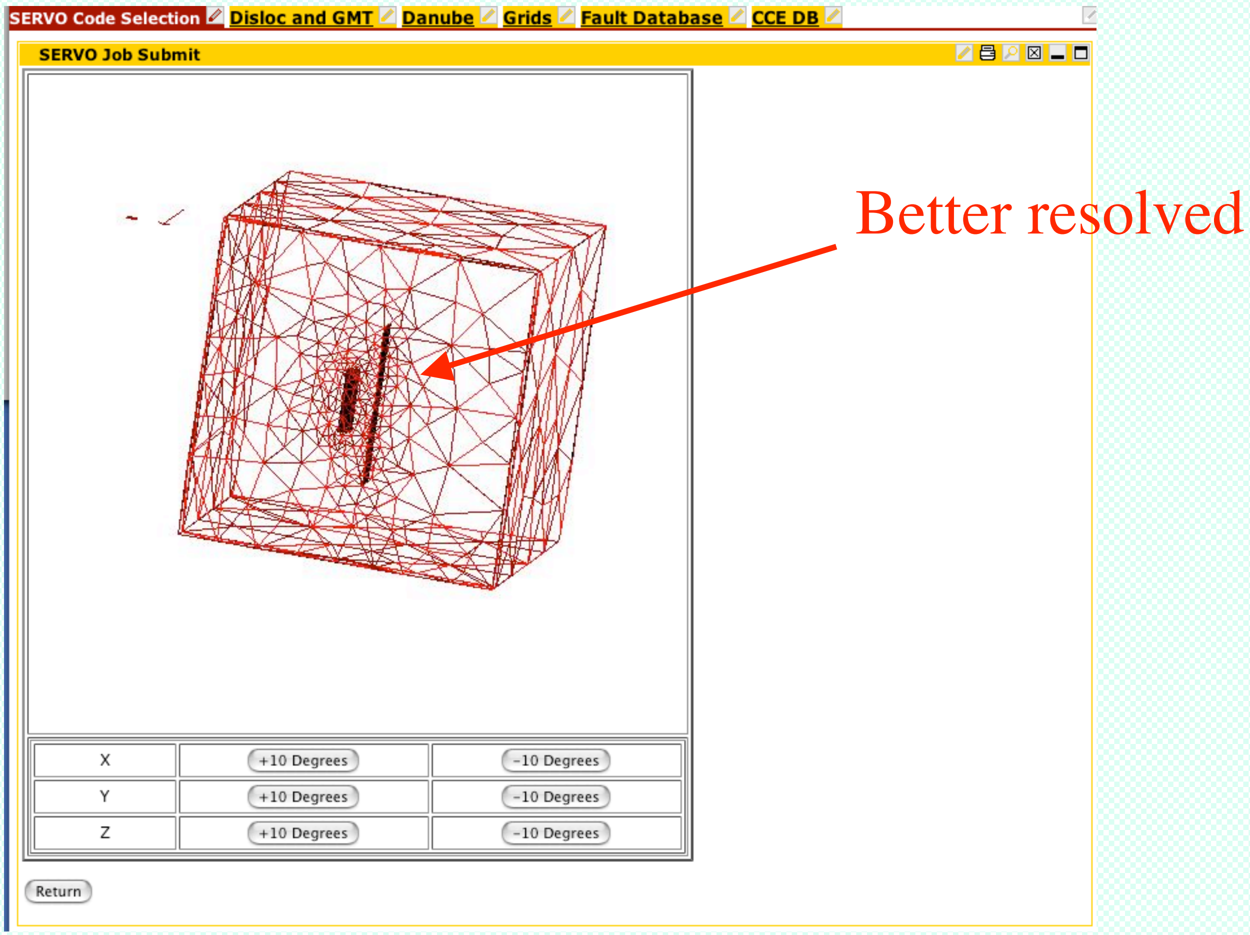
GeoFEST tutorial

QuakeSim

- Requesting refined meshing of domain

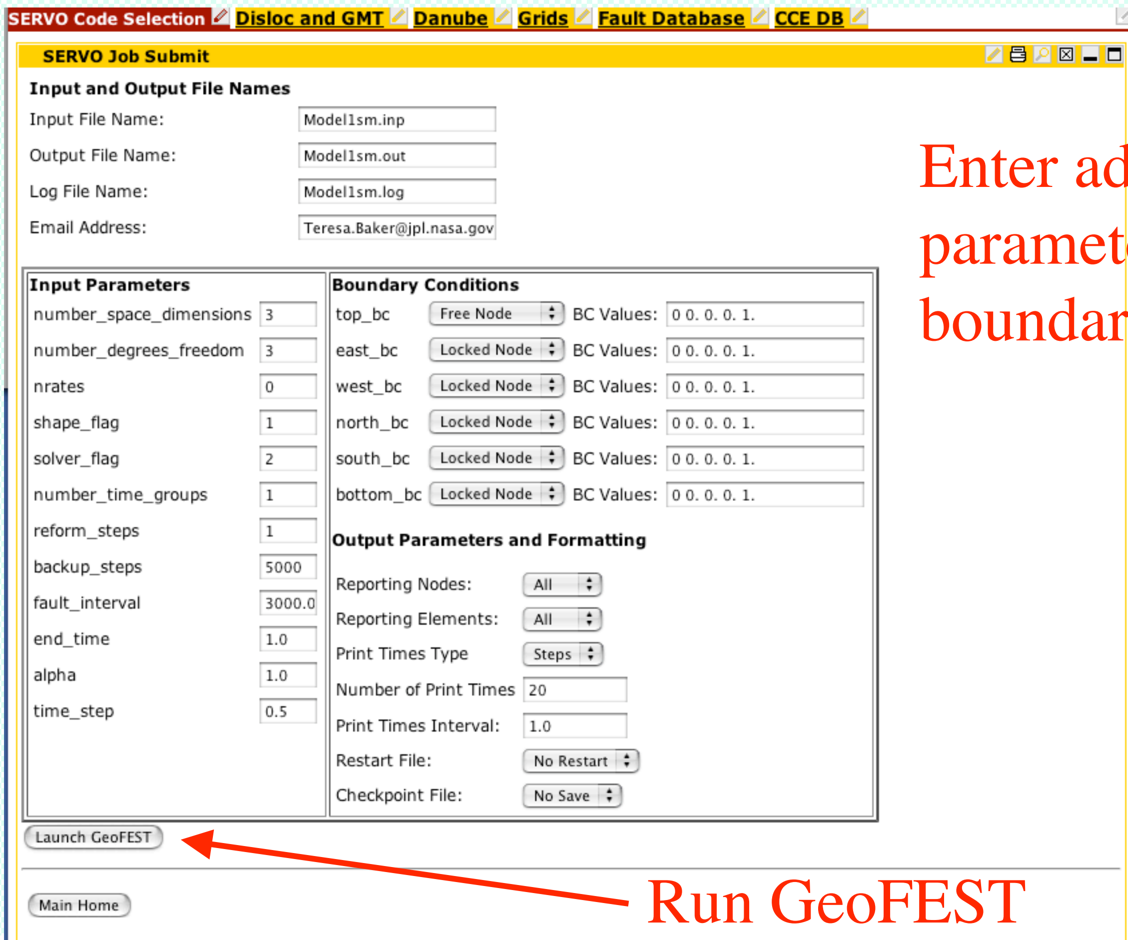


- Viewing refined meshing of domain



GeoFEST tutorial

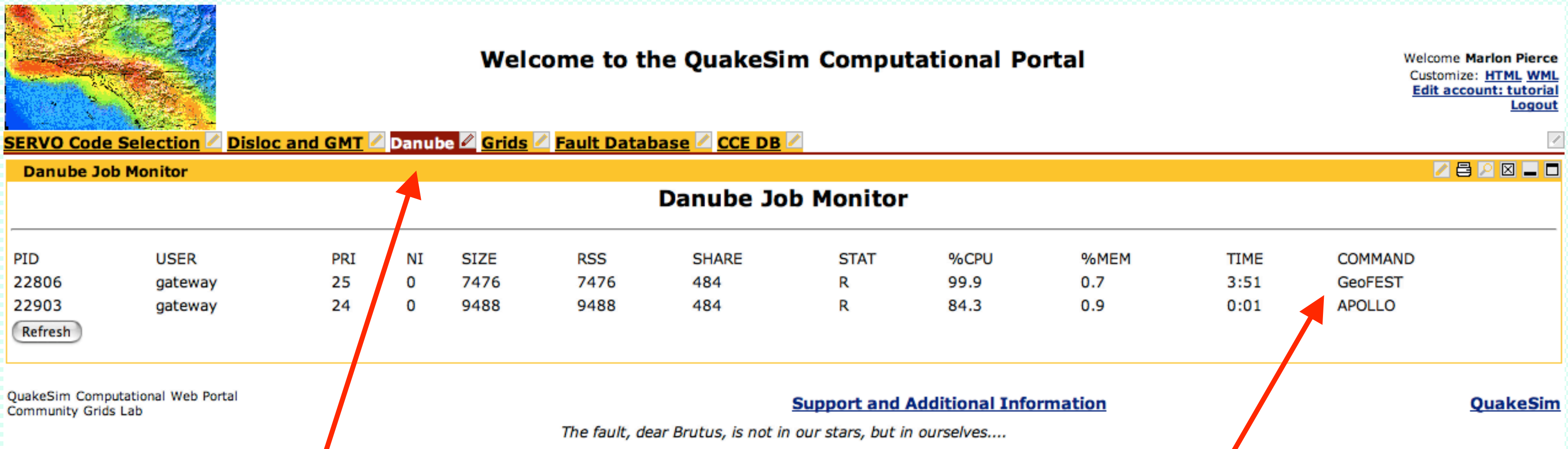
- Running prepared GeoFEST model



Enter additional run parameters and boundary conditions

Run GeoFEST

- Monitoring status of GeoFEST job execution



Welcome to the QuakeSim Computational Portal

Welcome **Marlon Pierce**
Customize: HTML WML
Edit account: tutorial
Logout

SERVO Code Selection | Disloc and GMT | Danube | Grids | Fault Database | CCE DB

Danube Job Monitor

Danube Job Monitor

PID	USER	PRI	NI	SIZE	RSS	SHARE	STAT	%CPU	%MEM	TIME	COMMAND
22806	gateway	25	0	7476	7476	484	R	99.9	0.7	3:51	GeoFEST
22903	gateway	24	0	9488	9488	484	R	84.3	0.9	0:01	APOLLO

Refresh

QuakeSim Computational Web Portal
Community Grids Lab

Support and Additional Information

QuakeSim

The fault, dear Brutus, is not in our stars, but in ourselves....

Job Monitor portal tab

Process running GeoFEST

- Accessing completed GeoFEST results files
- (Follow "Archived Data" link)

SERVO Code Selection | Disloc and GMT | Danube | Grids | Fault Database | CCE DB

SERVO Job Submit

Archived Data

You have the following archived data files. Click the link to download the file.

Project Name	Storage Host	Creation Date	Data File		
Model1sm	danube.ucs.indiana.edu	Wed Jun 23 17:46:20 EST 2004	Model1sm.inp	Model1sm.out	Model1sm.log

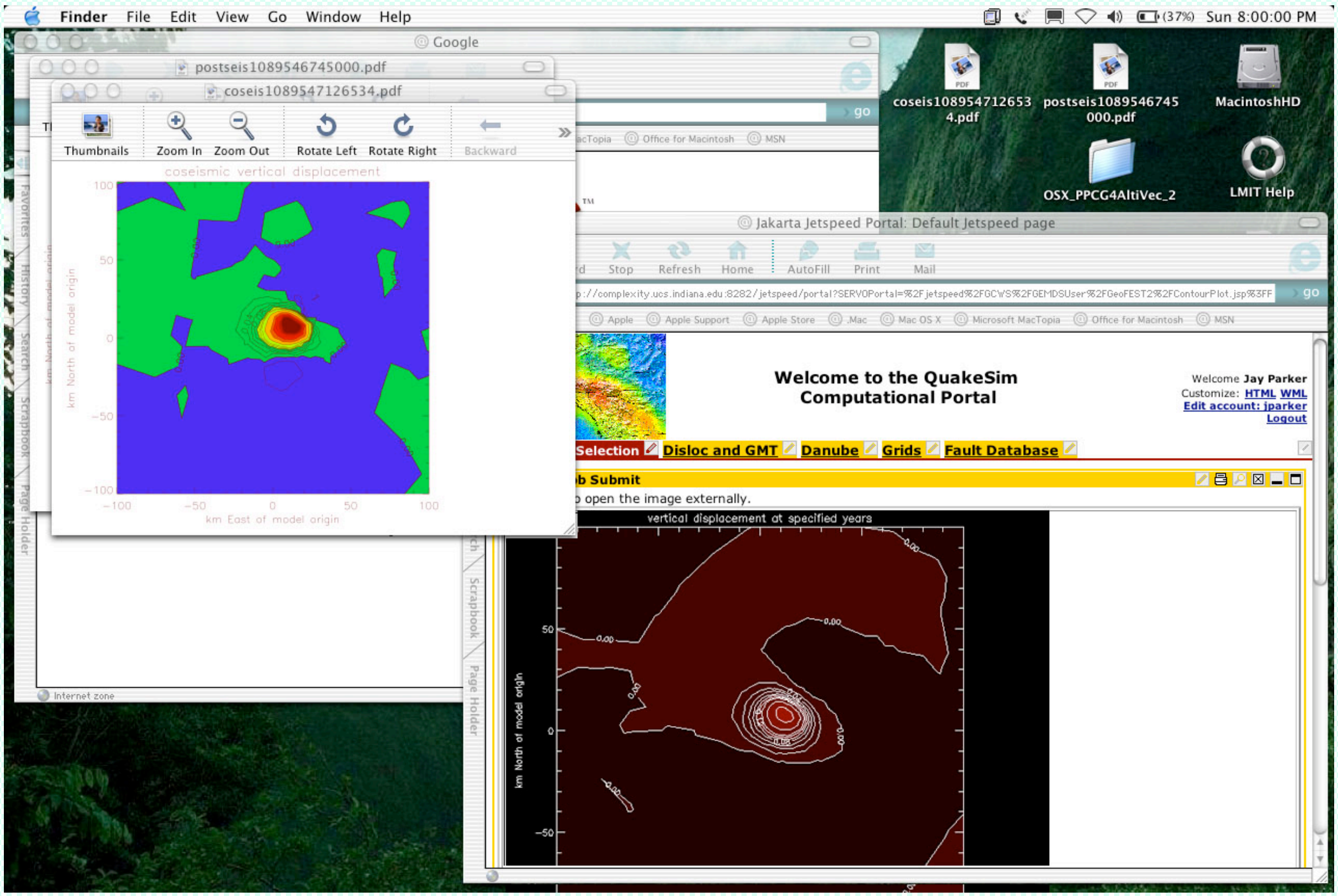
Main Home

ASCII input file

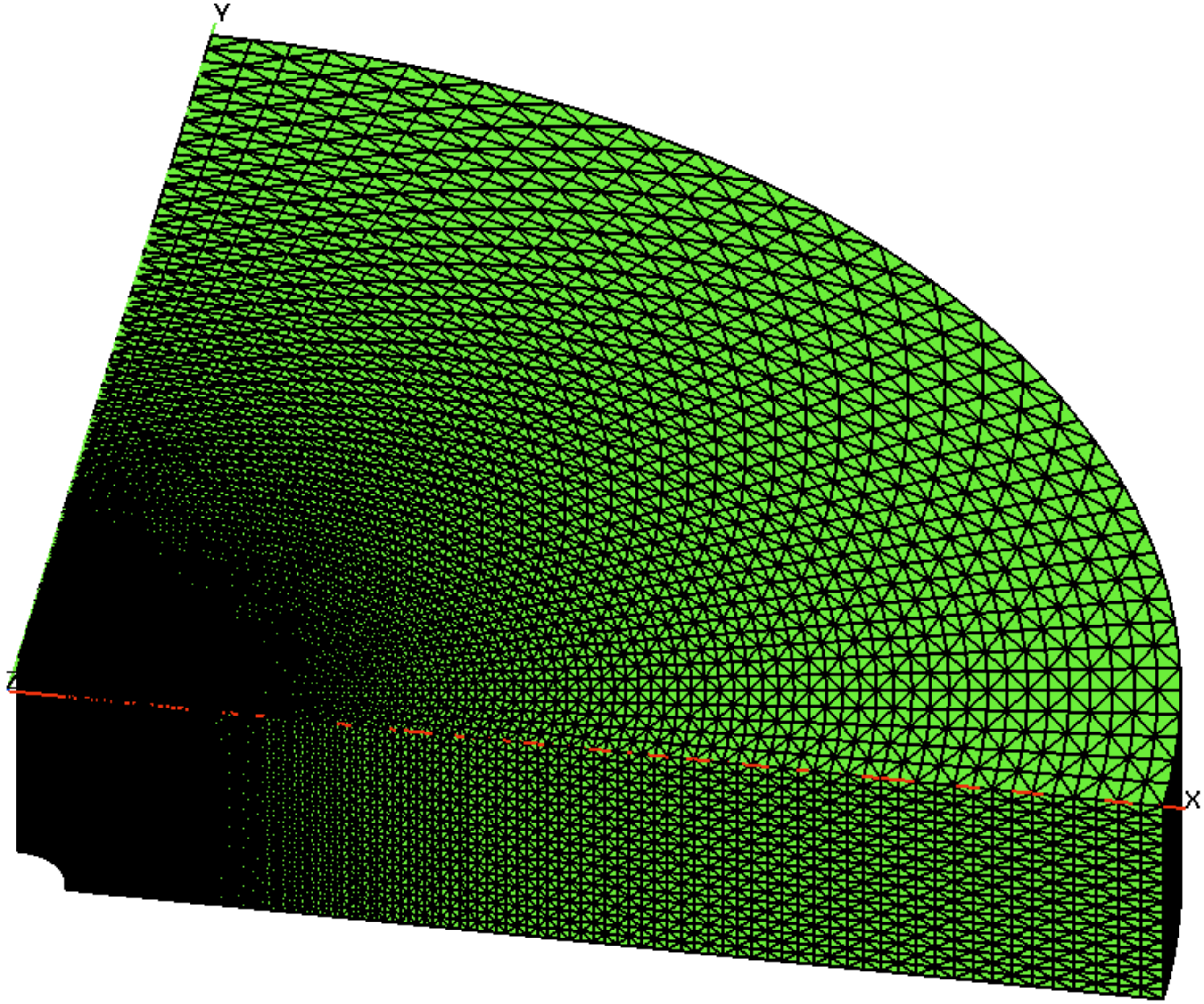
ASCII output file

GeoFEST tutorial

- Plotting, visualization of results via web portal



QuakeSim



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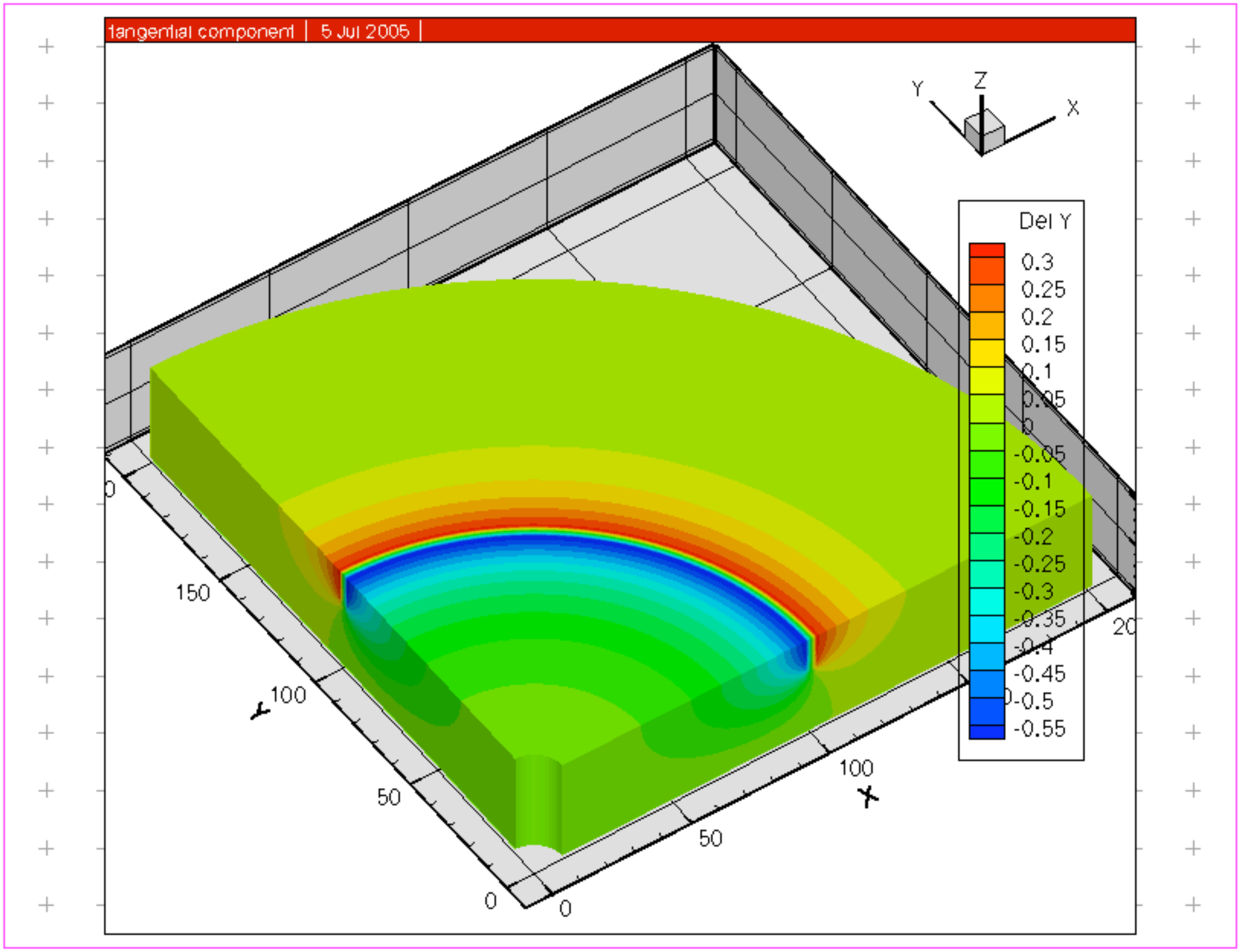
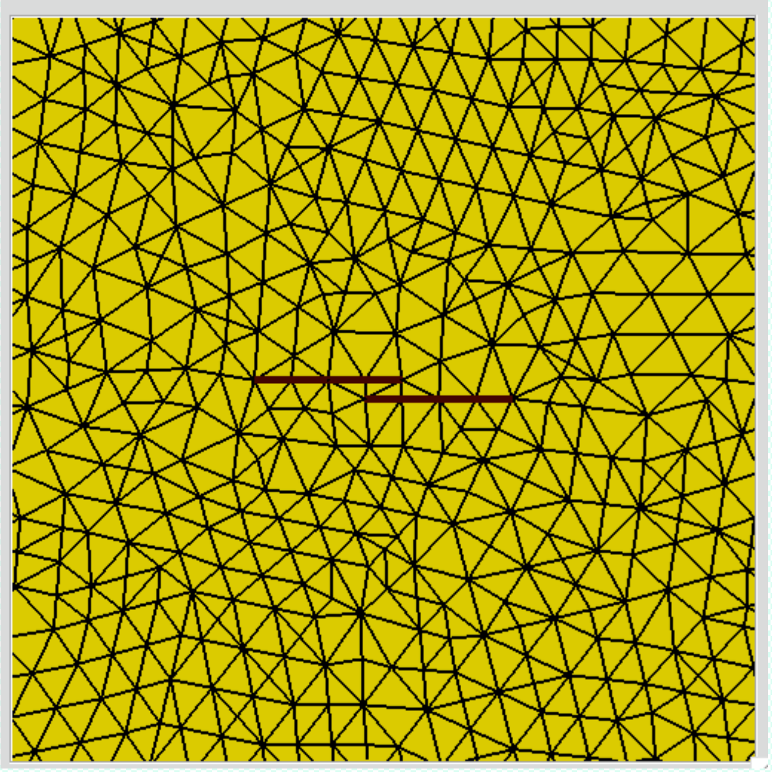
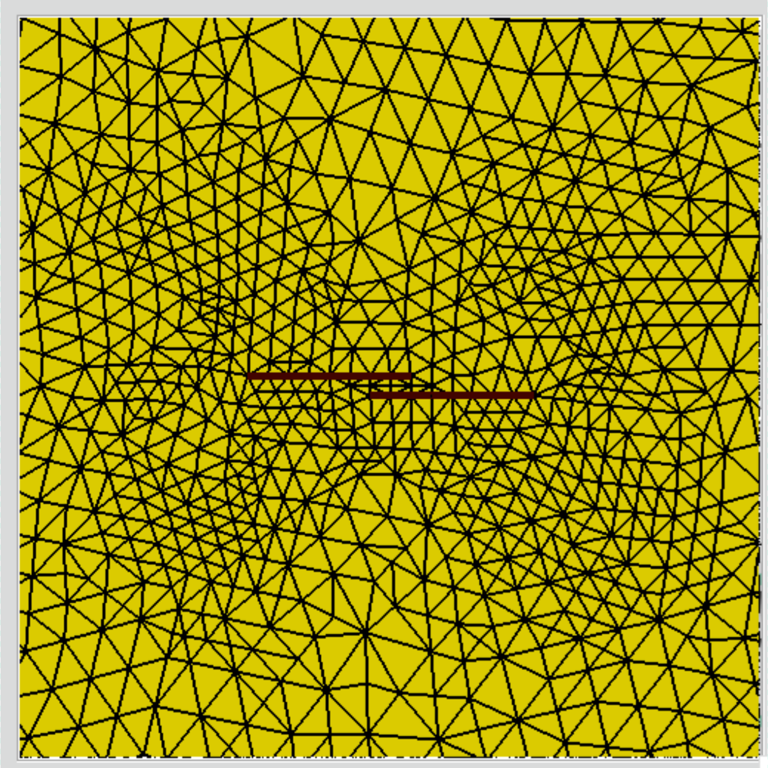
QuakeSim


tangential component | 5 Jul 2005 |
Del Y
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
-0.35
-0.4
-0.45
-0.5
-0.55
X
Y
Z
0
50
100
150
0
50
100





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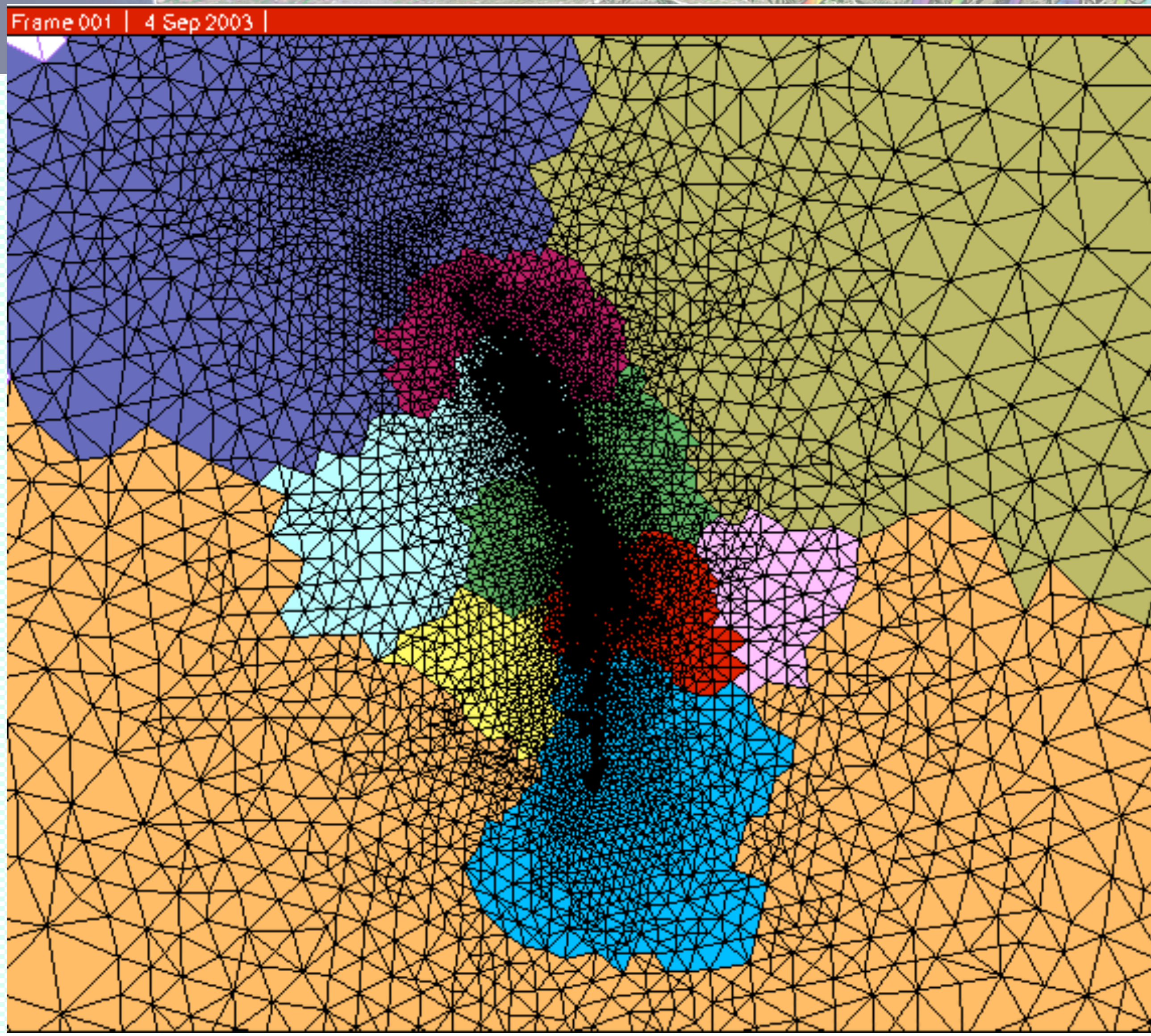

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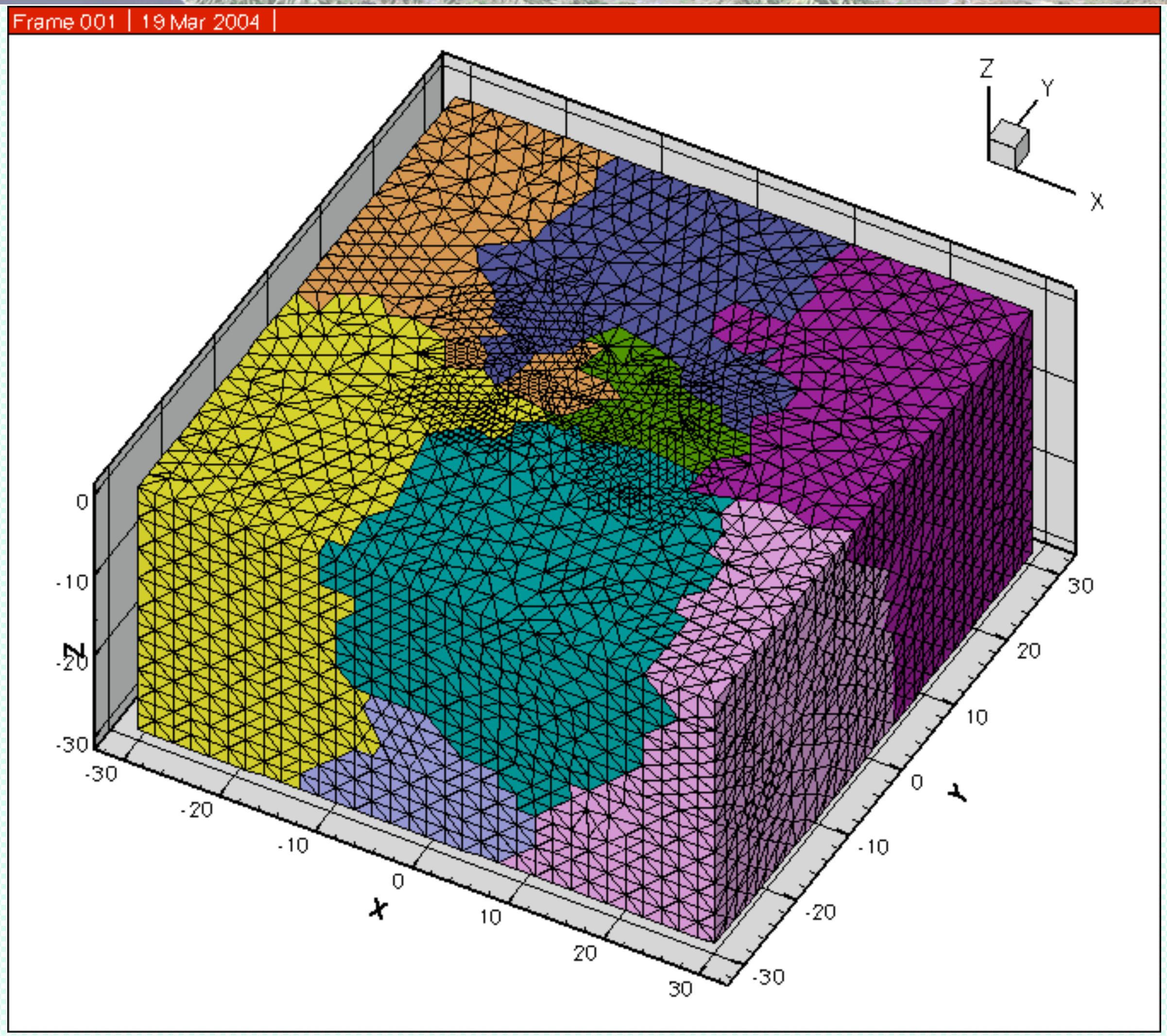
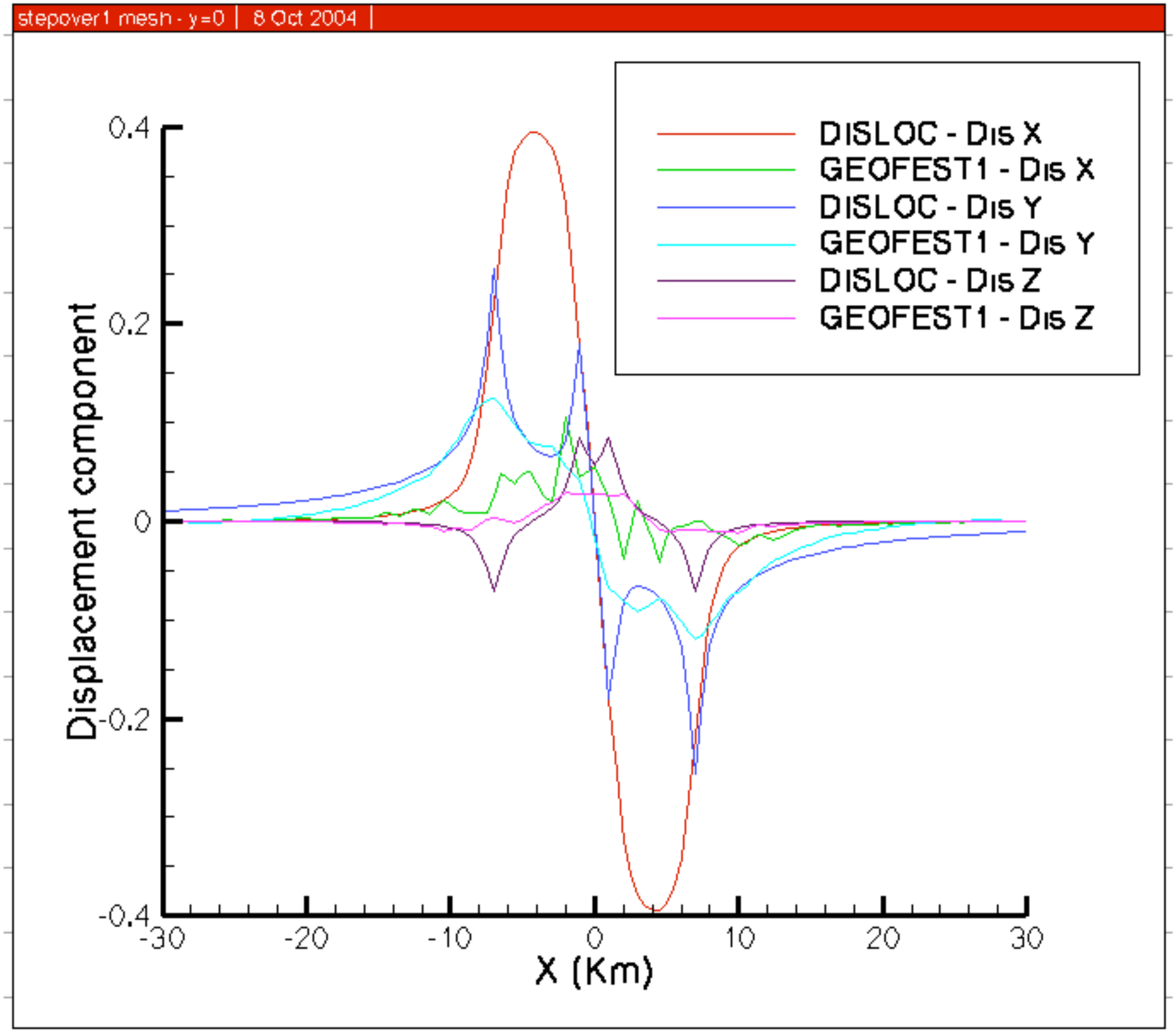
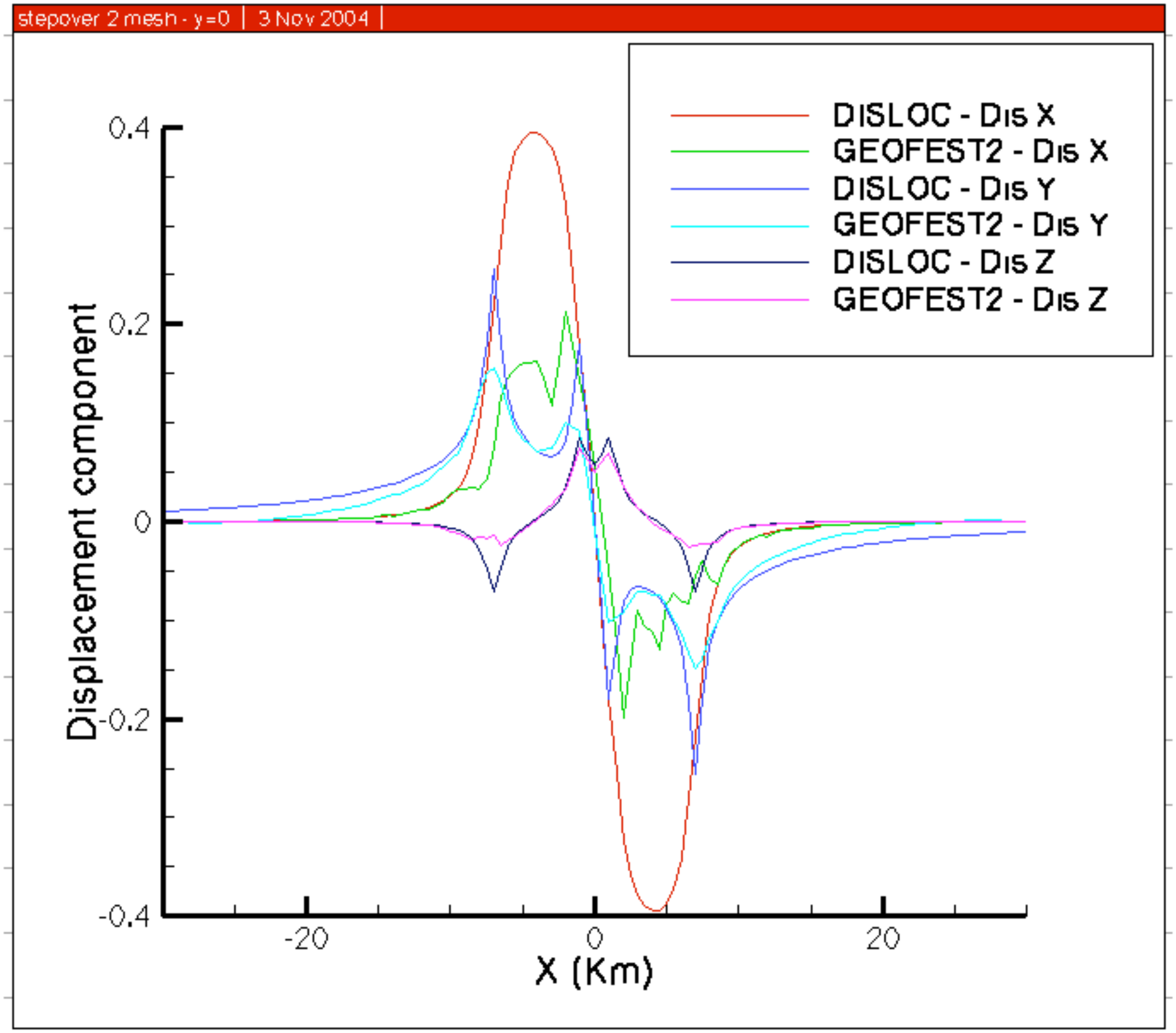
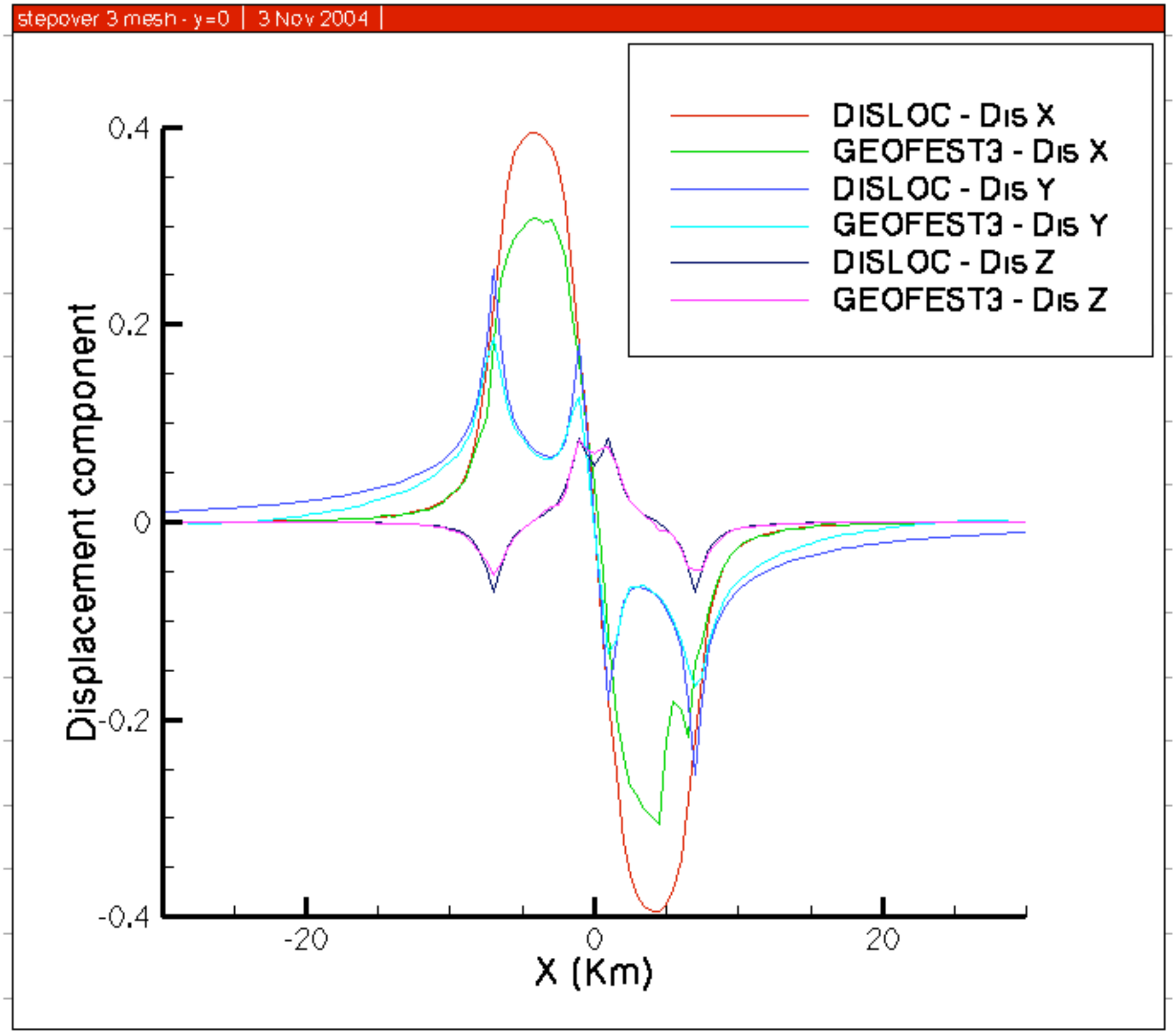
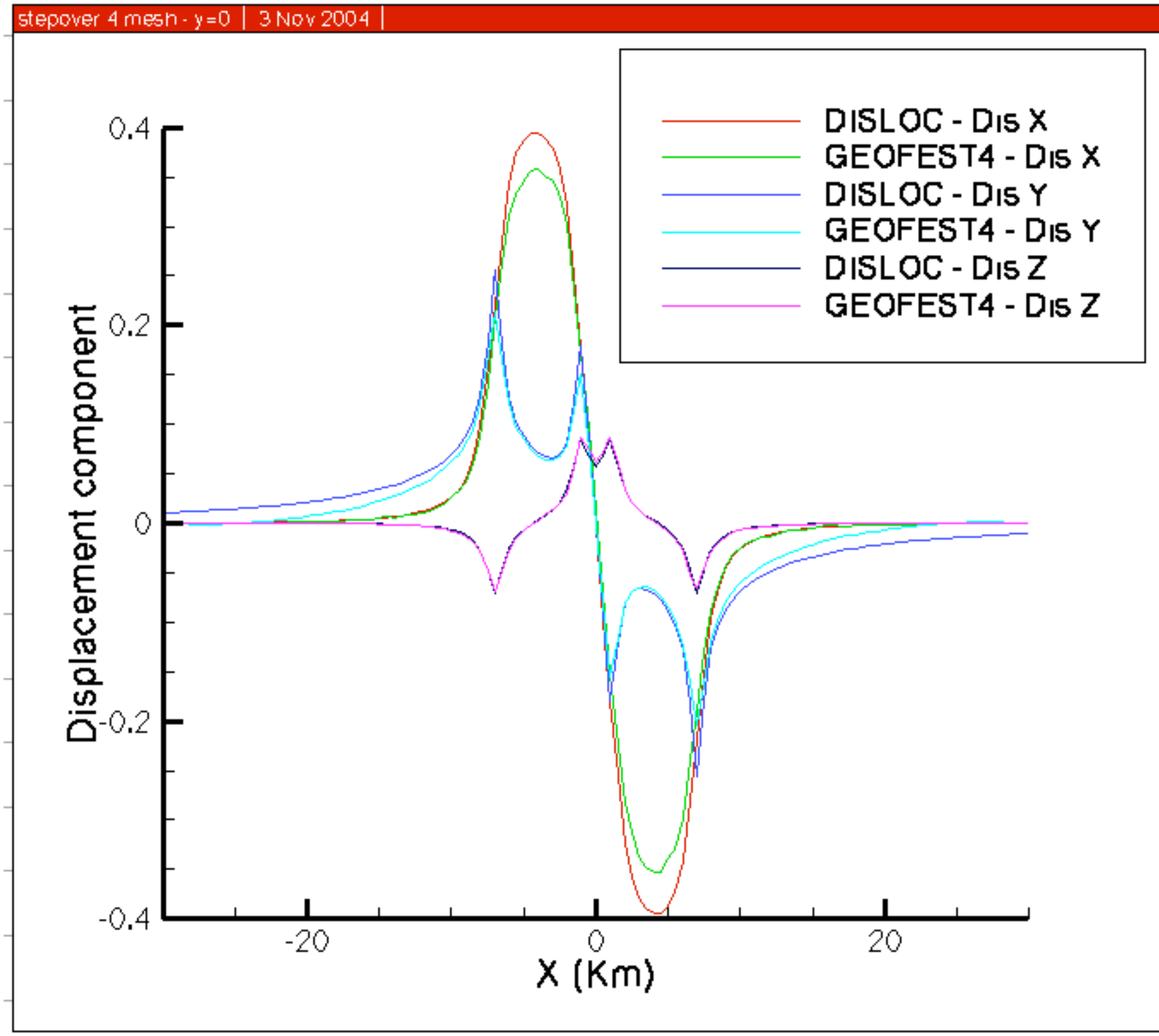
QuakeSim

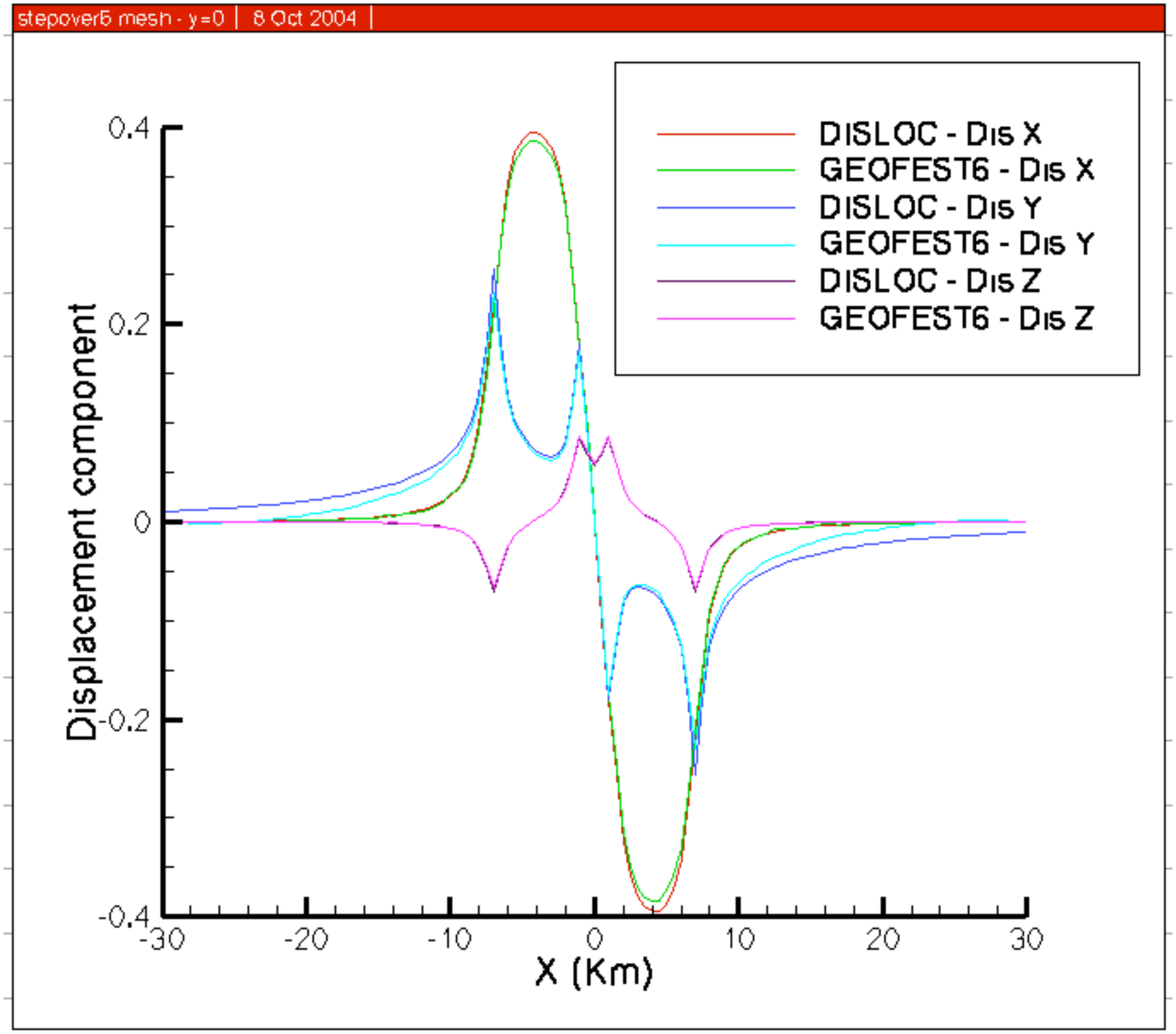

Frame 001 | 19 Mar 2004 |
Z
Y
X
0
-10
-20
-30
Z
-30
-20
-10
0
10
20
30
X
30
20
10
0
-10
-20
-30
Y


stepover1 mesh - y=0 | 8 Oct 2004
DISLOC - Dis X
GEOFEST1 - Dis X
DISLOC - Dis Y
GEOFEST1 - Dis Y
DISLOC - Dis Z
GEOFEST1 - Dis Z
Displacement component
0.4
0.2
0
-0.2
-0.4
-30
-20
-10
0
10
20
30
X (Km)

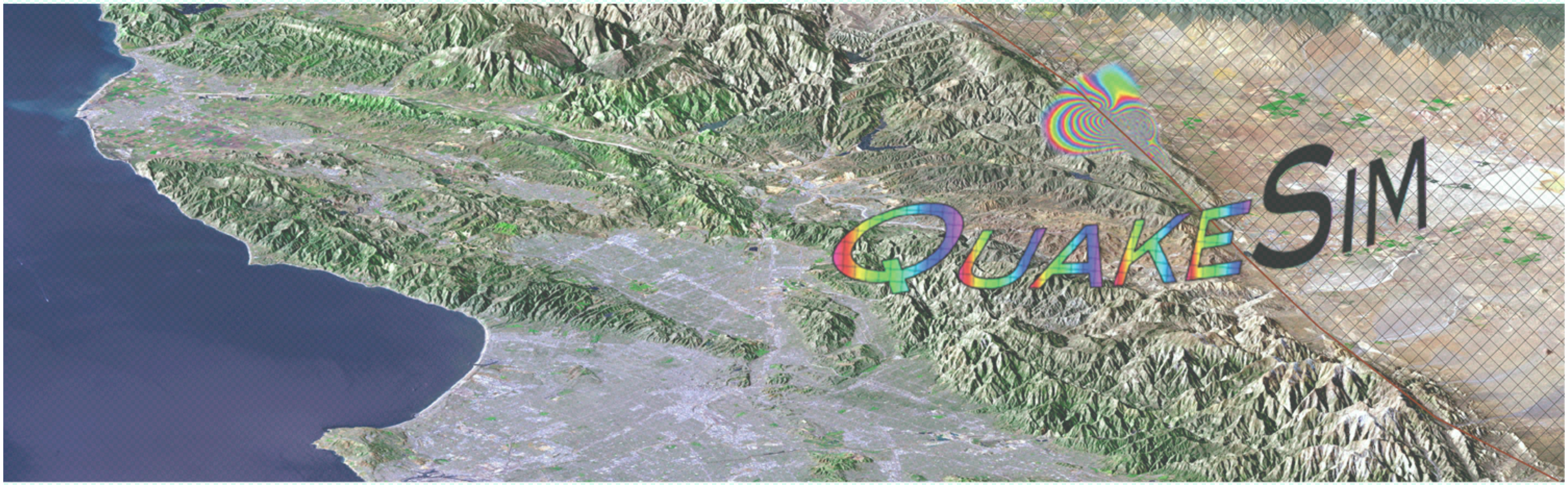

stepover 2 mesh - y=0 | 3 Nov 2004 |
DISLOC - Dis X
GEOFEST2 - Dis X
DISLOC - Dis Y
GEOFEST2 - Dis Y
DISLOC - Dis Z
GEOFEST2 - Dis Z
Displacement component
0.4
0.2
0
-0.2
-0.4
-20
0
20
X (Km)


stepover 3 mesh - y=0 | 3 Nov 2004 |
DISLOC - Dis X
GEOFEST3 - Dis X
DISLOC - Dis Y
GEOFEST3 - Dis Y
DISLOC - Dis Z
GEOFEST3 - Dis Z
0.4
0.2
0
-0.2
-0.4
Displacement component
-20
0
20
X (Km)


stepover 4 mesh - y=0 | 3 Nov 2004 |
DISLOC - Dis X
GEOFEST4 - Dis X
DISLOC - Dis Y
GEOFEST4 - Dis Y
DISLOC - Dis Z
GEOFEST4 - Dis Z
Displacement component
0.4
0.2
0
-0.2
-0.4
-20
0
20
X (Km)


stepover6 mesh - y=0 | 8 Oct 2004 |
DISLOC - Dis X
GEOFEST6 - Dis X
DISLOC - Dis Y
GEOFEST6 - Dis Y
DISLOC - Dis Z
GEOFEST6 - Dis Z
Displacement component
0.4
0.2
0
-0.2
-0.4
-30
-20
-10
0
10
20
30
X (Km)

Questions?



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