Overview of the PyLith Finite Element Code

www.geodynamics.org

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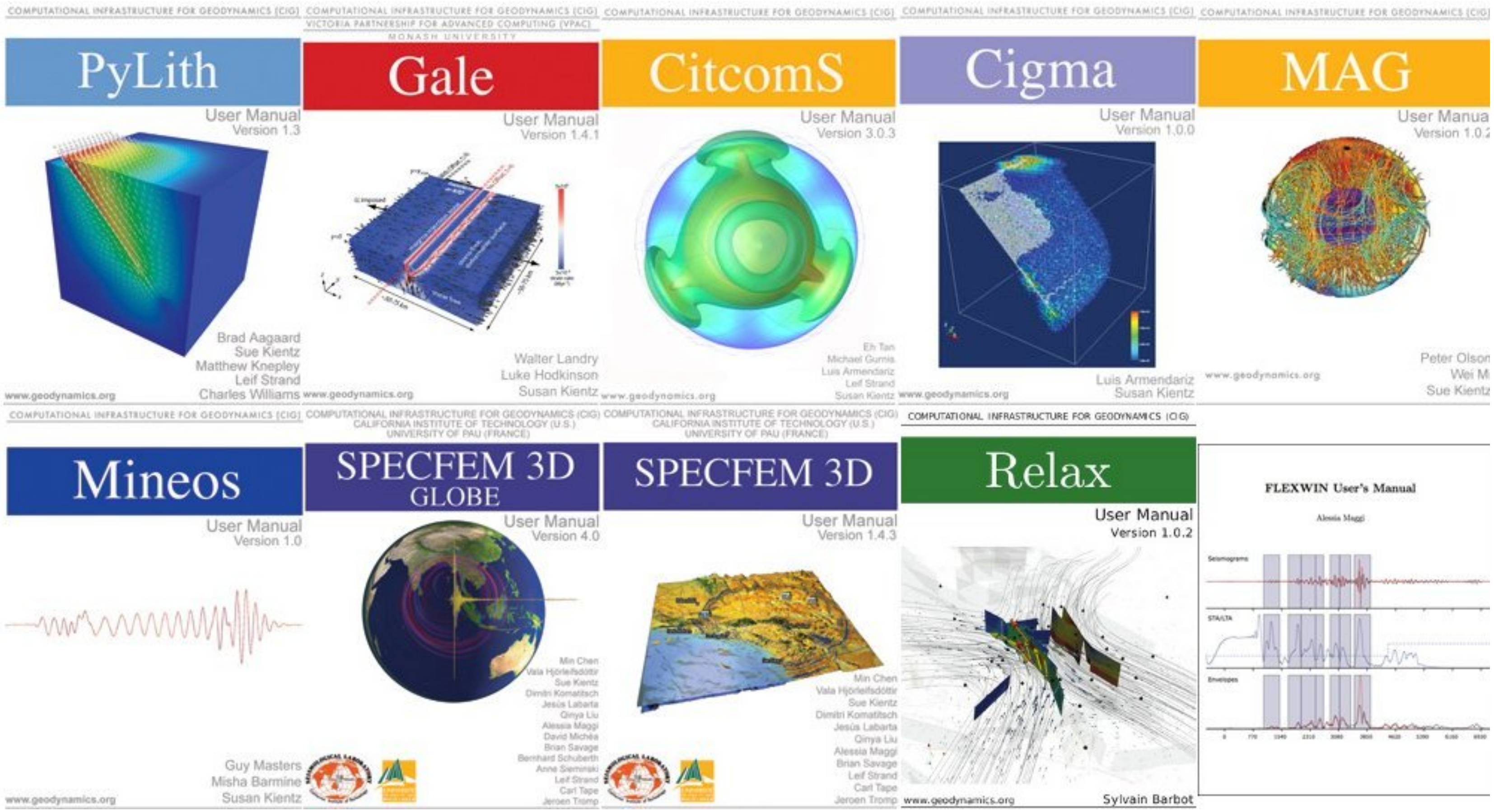
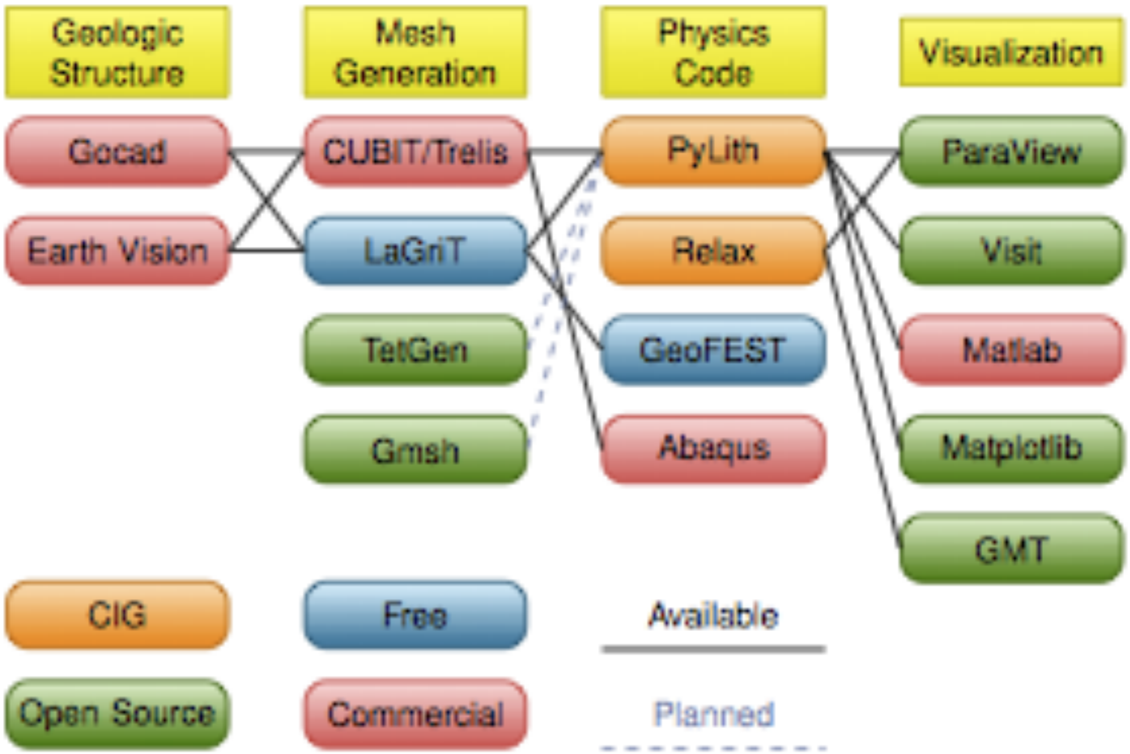
CIG Software



PyLith is a Tool for Crustal Deformation Modeling

- Typical CDM workflow



PyLith Problem Types

- Quasi-static modeling associated with earthquakes:
  - Strain accumulation associated with interseismic deformation:
    - What is the stressing rate on faults X and Y?
    - Where is strain accumulating in the crust?
  - Coseismic stress changes and fault slip:
    - What was the slip distribution in earthquake A?
    - How did earthquake A change the stresses on faults X and Y?
  - Postseismic relaxation of the crust:
    - What rheology is consistent with observed postseismic deformation?
    - Can aseismic creep or afterslip explain the deformation?

PyLith Problem Types (cont.)

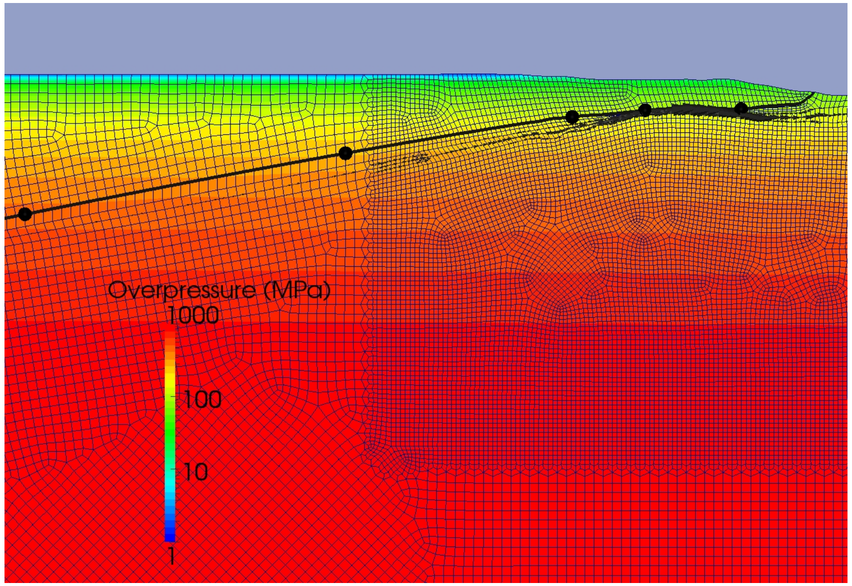
- Dynamic modeling associated with earthquakes:
  - Modeling of strong ground motions:
    - Forecasting the amplitude and spatial variation in ground motion for scenario earthquakes.
  - Coseismic stress changes and fault slip:
    - How did earthquake A change the stresses on faults X and Y?
  - Earthquake rupture behavior:
    - What fault constitutive models/parameters are consistent with the observed rupture propagation in earthquake A?

PyLith Problem Types (cont.)

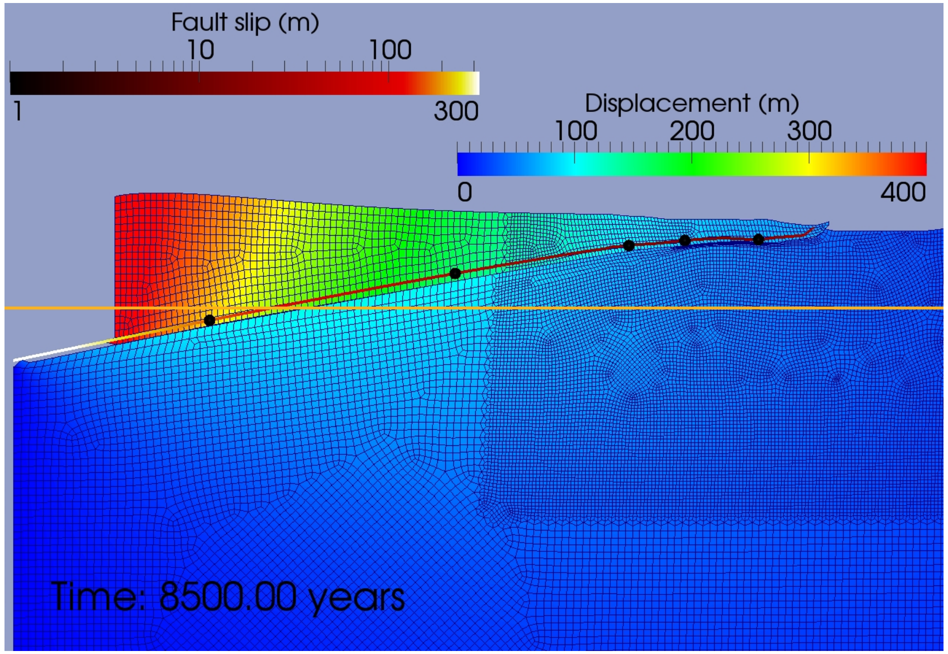
- Volcanic deformation associated with magma chambers and/or dikes/sills:
  - Magma chamber inflation/deflation:
    - What is the geometry and pressure associated with the magma chamber?
    - How close to failure is the material surrounding the chamber?
  - Dike/sill intrusions:
    - What is the orientation and amount of opening associated with the intrusion?

Usage Examples

Frictional fault behavior near a subducting seamount



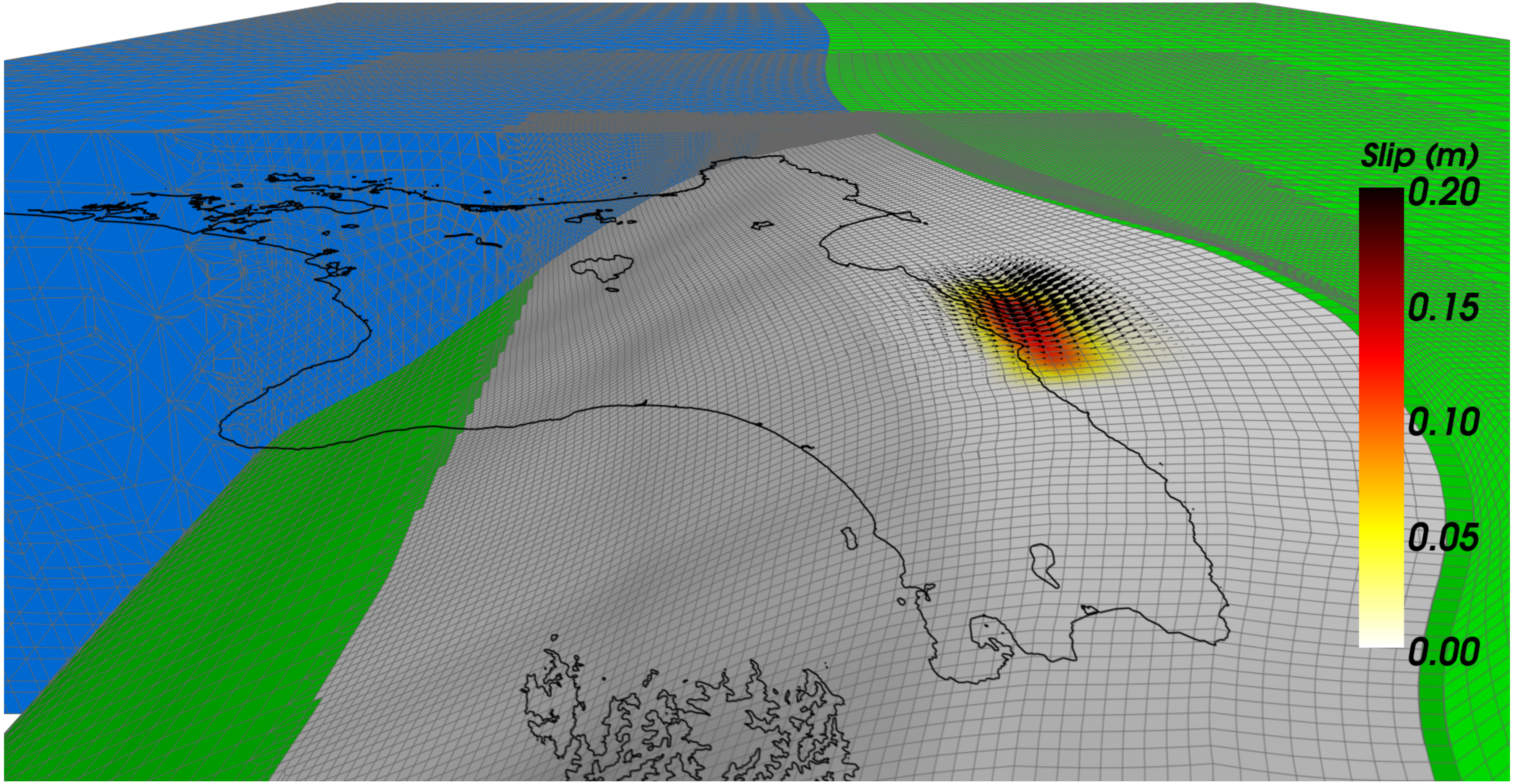
SUTRA fluid flow model



PyLith frictional model

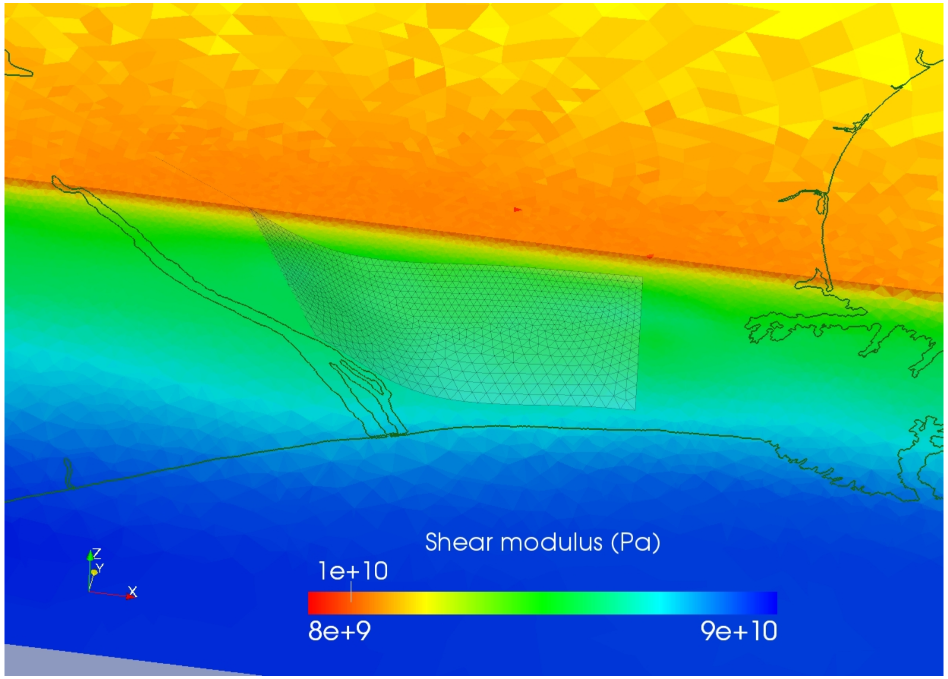
Usage Examples (cont.)

Modeling of Slow Slip Events

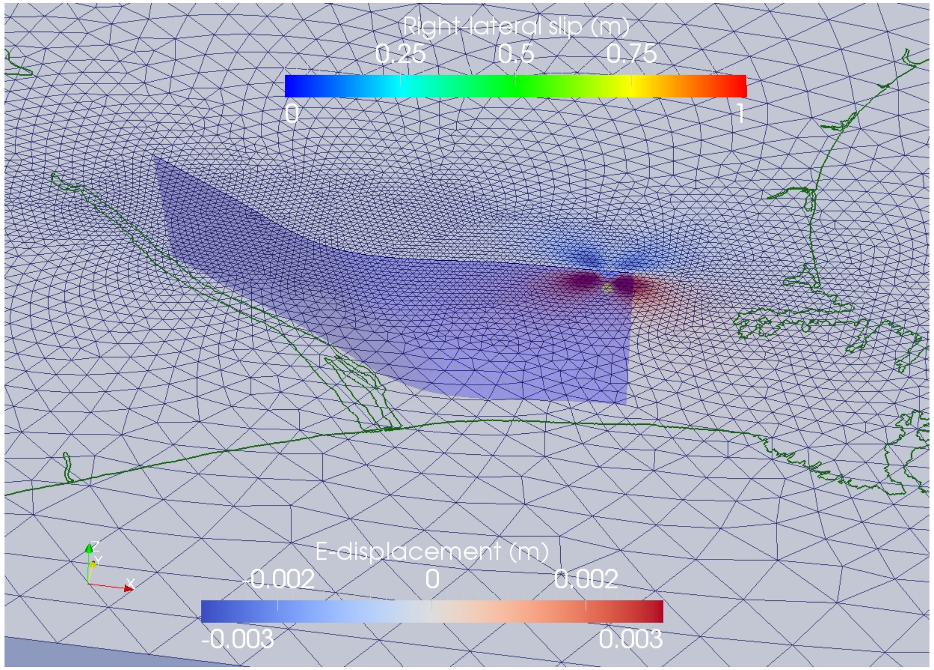


Usage Examples (cont.)

Generation of Green's Functions for Darfield Earthquake



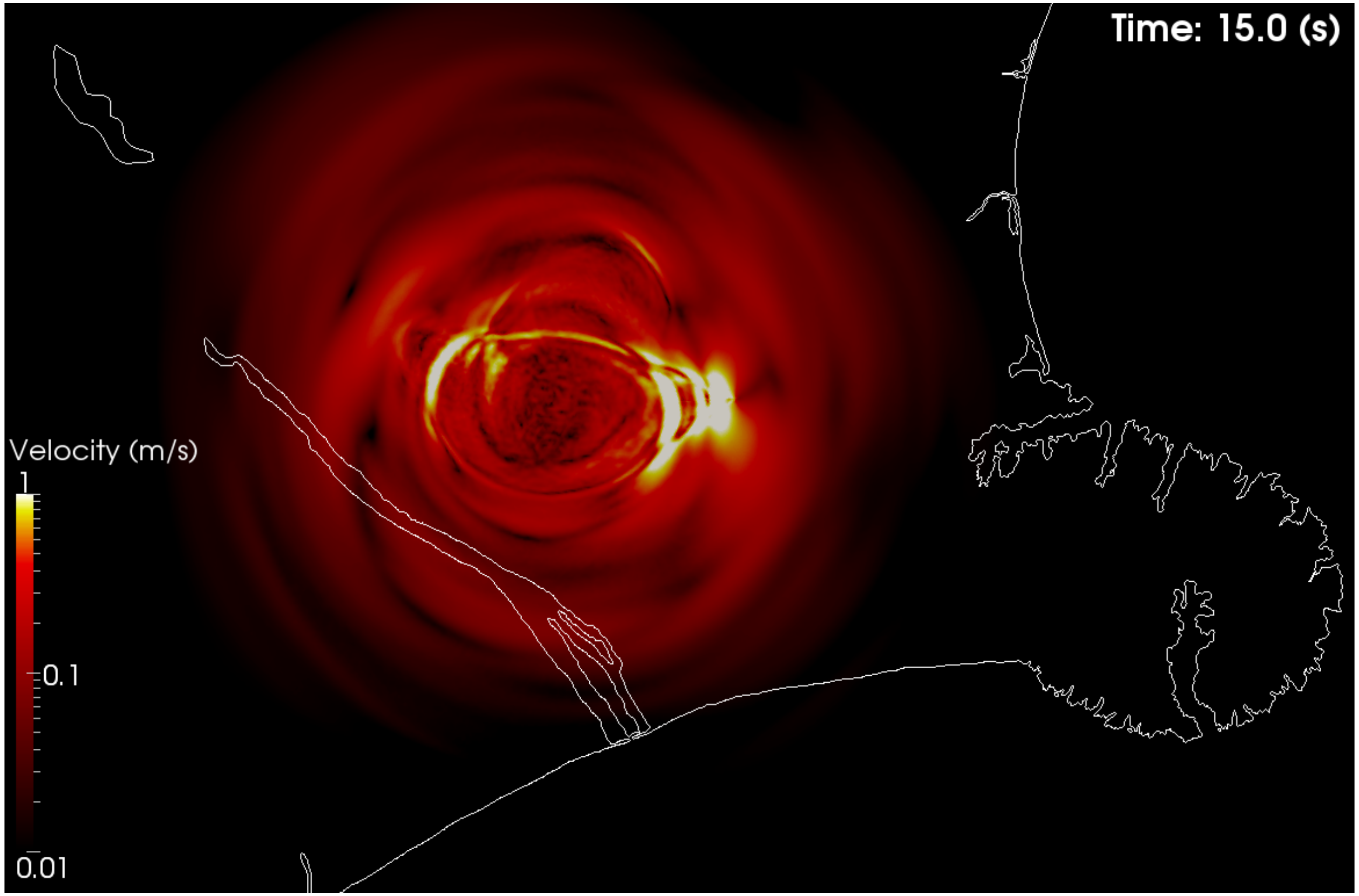
Elastic properties from NZ-wide velocity model



Surface response due to unit Slip on Greendale fault

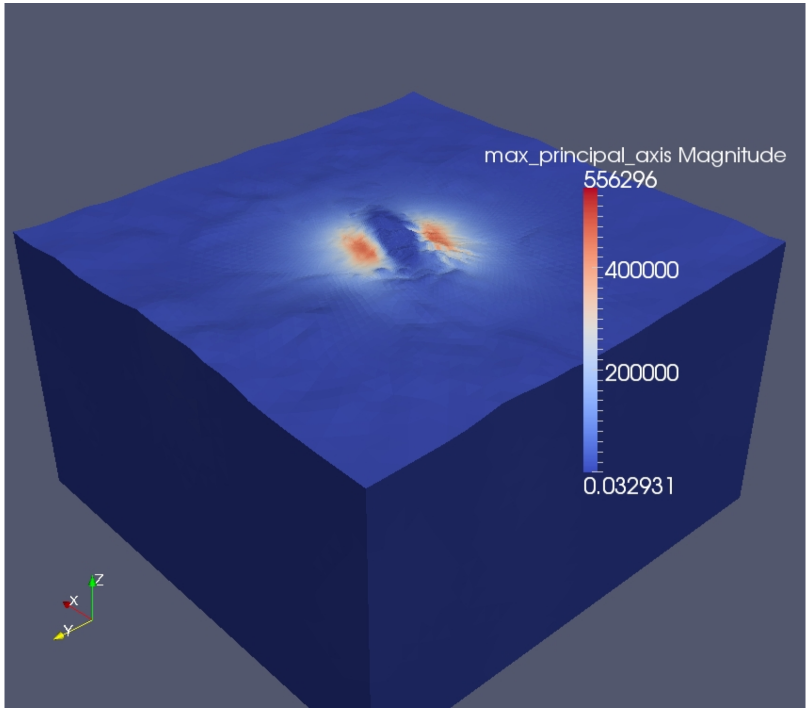
Usage Examples (cont.)

Dynamic rupture simulation of Darfield earthquake

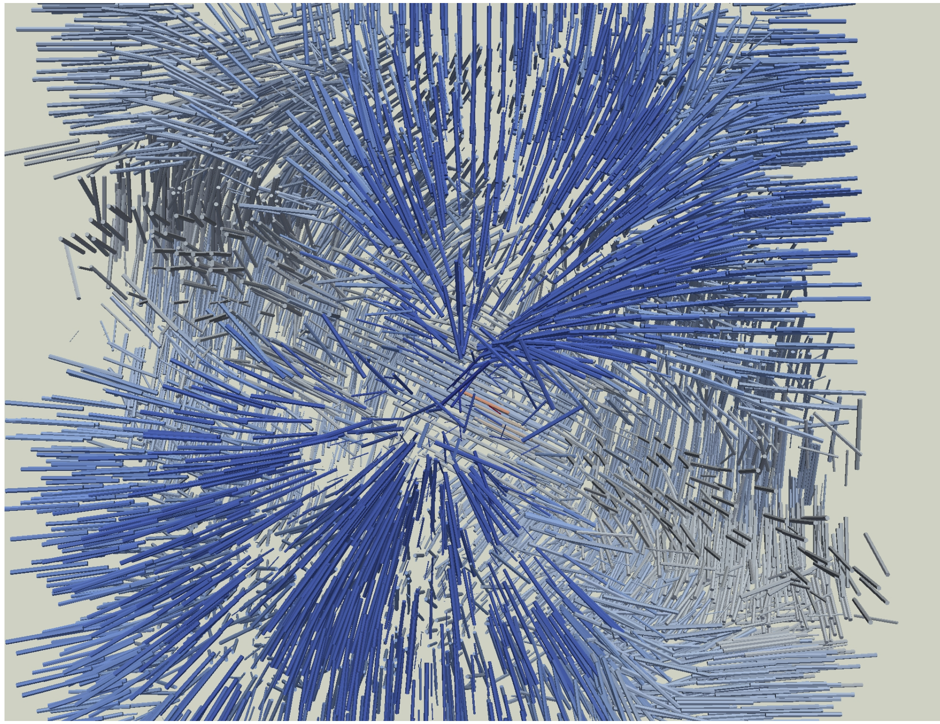


Usage Examples (cont.)

Stress changes due to dike intrusion at Mt. Asama volcano



Maximum principal stress magnitude



Maximum principal stress orientation

Ingredients for Running PyLith

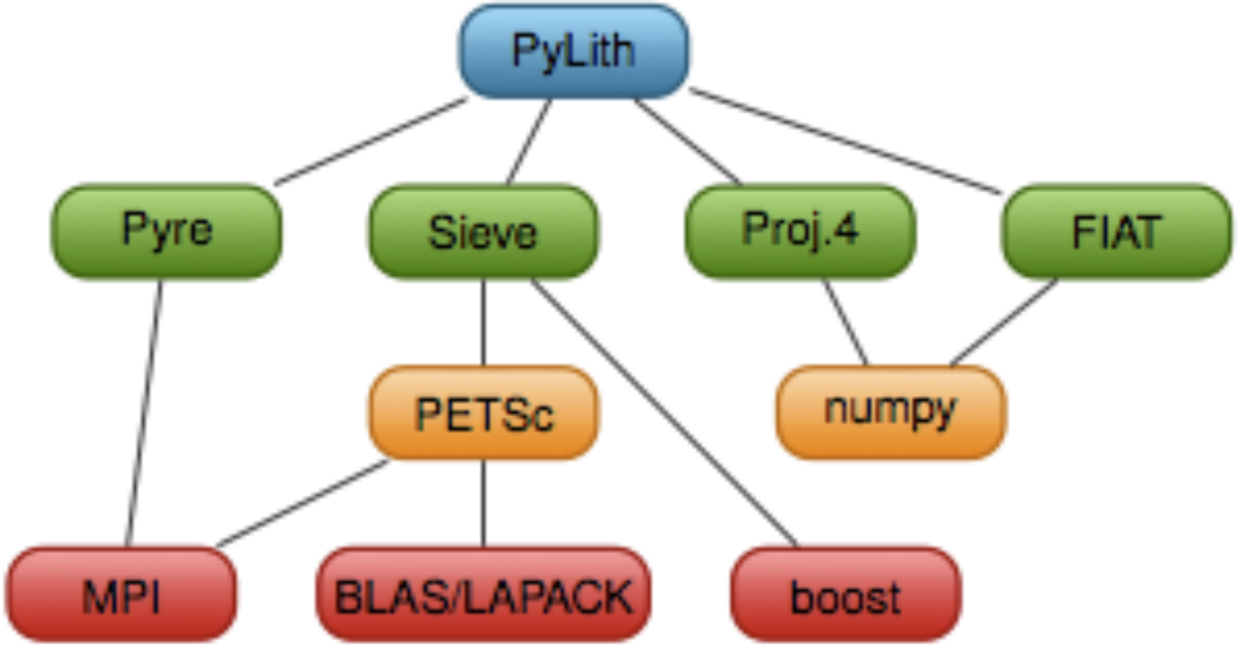
- Finite-element mesh
  - Mesh exported from LaGriT
  - Mesh exported from CUBIT
  - Mesh constructed by hand (PyLith mesh ASCII format)
- Simulation parameters
  - Command-line
  - Parameters in .cfg file
- Spatial databases for physical properties, boundary conditions, and rupture parameters
  - SCEC CVM-H, USGS Bay Area Velocity Model
  - Simple ASCII files

Spatial Databases

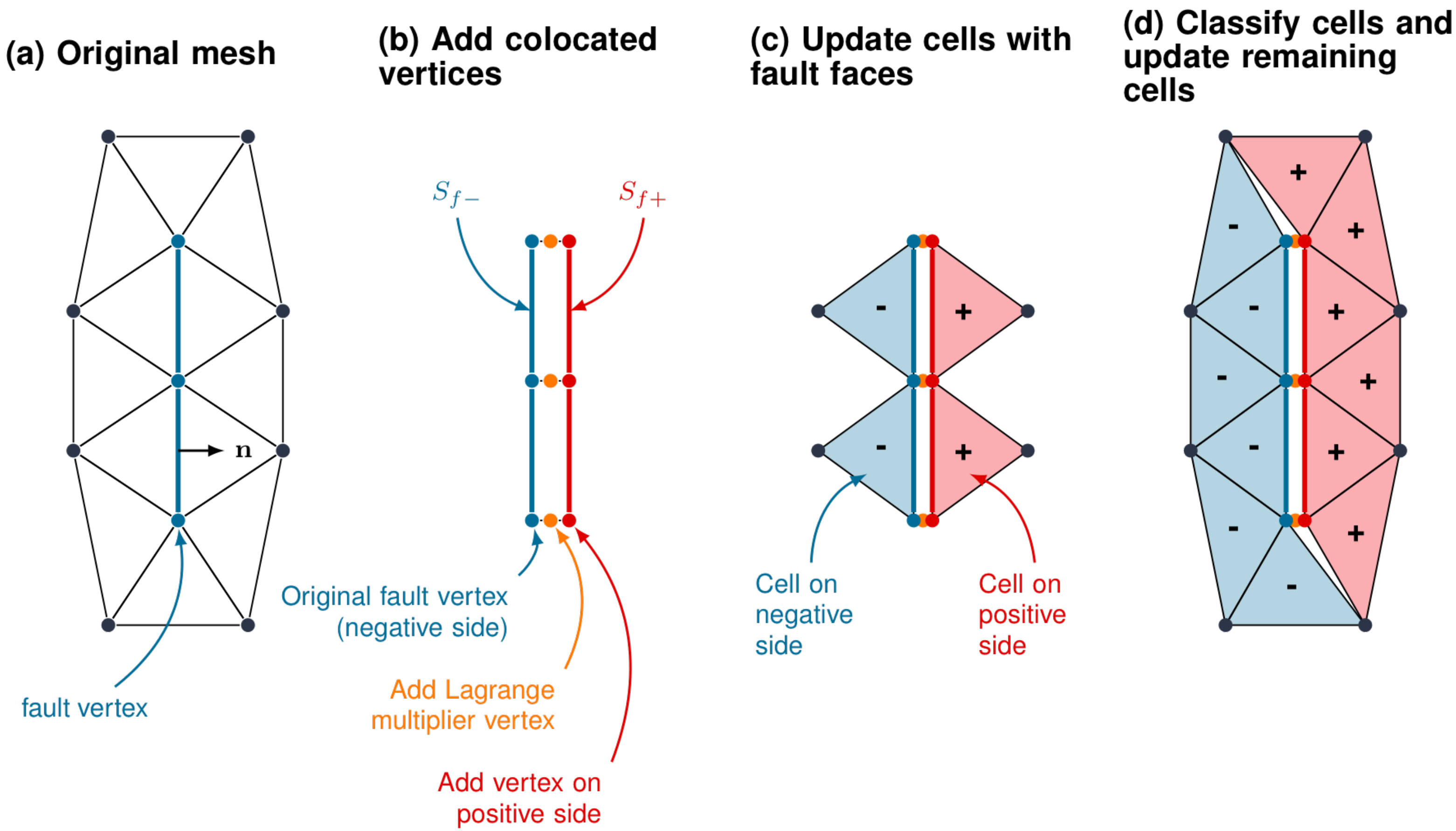
- Examples
  - Uniform value for Dirichlet (0D)
  - Piecewise linear traction variation for Neumann BC (1D)
  - SCEC CVM-H seismic velocity model (3D)
- Generally independent of problem discretization
- Available spatial databases
  - UniformDB Optimized for uniform value
  - SimpleDB Simple ASCII files (0D, 1D, 2D, or 3D)
  - SCECCVMH SCEC CVM-H seismic velocity model v5.3
  - SimpleGridDB Gridded data (1D, 2D, or 3D)
  - ZeroDispDB Special case of UniformDB

PyLith: Focus on Geodynamics

- Leverage packages developed by computational scientists



Fault Implementation



Implementing Fault Slip with Lagrange Multipliers

- Advantages
  - Fault implementation is local to cohesive cell
  - Solution includes tractions generating slip (Lagrange multipliers)
  - Retains block structure of matrix, including symmetry
  - Offsets in mesh mimic slip on natural faults
- Disadvantages
  - Cohesive cells require adjusting topology of finite-element mesh
  - Scalable preconditioner/solver is more complex

PyLith 1.9 Features

- Time integration schemes and formulations
  - Implicit for quasistatic problems (neglect inertial terms)
    - Infinitesimal strains
    - Small strains (~30-40%)
  - Explicit for dynamic problems
    - Infinitesimal strains
    - Small strains (~30-40%)
    - Numerical damping via viscosity

PyLith 1.9 Features (cont.)

- Bulk constitutive models
  - Elastic model (1D, 2D, and 3D)
  - Linear Maxwell viscoelastic models (2D and 3D)
  - Generalized Maxwell viscoelastic models (2D and 3D)
  - Power-law viscoelastic model (2D and 3D)
  - Drucker-Prager elastoplastic model (2-D and 3-D)

PyLith 1.9 Features (cont.)

- Boundary and interface conditions
  - Time-dependent Dirichlet BC
  - Time-dependent Neumann (traction) BC
  - Absorbing BC
  - Kinematic (prescribed slip) faults w/multiple ruptures
  - Dynamic (friction) fault interfaces
  - Time-dependent point forces
  - Gravitational body forces

PyLith 1.9 Features (cont.)

- Fault constitutive models
  - Kinematic (specified slip)
  - Static friction
  - Linear slip-weakening friction
  - Linear time-weakening friction
  - Dieterich-Ruina rate and state friction w/aging law

PyLith 1.9 Features (cont.)

- Automatic and user-controlled time stepping
- Ability to specify initial stress/strain state
- Importing meshes
  - LaGriT: GMV/Pset
  - CUBIT: Exodus II
  - ASCII: PyLith mesh ASCII format (for toy problems)

PyLith 1.9 Features (cont.)

- Output: VTK and HDF5 files (parallel I/O for HDF5)
  - Solution over volume
  - Solution over surface boundary
  - Solution interpolated to user-specified points
  - State variables (e.g., stress and strain) for each material
  - Fault information (e.g., slip and tractions)

PyLith 1.9 Features (cont.)

- Automatic conversion of units for all parameters
- Ability to use geographic projections (using Proj.4)
- Automatic generation of static Green's functions
- Parallel uniform global refinement
- PETSc linear and nonlinear solvers
  - Custom preconditioner with algebraic multigrid solver

PyLith Development

- Short-term priorities
  - Under-the-hood improvements
    - New finite-element data structures [done]
    - Support higher order basis functions [in progress]

      Provides much higher resolution for a given mesh
    - Prepare for multi-physics [done]
  - Multi-cycle earthquake modeling
    - Resolve interseismic, coseismic, and postseismic deformation
    - Elastic/viscoelastic/plastic rheologies
    - Coseismic slip, afterslip, and creep
- Long-term priorities
  - Multiphysics: Elasticity + Fluid flow + Heat flow
  - Scaling to 1000 processors

PyLith Development: Planned Releases

- v2.0 (Summer 2013)
  - New finite-element data structures
  - Support for higher order basis functions
- v2.1 (Spring 2014)
  - Coupling of quasi-static and dynamic simulations
  - Moment tensor point sources
- v2.2 (Fall 2014)
  - Support for incompressible elasticity
  - Heat and fluid flow coupled to elastic deformation
- v2.x
  - Support for finite-element integrations on GPUs

Where to Get More Info

- Mini-workshop this afternoon
  - Simple example including topography, a spherical magma chamber, and a dike
  - Instructors
    - Charles Williams
    - Adrian Shelley
- CIG website
  - www.geodynamics.org
    - Binaries available for Mac OS X, Linux, and Windows
    - Source code + installer available
    - Extensive manual + example problems
- Subscribe to cig-short mailing list
  - Low/moderate traffic list to report problems, get help, etc.