Numerical Simulation of Fault Systems with Virtual Quake

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Overview

- Introduction
- The Computational Infrastructure for Geodynamics
- Virtual Quake
- Research Code Development Guidelines

My Background

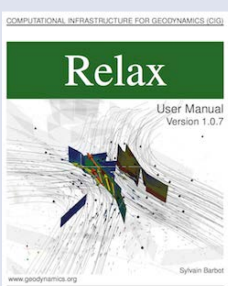
- University of California, Berkeley 2002
- Ph.D. Computer Science, Osaka University, 2010
- Postdocs at UCDavis, INRIA Grenoble Rhone-Alpes
- My research orientation is scientific computation with a computer science focus
- Past projects include work in radio and optical astronomy, symbolic mathematics, evolutionary algorithms, large scale computing systems, biophysics simulations, supercomputer system analysis, geophysics simulation
- Until recently, worked at Computational Infrastructure for Geodynamics (CIG) at UCDavis

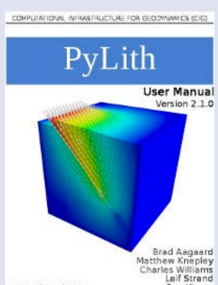
CIG

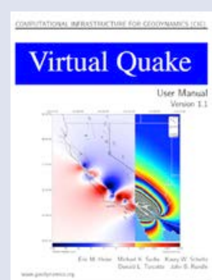
- Computational Infrastructure for Geodynamics
- NSF funded research center
- CIG I – started in 2005 at California Institute of Technology
- CIG II – moved to the University of California, Davis in 2010
- CIG III – scheduled to start in 2015 at UCDavis
- 72 member institutions and international affiliates around the world
- Goal is to “[advance] earth science by developing and disseminating software for geophysics and related fields”
- CIG provides training for earth scientists, organizes workshops, develops research code
- Homepage is at http://geodynamics.org/

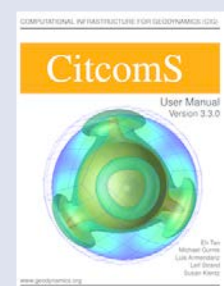
CIG

- Why rewrite geophysics codes that have been already written? Don’t!
- “If I have seen further it is by standing on the shoulders of giants.” – Isaac Newton
- CIG supports researchers and scientists to share and reuse geophysics scientific code
- Covers a wide range of solid earth disciplines including seismology, short term tectonics, long term crustal deformation, mantle convection, geodynamo
- I’ll briefly discuss some codes that may be useful to your research
- All these and more are available at geodynamics.org/cig/software/





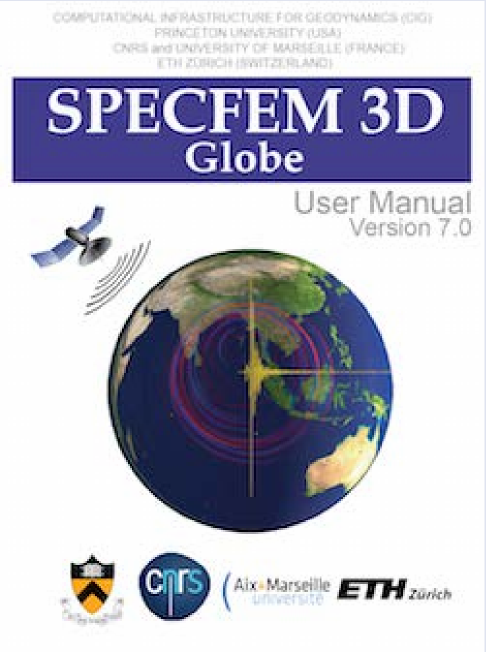




SPECFEM

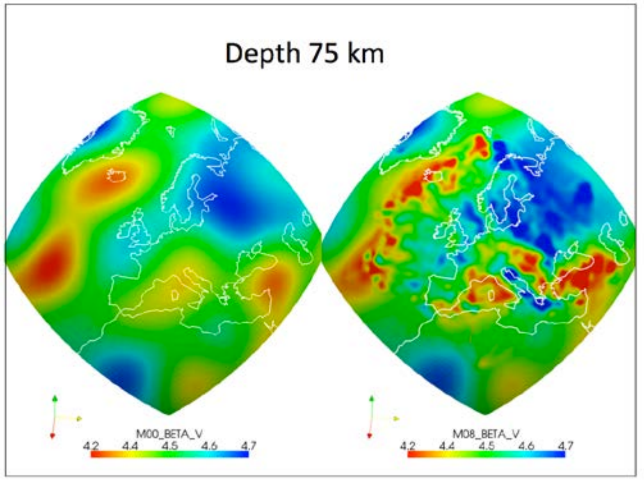
COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

- Numerical modeling of seismic wave propagation using spectral elements
- Multiple variants, including SPECFEM1D, SPECFEM2D, SPECFEM3D Cartesian, SPECFEM3D Globe
- Specify a source mechanism and topography, then determine ground acceleration and shaking at different locations
- Used for seismic tomography inversions



SPECFEM

- Simulate seismic wave propagation through hypothetical model
- Compare synthetic seismograms with actual seismograms
- Update mantle/crust material model accordingly
- Allows for high resolution imaging of whole earth structure
- Huge computational cost (10^3 or more core-years)



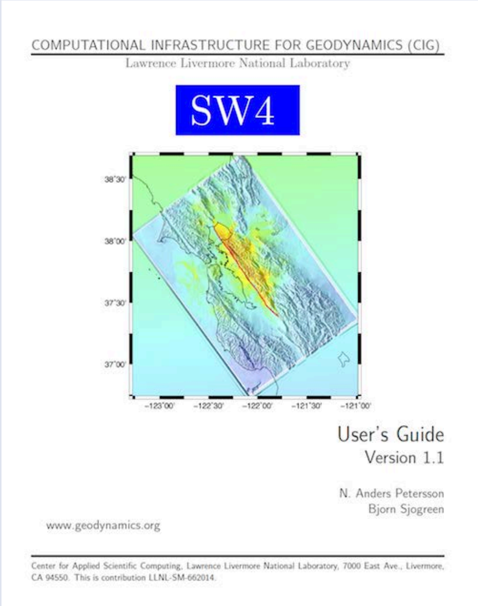
Initial mantle tomography (left) and iteratively refined tomography (right)

SPECFEM

- Example visualization of SPECFEM3D simulation of 1964 Alaska M9.2 earthquake

SW4

- Seismic wave propagation modeling with arbitrary 3D heterogeneous material
- User specified source function
- Free surface condition on top boundary (allows arbitrary topography)
- Developed at Lawrence Livermore National Laboratory
- Used for ground motion prediction
- Available at geodynamics.org/cig/software/sw4/


COMPUTATIONAL INFRASTRUCTURE FOR GEODYNAMICS (CIG)
Lawrence Livermore National Laboratory

SW4

User's Guide
Version 1.1

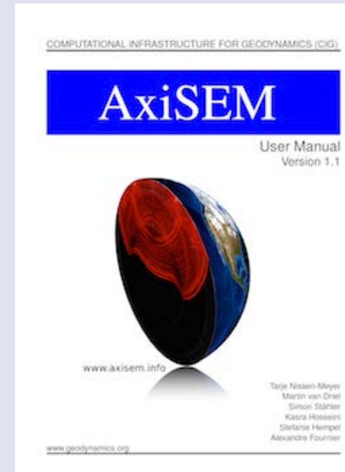
N. Anders Petersson
Bjorn Sjogreen

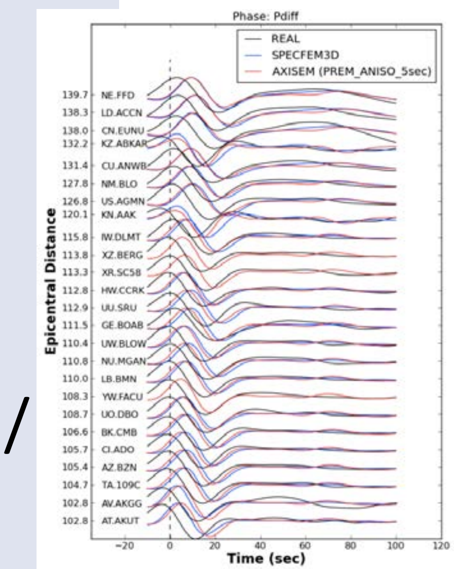
www.geodynamics.org

Center for Applied Scientific Computing, Lawrence Livermore National Laboratory, 7000 East Ave., Livermore, CA 94550. This is contribution LLNL-SM-662014.

AxiSEM

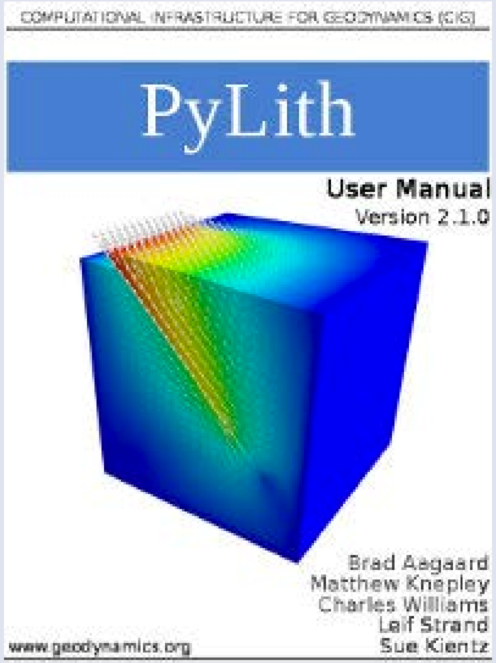
- Spectral element method for 3D (an-)elastic, anisotropic and acoustic wave propagation in spherical domains
- Uses 2.5D approach for fast computation – spherical shell layers are assumed homogeneous
- Uses series of multipoles to calculate response to point source
- Generate synthetic seismograms from source functions propagated through whole globe at high frequencies
- Available at geodynamics.org/cig/software/axisem/





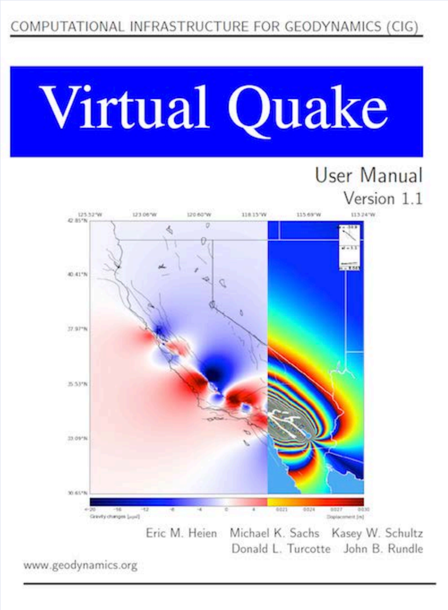
PyLith

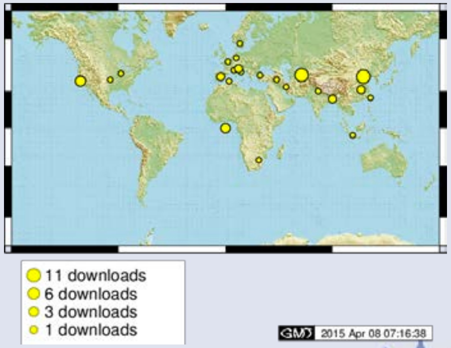
- Finite element code for dynamic and quasistatic simulations of crustal deformation, primarily earthquakes and volcanoes
- Primarily used to do highly detailed study of stress buildup and rupture process of a single fault
  - Strain accumulation associated with interseismic deformation
  - Coseismic stress change and fault slip
  - Postseismic relaxation of the crust
- Available at geodynamics.org/cig/software/pylith/



Virtual Quake

- Virtual Quake (VQ) is a boundary element code that performs simulations of fault systems based on stress interactions between fault elements
- Allows statistical study of fault system behavior and interaction
- Over 100 downloads of the software from dozens of countries
- Freely available at geodynamics.org/cig/software/vq





Overview

- Introduction
- The Computational Infrastructure for Geodynamics
- **Virtual Quake**
- Research Code Development Guidelines

Virtual Quake

- First version written by Prof. John Rundle in 1988
  – Could only model small strike slip fault systems
- Updated in early to mid-2000s by Yakovlev to include major strike-slip faults in California and named “Virtual California”
- In 2010 rewritten by Heien to allow parallel simulation, arbitrary fault systems
- Advanced tools for visualization and analysis written in 2011-2013
- Renamed “Virtual Quake” and publicly released in 2014

Virtual Quake

- Ensemble-domain vs. time-domain simulations
- Time-domain: Understand system behavior by time stepping through single system
  - Generally finite element, or finite difference
  - Examples: SPECFEM, AxiSEM, PyLith
  - Pros: based on PDE rules, can confirm results compared to analytical solutions
  - Cons: very sensitive to initial conditions, very sensitive to model configuration, expensive to calculate (months or years of computer time)

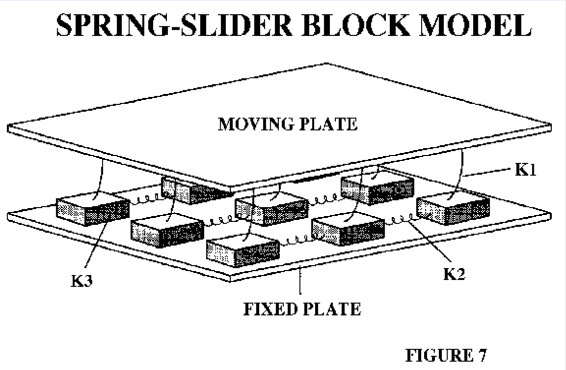
Virtual Quake

COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

- Ensemble-domain: Understand system behavior in a statistical manner by studying multiple systems
  - Examples: Virtual Quake, climate simulations
  - Pros: less sensitive to initial conditions or system configuration, can be less expensive to calculate (hours or days of computer time)
  - Cons: difficult to exactly compare with mathematical or experimental models
- We don't know the current stress state of the faults
  - Run an ensemble of simulations to determine which paths (series of earthquake events) are most likely

Virtual Quake

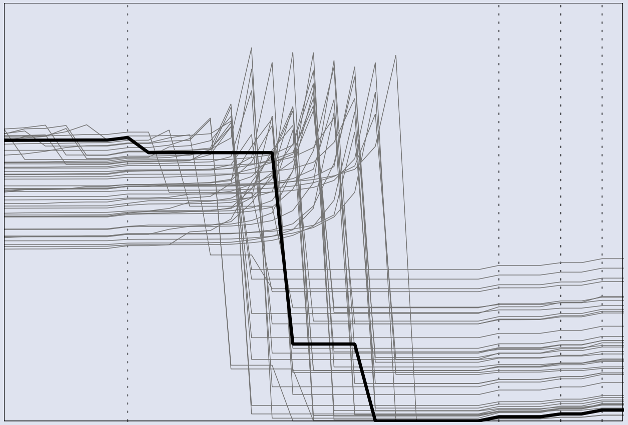
- In VQ the earthquake cycle is divided into two parts
  - Long term stress accumulation (slider block model)
  - Rapid release of stress during rupture
- Long term stress accumulation
  - Displacements of faults in the crust generate stress in surrounding areas
  - Displacement is modeled by movement of fault patches at a specified constant rate (long term slip rate)
  - Fault patches do not actually move over time, but rather slip back to their original position during a rupture event



Courtesy (Bak, 1996)

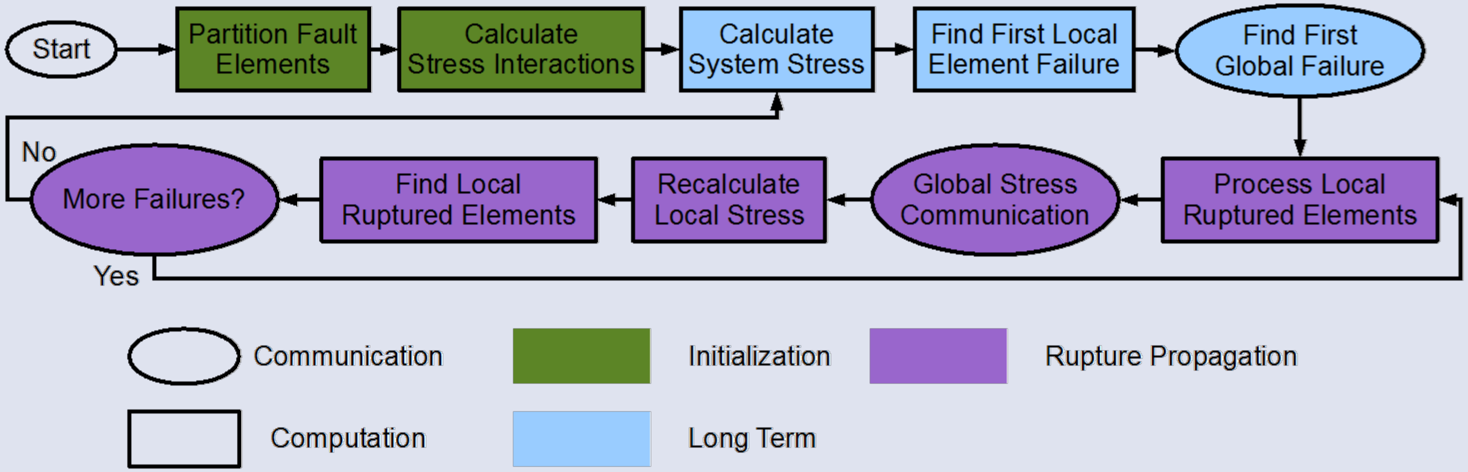
Virtual Quake

- Release of stress during rupture
  - Fault element failure (rupture) is determined by Coulomb failure function (CFF)
  - Faults can experience either static or dynamic failure
  - Static failure: normal stress is overcome by shear stress and fault fails (CFF > 0)
  - Dynamic failure: change in stress during a rupture is high enough that element fails while CFF < 0
  - Rupture occurs in multiple steps, or "sweeps" (shown right)



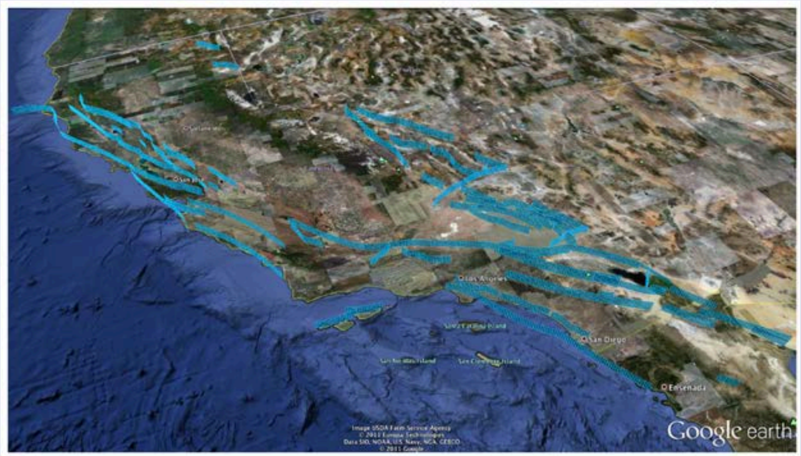
Virtual Quake

- Simulation flow
  - Stress accumulation in blue
  - Rupture propagation in purple



Virtual Quake

- Fault System Mesher
  - Before running a simulation, fault geometry must be specified
  - Define points along fault traces and specify fault parameters at each point (depth, rake, dip, etc)
  - The mesher creates a set of elements corresponding to the faults with the specified parameters
  - The simulation uses this mesh to calculate stress interaction and rupture mechanics



California fault system meshed with 3km x 3km elements

Virtual Quake

- Mesher supports:
  - Input from fault traces (CA faults included with VC), EQSim format
  - Output to ASCII, HDF5, KML
  - Mixing elements of different resolution
  - Simple addition/removal of faults
  - Merging duplicate vertices to reduce space, clarify fault element connectivity
  - Automatic stress/friction calculation appropriate to model

TableView - vertices - / - /Users/eheien/Downl...

Table

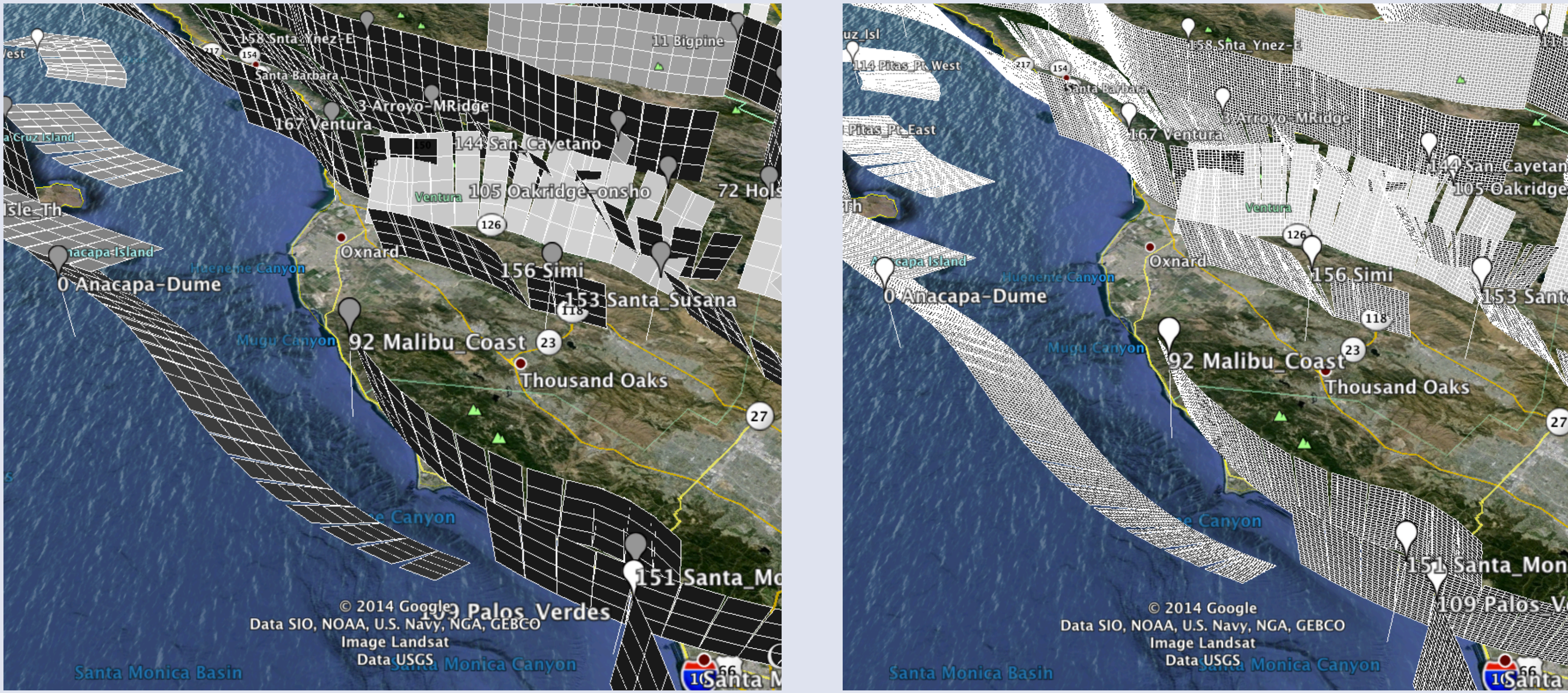
0, id = 0

	id	latitude	longitude	altitude
0	0	33.987	-119.48	0.0
1	1	33.967983	-119.482...	-2121.122
2	2	33.98408	-119.447...	0.0
3	4	33.94897	-119.484...	-4242.244
4	5	33.96507	-119.4502	-2121.122
5	7	33.929955	-119.487...	-6363.36...
6	8	33.946053	-119.452...	-4242.244
7	10	33.91094	-119.489...	-8484.488
8	11	33.92704	-119.455...	-6363.36...
9	13	33.965046	-119.449...	-2123.95...
10	14	33.981827	-119.415...	0.0
11	15	33.965046	-119.449...	-2123.95...
12	16	33.94601	-119.451...	-4247.90...
13	17	33.96279	-119.417...	-2123.95...
14	18	33.94601	-119.451...	-4247.90...
15	19	33.92698	-119.453...	-6371.85...
16	20	33.94376	-119.419...	-4247.90...
17	21	33.92698	-119.453...	-6371.85...
18	22	33.907944	-119.455...	-8495.809
19	23	33.924725	-119.421...	-6371.85...
20	24	33.981827	-119.415...	0.0
21	25	33.962738	-119.416...	-2120.46...
22	26	33.98	-119.382...	0.0
23	27	33.962738	-119.416...	-2120.46...
24	28	33.94365	-119.418...	-4240.93...
25	29	33.96091	-119.384...	-2120.46...
26	30	33.94365	-119.418...	-4240.93...
27	31	33.92456	-119.420...	-6361.40...

HDF5 CA Model File

Virtual Quake

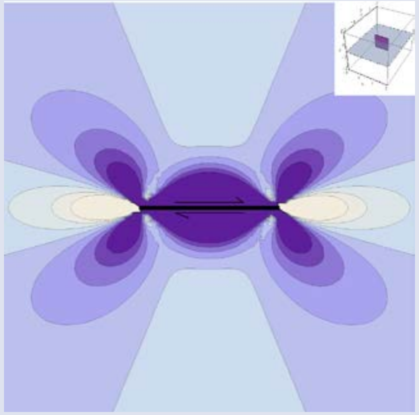
COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS



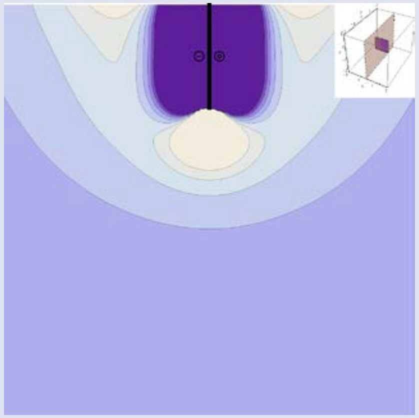
Southern CA faults meshed at 3km resolution (left) and 500m resolution (right)

Virtual Quake

- Long term stress accumulation
  - Interaction between fault elements is modeled by Okada implementation[1] of stress transfer Greens function
  - Functions relate point or rectangular patch displacement to surrounding a) displacement field, b) stress field, c) gravity changes
  - Interactions between N elements is stored as an NxN matrix



Strike slip fault stress field (top view)



Strike-slip fault stress field (side view)

[1] Internal Deformation Due to Shear and Tensile Faults in a Half-Space, Y. Okada 1992

Virtual Quake

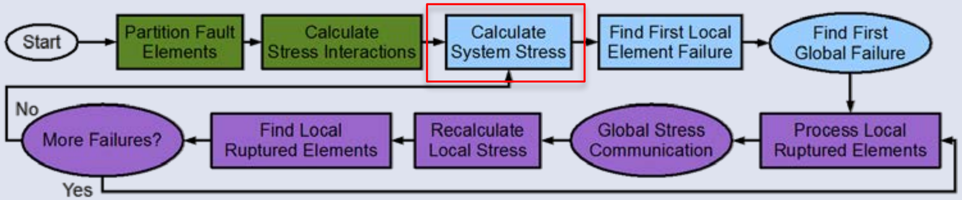
- Long term stress accumulation
  - Calculate stress interaction between all elements and store in a matrix where T^{AB} is the stress change on A caused by B moving a unit distance
  - Buildup of stress on element A is determined by

$$\sigma_{ij}(x,t) = \int dx'_k T^{kl}_{ij}(x-x')s_l(x',t)$$

  - or in the matrix notation

$$\sigma^A_{ij}(t) = \sum T^{AB}_{ij} s_B(t)$$

  - This is equivalent to a matrix-vector multiply

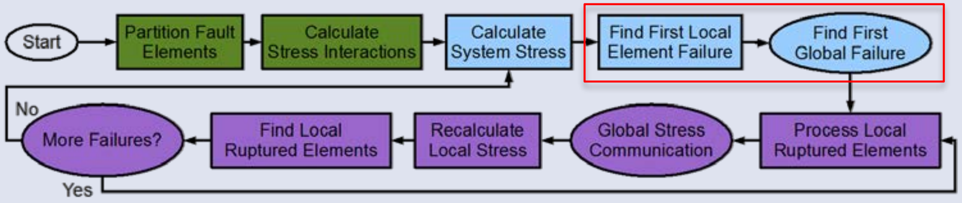


Virtual Quake

- Initial fault element failure
  - VQ uses the CFF (Coulomb Failure Function) to determine when an element fails

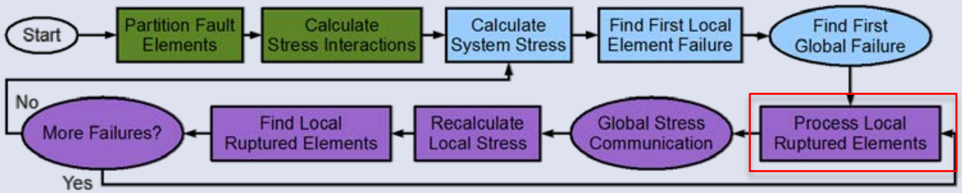
$$CFF^A(t) = \sigma_s^A(t) - \mu_s^A \sigma_n^A(t)$$

  - VQ treats normal stress as constant and shear stress as increasing, so eventually a fault will fail due to the CFF criteria
    - Can have variable normal stress for thrust faults
  - An element fails when CFF > 0, which means shear stress overrides normal stress and friction



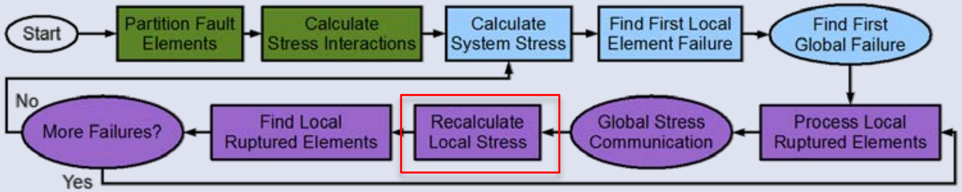
Virtual Quake

- Rupture propagation
  - For a failed element, initial slip is determined by the relation $\Delta s = \frac{1}{K_L}(\Delta\sigma - CFF).$
    where K_L is the self-shear stress of the element
  - In previous versions of VQ (and most other similar codes), element slip was prescribed in the model by modifying the stress drop (Δσ)
  - This allowed the user to force faults to have arbitrary magnitude earthquakes
  - In the current version of VQ, initial slip is determined mathematically to ensure faults obey scaling laws



Virtual Quake

- Rupture propagation
  - After elements have been processed, we determine if more elements will fail
  - Elements can rupture due to static failure (CFF>0) or dynamic failure
  - Dynamic failure occurs if $\frac{CFF_{init} - CFF_{final}}{CFF_{init}} > \eta$ and corresponds to how likely the crack tip will propagate
  - The value of η determines how much a rupture will grow (small η means larger earthquakes)



Virtual Quake

- Rupture propagation
  - We have tried using rate state friction based on the standard formulation
  - This is an advanced friction model that allows for fault healing and slow stress buildup
  - Nondimensional version on the equations is shown to the right
  - For a single block within a range of parameters this works as a good model
  - However, because of the ln(V) and ln(Θ) terms in the force, V and Θ must not become negative
  - With coupled block systems you cannot guarantee these will not be negative because of the interaction with other blocks
  - Most "rate-state" simulators use a simplified form of these equations

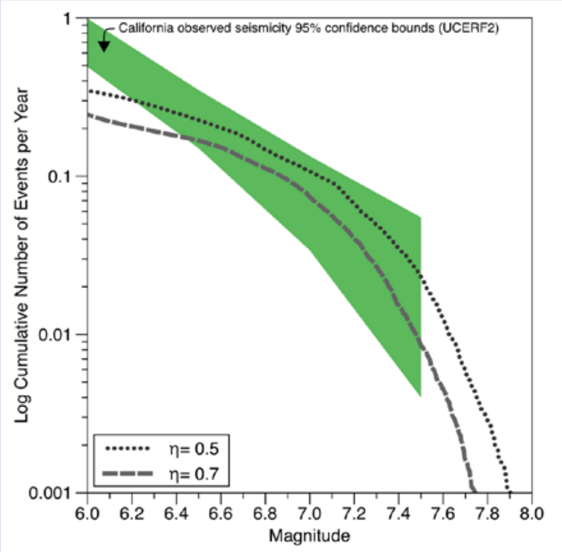
$$R\frac{dV}{dT} = T - X - KF, \qquad \frac{dX}{dT} = V$$

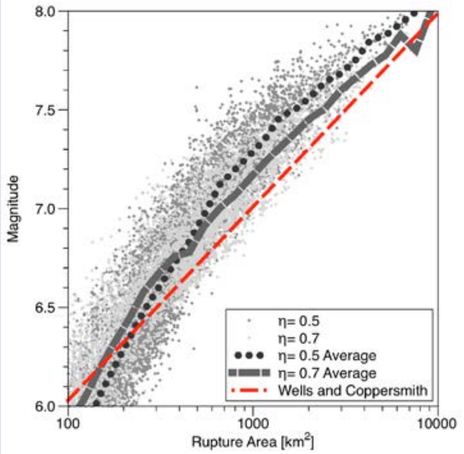
$$F = 1 + A\ln V + B\ln\Theta$$

$$\frac{d\Theta}{dT} = 1 - \Theta V, \qquad \text{slowness law}$$

Virtual Quake

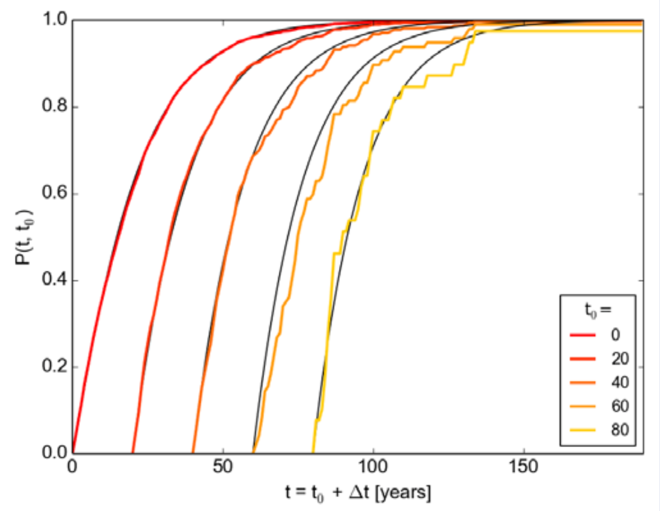
- The parameter η must be tuned to best match actual magnitude-frequency distributions
- In our experience, η=0.4 to 0.8 is generally best
- Plots on the right show how well frequency magnitude corresponds to common models
  - Top is UCERF2 observed seismicity
  - Bottom is Wells and Coppersmith relation
- Within the η=0.5 to 0.7 range we get good fit to observed seismicity





Virtual Quake

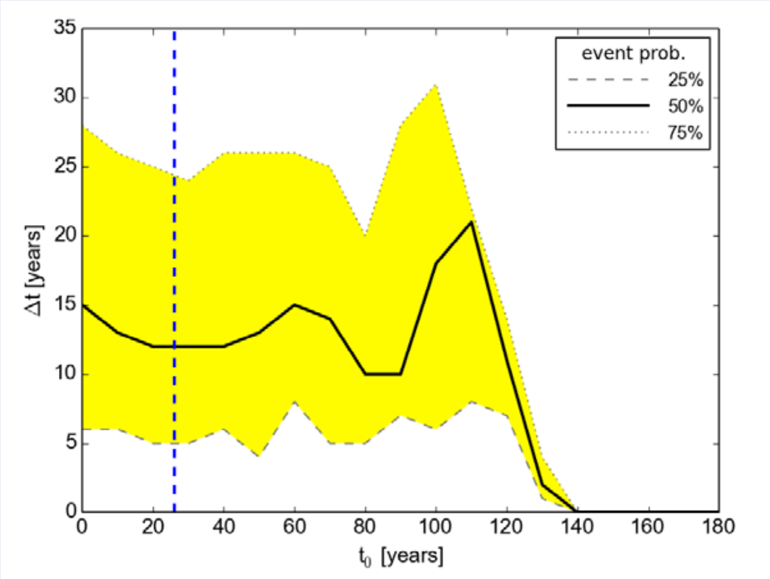
- By running a long simulation and analyzing the event catalog, we can make forecasts about interval times
- Figure on the right shows the conditional cumulative probability of a M≥7.0 earthquake on forecasted faults (Northern CA)



- Based on event catalog from VQ simulation covering thousands of years (multiple event cycles)
- Distribution is evaluated at $t=t_0+\Delta t$ with the last earthquake occurring t_0 years ago

Virtual Quake

- Forecast waiting times for next M≥7.0 earthquake on northern CA faults
- Dark line is median waiting time (50% probability)
- Yellow band is 25-75% probability band



- The dashed vertical line indicates elapsed time since last M≥7.0 (Loma Prieta 1989)
- Based on this, 25% probability of M≥7.0 in northern CA within ~5 years

Virtual Quake

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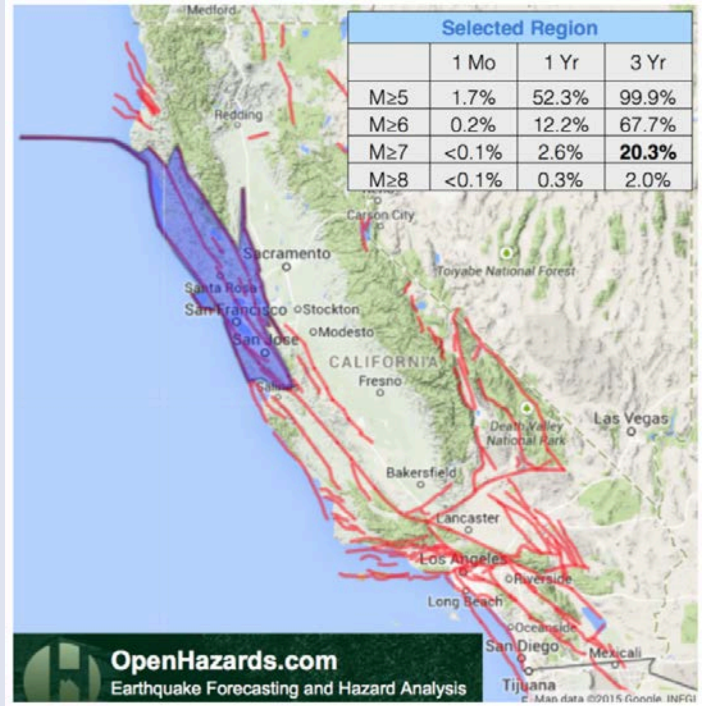
- VQ comparison to other forecasts
- OpenHazards.com
  - Provides free magnitude/time estimates for arbitrary regions
  - Operated by Prof. John Rundle
- Estimate of M≥7 over next 3 years is 20.3%
- VQ prediction of M≥7 in same area is 14.7%



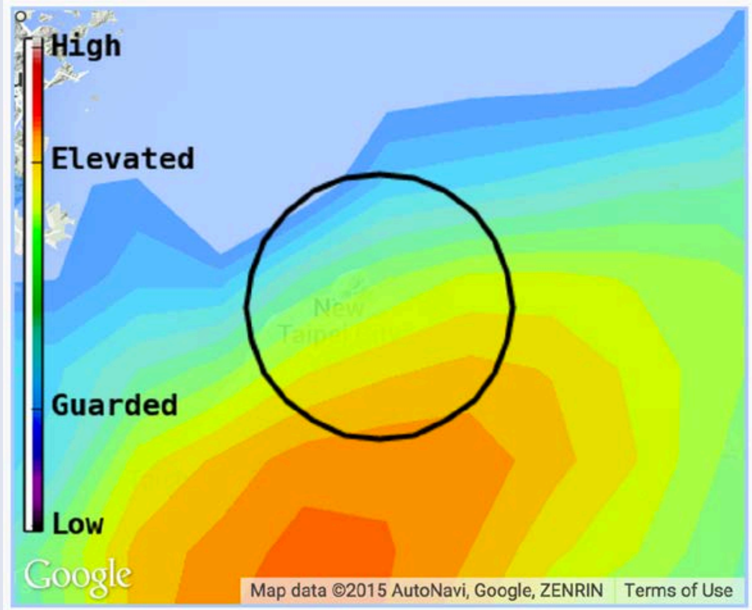
Selected Region

	1 Mo	1 Yr	3 Yr
M≥5	1.7%	52.3%	99.9%
M≥6	0.2%	12.2%	67.7%
M≥7	<0.1%	2.6%	**20.3%**
M≥8	<0.1%	0.3%	2.0%

NSF

Virtual Quake

- Estimate for Taipei area (as of this morning)
- M≥5 in 1 year, 91% probability
- M≥7 in 1 year, only 1.7% probability
- Conditional Weibull method of forecasting (counting earthquakes)



Probability of Earthquake Within 50 Miles of Taipei-Keelung Highway & Tai'an Road, Qidu District, Keelung City, Taiwan 206

	1 Month	1 Year	3 Years
M≥5	3.31%	91.40%	99.9%
M≥6	0.22%	8.58%	53.81%
M≥7	<0.05%	1.68%	13.86%
M≥8	<0.05%	0.16%	1.45%

Fri Apr 10 2015 08:28:45 GMT+0800 (CST)

QuakeLib/PyVQ

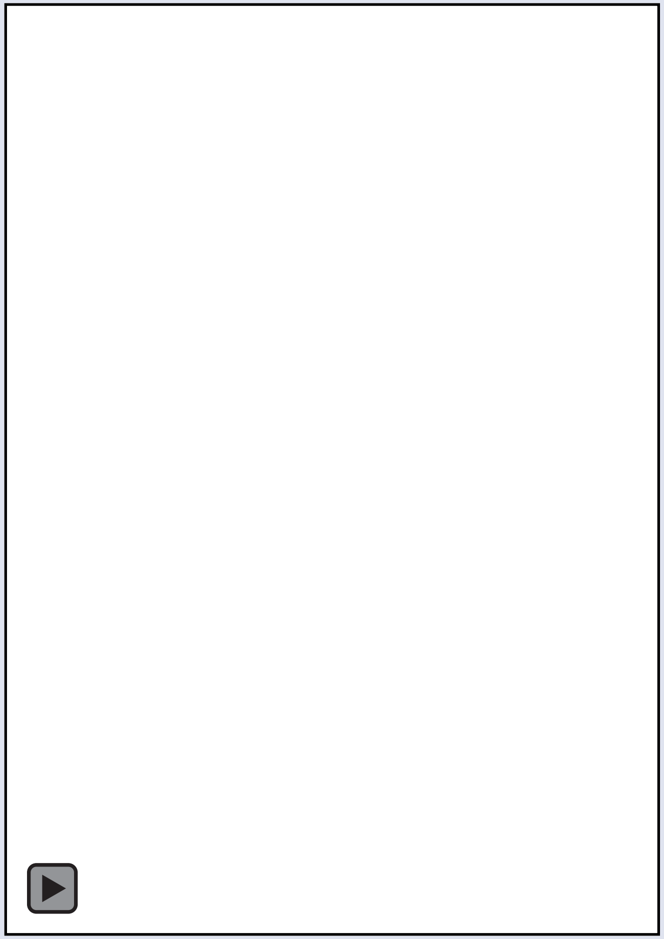
- VQ usage involves the following steps:
  - Create 1D model of fault system based on traces
  - Run trace model through mesher to generate 3D model of fault system
  - Define simulation parameters (simulation length, dynamic rupture propagation parameter, etc)
  - Run simulation(s)
    - Read model file
    - Calculate Greens function
    - Output data files from simulation
  - Analyze output files, generate visualization

QuakeLib/PyVQ

- Most of these steps have computational steps in common
  - Read and write files with the fault model and event history
  - Vector mathematics
  - Manipulating and querying fault representations
  - Stress, displacement, gravity anomaly calculations (based on Greens functions)
- Rather than implementing the same functionality multiple times, VQ uses QuakeLib
- QuakeLib provides access to shared functionality through a C, Python, or other interface

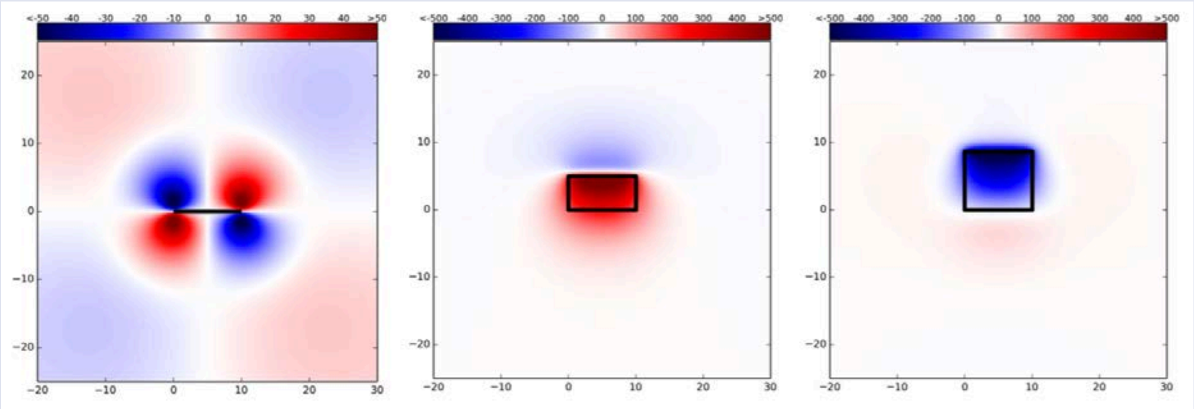
QuakeLib/PyVQ

- Once data is generated from the simulation, tools are needed to analyze and visualize results
- PyVQ is a Python based toolkit built on QuakeLib
- Provides functionality to plot events on maps, magnitude-frequency/cumulative distributions, analyze interevent times, fault interconnectivity
- Right graphic shows a visualization of InSAR interferogram fringes of multiple events from a VQ run



QuakeLib/PyVQ

- PyVQ also calculates gravity changes from displacement of a fault patch
- This will be correlated with NASA GRACE (Gravity Recovery and Climate Experiment) mission data to evaluate gravity changes as a means of detecting faults
- Figure below shows the surface gravitational anomalies for a strike slip fault (left), normal fault (center), and thrust fault (right)
- Gravity anomaly calculations based on Okubo[2]

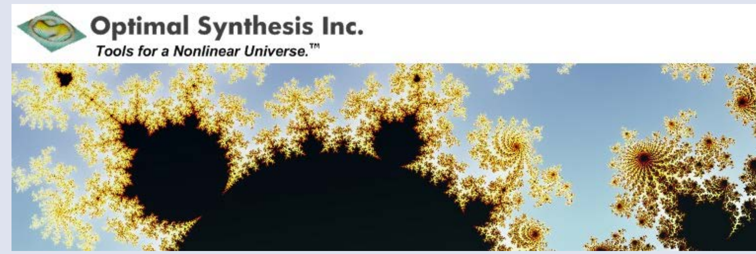


[1] Gravity and potential changes due to shear and tensile faults in a half-space., S. Okubo 1992

GPGPU Support

CIG COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

- Working with Optimal Synthesis we implemented GPU (CUDA) based support for VQ calculations



- Focused on two compute intensive sections of code
  - Green's function calculation (N^2 calculations, each requiring 14,000-45,000 flops)
  - Long term stress calculate (N^2 flops between each event, 1e5-1e7 events per simulation)

Model Name	Elements (N)	Matrix Size	CPU Times (12-Core)
AllCal2_Trunc7453	7453	423.96 MB	371.49s (6m 12s)
AllCal2_NoCreep_13482	13482	1.35 GB	5137.03s (1h 25m)
AllCal_17757	17757	2.35 GB	3432.16s (57m 12s)

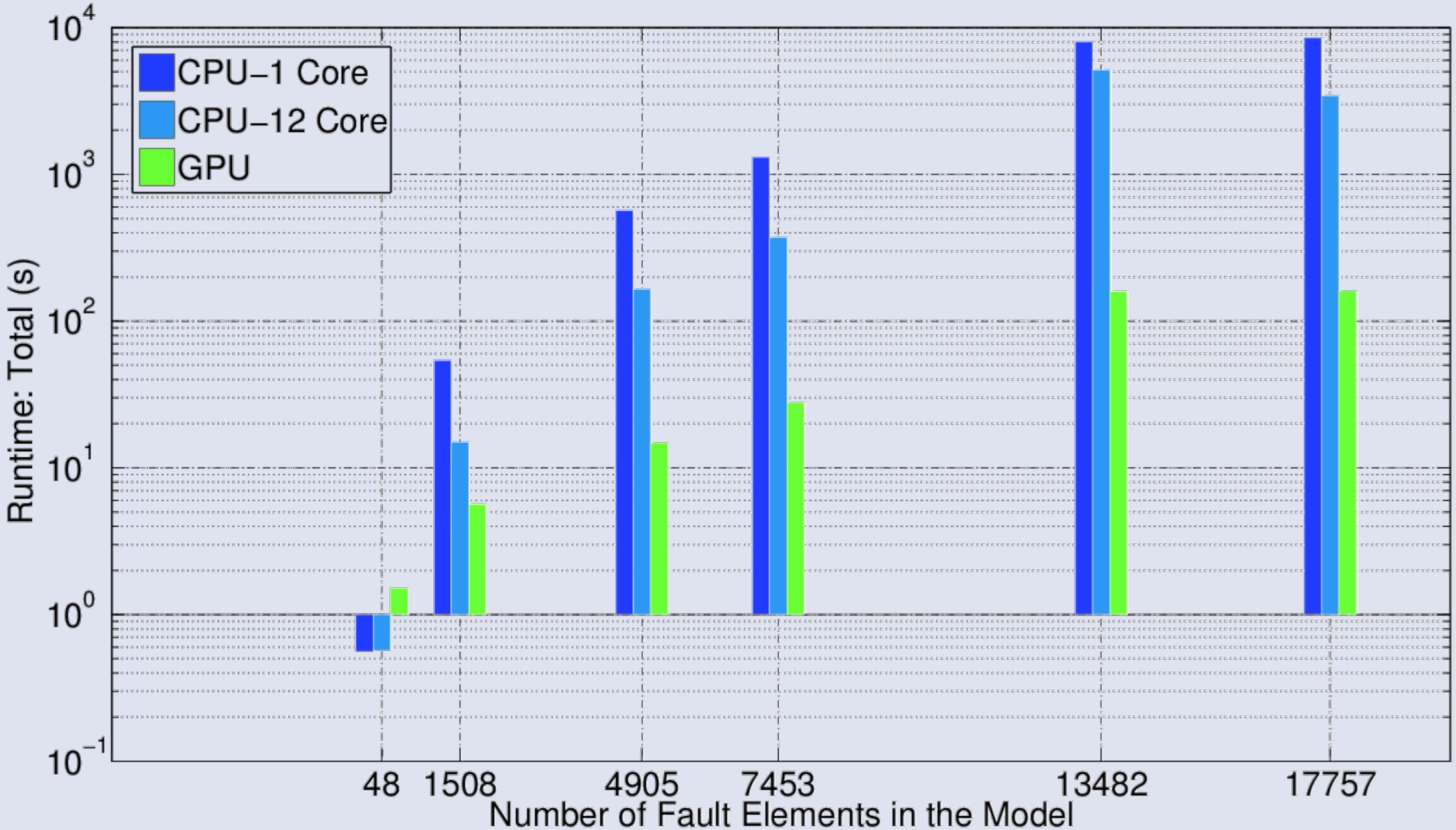
GPGPU Support

- Results on GPU are highly promising
- Green's function calculation is 80x faster than single CPU core, 7.3x faster than 12 cores
  - Branching rarely affects Green's function in normal fault configurations

NVIDIA Titan

- Matrix-vector multiply (stress accumulation phase) is 45x faster than single core, 47x faster than 12 cores (memory bandwidth limited)
- Total simulation runtime is 32-50x faster on GPU

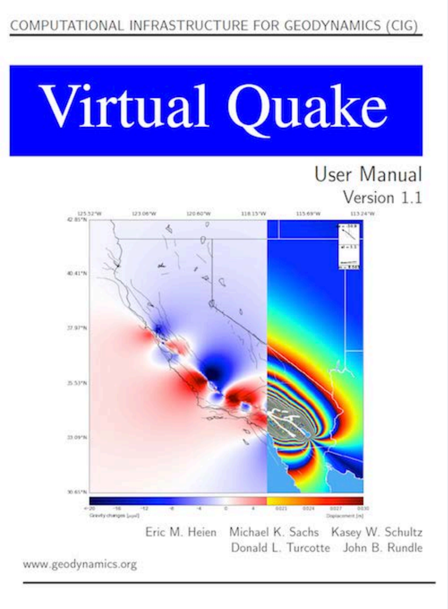
GPGPU Support



(graph courtesy Optimal Synthesis)

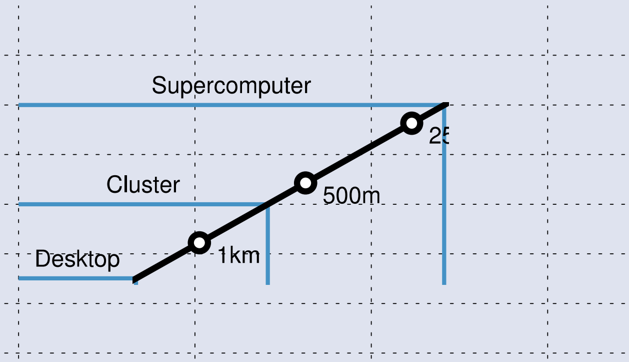
Virtual Quake

- Current version is available at
  - geodynamics.org/cig/software/vq
- Includes
  - Improved mesher
  - Example files, introductory tutorial
  - Manual describing code background, physics equations, and input/output file formats
  - QuakeLib and Python wrappers used for PyVQ and WebVC visualization/analysis
  - 235 unit tests covering all aspects of the code
  - Parallel calculation with OpenMP and MPI



Virtual Quake

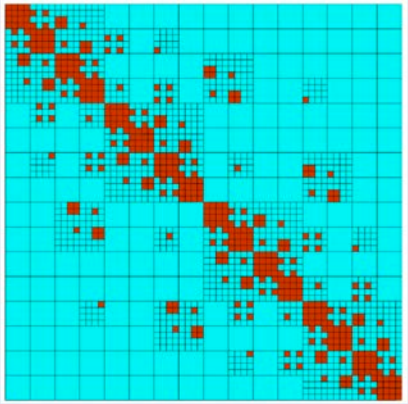
- We want arbitrarily small elements so we can properly model small magnitude earthquakes
- 3000m x 3000m elements result in minimum magnitude of around M=5.6



- Memory and speed are significant limitations
  - Interaction matrix size grows as N^2 in elements
  - Elements grow as N^2 in resolution
  - Therefore, memory requirements grow as N^4
    - Example: for CA fault system, 3000m resolution requires ~1GB of memory, 500m resolution requires ~5000GB of memory

Future Development

- Currently limitation to detailed simulations is memory usage
  - Grows as O(N^4) – CA model at 250m resolution (2 million elements) would require 30 TB memory
  - Hierarchical matrix implementation reduces this to O(N^2) – (e.g. 32GB for 2 million elements)
  - Also significantly improves runtime



Sample Hierarchical Matrix

- Dynamic fault geometry
  - Current fault configuration is static – what happens when faults change over time?
- Improve analysis/visualization tools (PyVQ, WebVQ)
  - Simplify analysis for users, provide web frontend

Overview

- Introduction
- The Computational Infrastructure for Geodynamics
- Virtual Quake
- **Research Code Development Guidelines**

Research Code Guidelines

- My background is in computer science
- There are several practices common in computer science that benefit research code development
  - Version control
  - Unit testing
  - Continuous integration
  - Use libraries/modules
- Using these tools will make your research more efficient, accurate, and reproducible

Research Code Guidelines

- Version control
  - Code changes over time
  - Very useful to track what was changed when
  - Version control keeps a record of what was changed for what reason at what date
  - Helps ensure reproducibility, keeps a record of who changed what at what time
  - Allows multiple researchers to collaborate on the same project simultaneously
  - I recommend Git and Github (try.github.io)
  - Makes it easy to share your code with others – becoming a requirement for many journals

Git development history for VQ

Research Code Guidelines

- Continually add tests to confirm code validity
- Virtual Quake:
  - 235 tests run automatically after each code change
  - Tests are run on multiple platforms to find platform dependent problems
  - Confirm basic mathematical and vector operations function correctly
  - Verify that simulations produce expected results
  - Verify that multiple processors yield same results as single processor
  - Confirm Green’s function calculation produces results within expected tolerances
  - Confirm file reading/writing function as expected

Research Code Guidelines

- Libraries
  - Much of the functionality you need for your research has already been written
  - Finite element: deal.II, PETSc, Fenix
  - Linear algebra: Trilinos, PETSc, LAPACK
  - Data analysis and visualization: matplotlib, scipy, numpy
  - Earthquake/Seismic: ObsPy, QuakeLib, OpenSHA
- Research is an iterative process
  - Automate as much as possible
  - If you are typing the same thing over and over, or copying/pasting data, you are wasting your time

Conclusion

- Virtual Quake is a boundary element code to simulate long term fault stress interactions for statistical study
- Uses Greens functions for stress interaction between faults, static/dynamic failure model for rupture propagation
- Results with California model show good agreement with observed seismicity
- Provides a means to do event recurrence forecasting
- Provides tools for analysis and visualization of data

Thank you

Any questions?