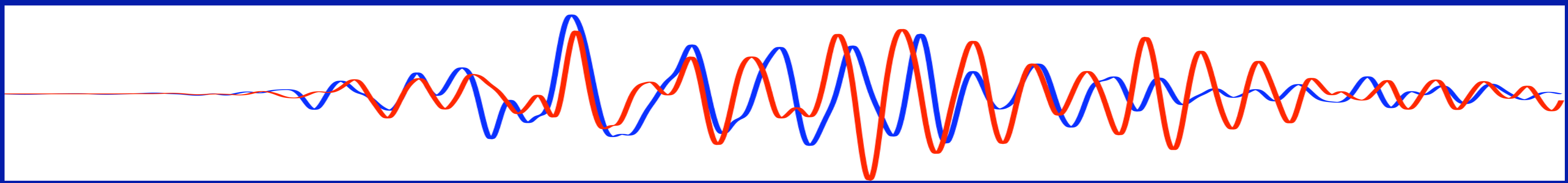
Wave Propagation Project (WPP): A New Open-Source Tool Supporting Computational Seismology at LLNL



Arthur Rodgers

Seismology Group

Atmospheric, Earth and Energy Division

Chemistry, Materials, Earth and Life Sciences Directorate

Lawrence Livermore National Laboratory

UCRL-PRES-235457

Computational Seismology at LLNL

- Nuclear explosion monitoring
  - Modeling can help understand the complex seismic waves emerging from explosions
    - S-wave generation from explosions
    - Non-linear (hydrodynamic) wave propagation
    - Regional surface waves
  - Hydroacoustic modeling
    - T-phase reflection off continental margin
- Strong earthquake ground motion
  - Large earthquakes and Performance-Based Design
    - GNEP (Global Nuclear Energy Partnership)
    - YMP (Yucca Mountain Project)
- Earth structure
  - Test 3D models inferred from various geophysical data

We Are A Multidisciplinary Team

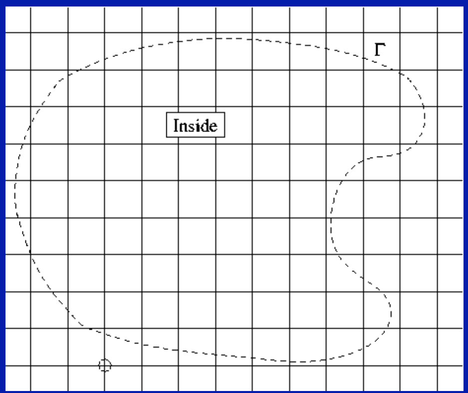
- Applied Mathematicians
  - Anders Petersson, Bjorn Sjogreen, Daniel Appelo
    - Center for Applied Scientific computing
- Computer Scientist
  - Kathleen McCandless
    - Computer Applications and Research Dept.
- Seismologist
  - Arthur Rodgers
- Other experts
  - Geologist, Visualization, Mechanical/Structural Engineers

WPP Methodology

- Elastic wave equation in displacement formulation

$$\rho \frac{\partial^2 \mathbf{u}}{\partial t^2} = \nabla \cdot \mathbf{T} + \mathbf{F}(\mathbf{t})$$

- 2nd order system for displacements
  - Explicit time stepping
- Node-centered Cartesian mesh
  - Allows generalizations to embedded boundary methods for non-planar topography & material discontinuities
  - Stable with free surface boundary condition for all V_P/V_S



WPP: Open source parallel code for 3D seismic wave propagation

- Code is open-source
  - Born parallel (uses mpich
    - But can run on single processor
  - Available for download
    - http://www.llnl.gov/CASC/serpentine/software.html
    - ~50 page user's guide & example input files
- Supported by LLNL institutional funds
  - LDRD (05-ERD-079)

WPP Current Features (version 1.0)

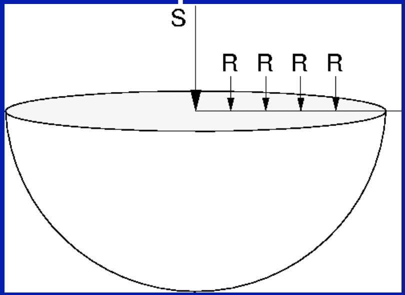
- 3D P- and S-wave velocity and density models
  - Block, vfile (binary raster) and etree models
  - Handles water regions (μ=0) accurately
- Purely elastic (no attenuation)
  - Handles acoustic case, where μ=0
  - Absorbing (Clayton and Enquist) boundary conditions
  - Free surface boundary conditions
- Models arbitrary number of sources
  - Point moment tensor
  - Point forces
  - Many source-time (moment) functions
- Writes time-series of motion as SAC files
- Writes 2D and 3D images

Building WPP

- You can build a wpp executable on your platform with source code:
  - wpp source code
  - mpich library, MPI-2 standard
  - blitz++ array class library
- To compile:
  - gcc, g++, g77
  - python scripting language
  - scons, python-based software construction tools
- Runs on Linux workstations/clusters & Mac OSX

The WPP Input file

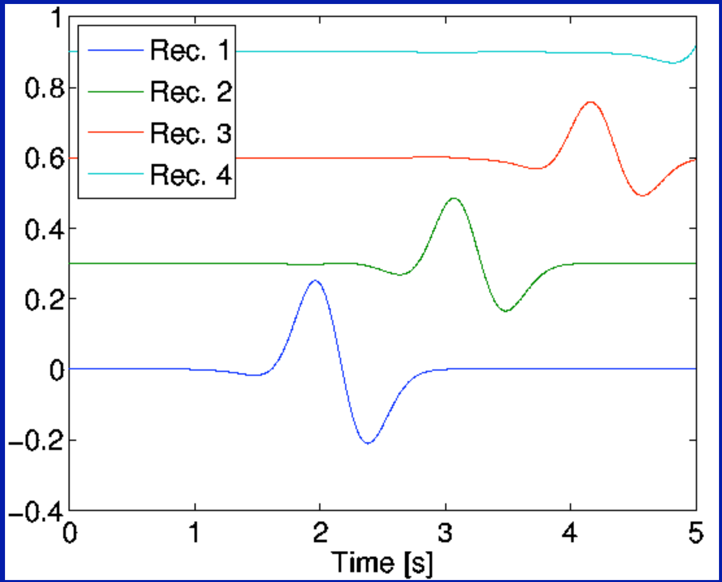
- A (the?) simplest example - Lamb's problem
  - Veritcal point force on free surface of homogeneous half-space




```
grid x=10000.0 y=10000.0 z=5000.0 h=10
time t=5.
block vp=1732 vs=1000 r=1000
source x=5000 y=5000 z=0 fx=0 fy=0 fz=1e13 type=RickerInt \
   freq=1.0 t0=1.0
sac x=6000 z=0 y=5000 file=s1
sac x=7000 z=0 y=5000 file=s2
sac x=8000 z=0 y=5000 file=s3
sac x=9000 z=0 y=5000 file=s4
```

Line continuation

Vertical displacement



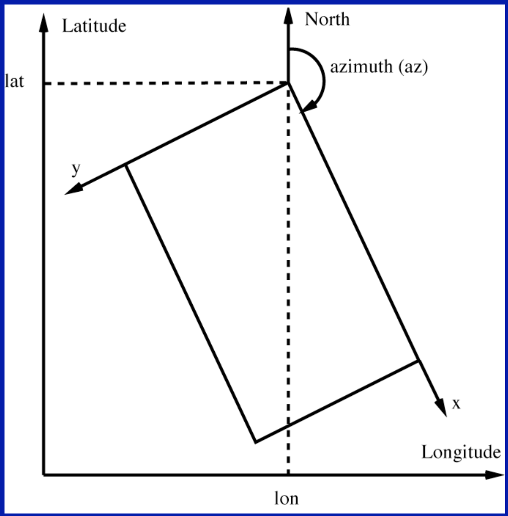
Grid and Coordinates

- Can specify x,y,z

  grid x=10000.0 y=10000.0 z=5000.0 h=40
- Can specify nx,ny,nz

  grid nx=251 ny=251 nz=126 h=40
- Can specify (approximate!) geographic domain

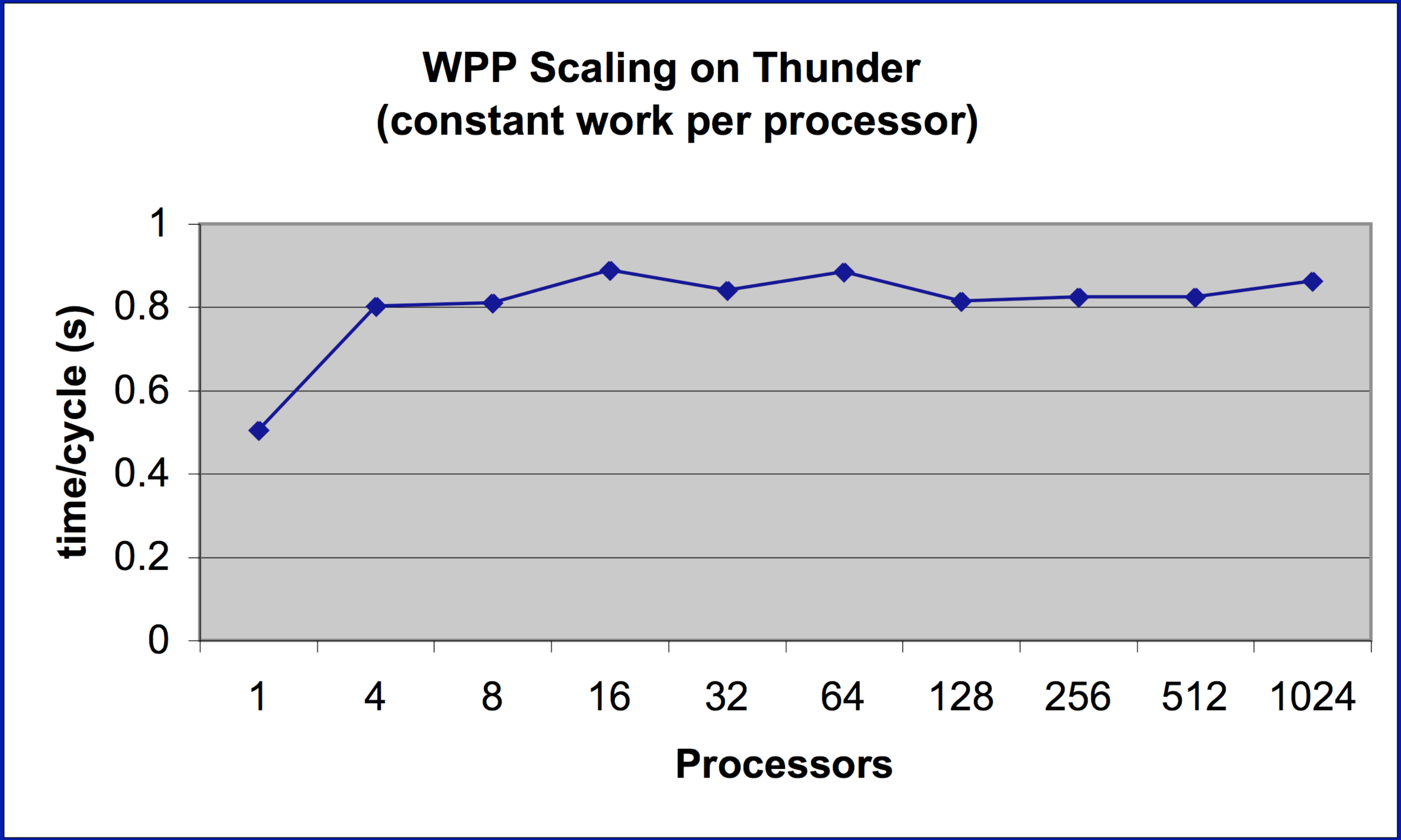
  grid x=10e3 y=100e3 z=50e3 h=40 lat=38 lon=-117 az=144



$$\varphi = \text{lat} + \frac{x\cos(\alpha) - y\sin(\alpha)}{M}, \quad \alpha = az\frac{\pi}{180},$$

$$\theta = \text{lon} + \frac{x\sin(\alpha) + y\cos(\alpha)}{M\cos(\varphi\pi/180)},$$

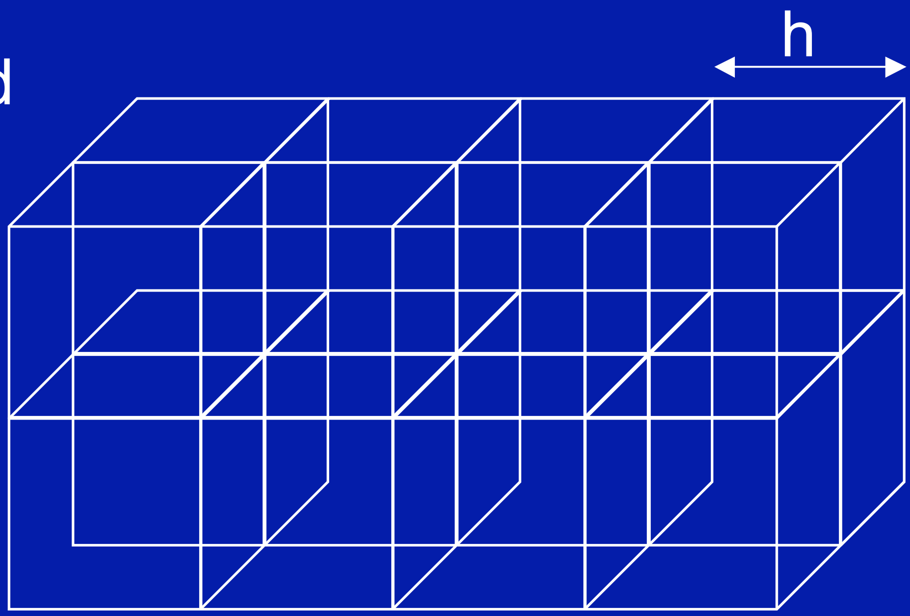
WPP Scaling



Thunder: Linux Cluster, 4096 CPU's

A Few Words on FD Methods

Medium is discretized on a grid



Maximum frequency:

$f_{max} = v_{min}/\lambda_{min}$

$\lambda_{min} = n*h$

… more accurate for larger n

Courant–Friedrichs–Levy condition (CFL condition)

For stability of solution

$v_{max}*\delta t/h < C$ …. $\delta t < C*h/ v_{max}$

So the high frequencies require small h and high velocities require small δt.

So you want high frequency …

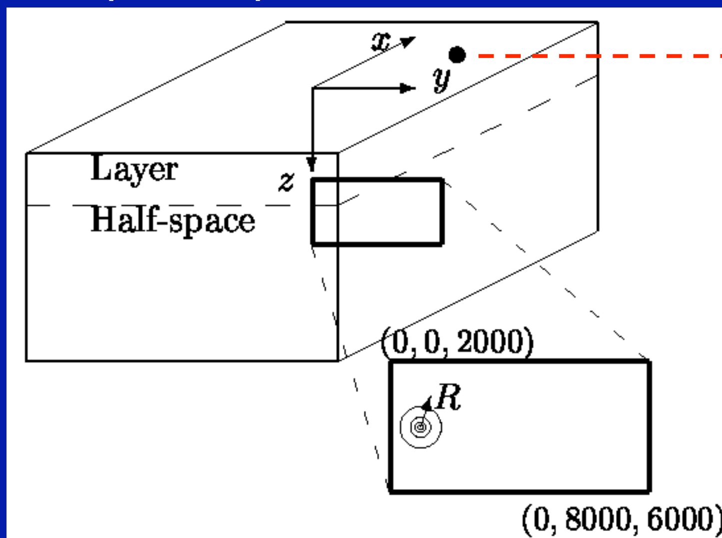
- Doubling the frequency content while maintaining the same resolution implies:
  - h -> h/2, halving the grid spacing
    - requires 2*2*2=8 more grid points in 3D
  - δt -> $\delta t/2$, halving the time step
    - requires 2* more time steps
- So doubling
  - Once, 8x more memory
  - Twice, 64x
  - Thrice, 512x
- Large velocity differences lead to uneven sampling in terms of grid points/wavelength
  - **Mesh refinement improves these problems**

Planned Features

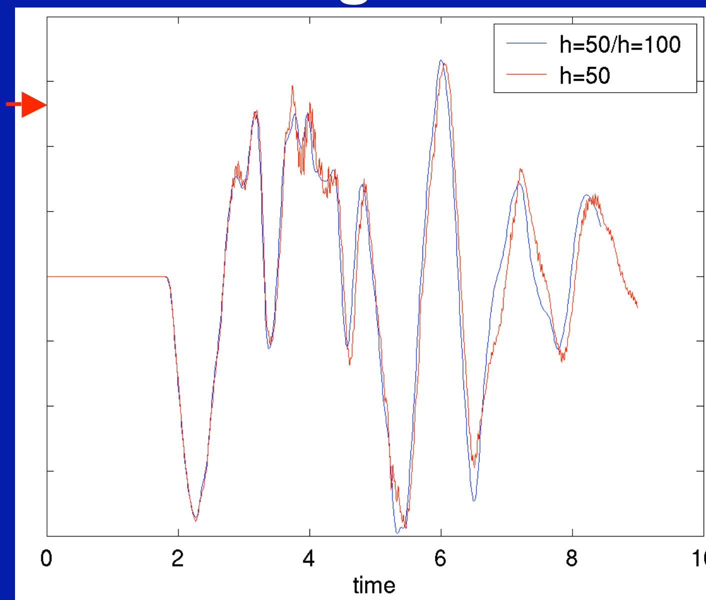
- Mesh refinement
  - Allows much more efficient calculations over fixed grid
    - Solve a problem faster with less memory
    - Higher frequency for the same resource
    - Use 4th order interpolation at mesh refinement boundaries
- Attenuation
  - Anelastic damping required for realistic simulations
    - Constant Q
  - Perfectly Match Layer (PML) boundary conditions
    - Can make domain smaller
- Topography
  - Non-planar free surface
- Embedded boundaries
  - Internal material discontinuities

Mesh Refinement Will Allow Higher Frequency Simulations

Test problem LOH-2: Layer over half-space:
unit slip over planar fault



Results agree well:

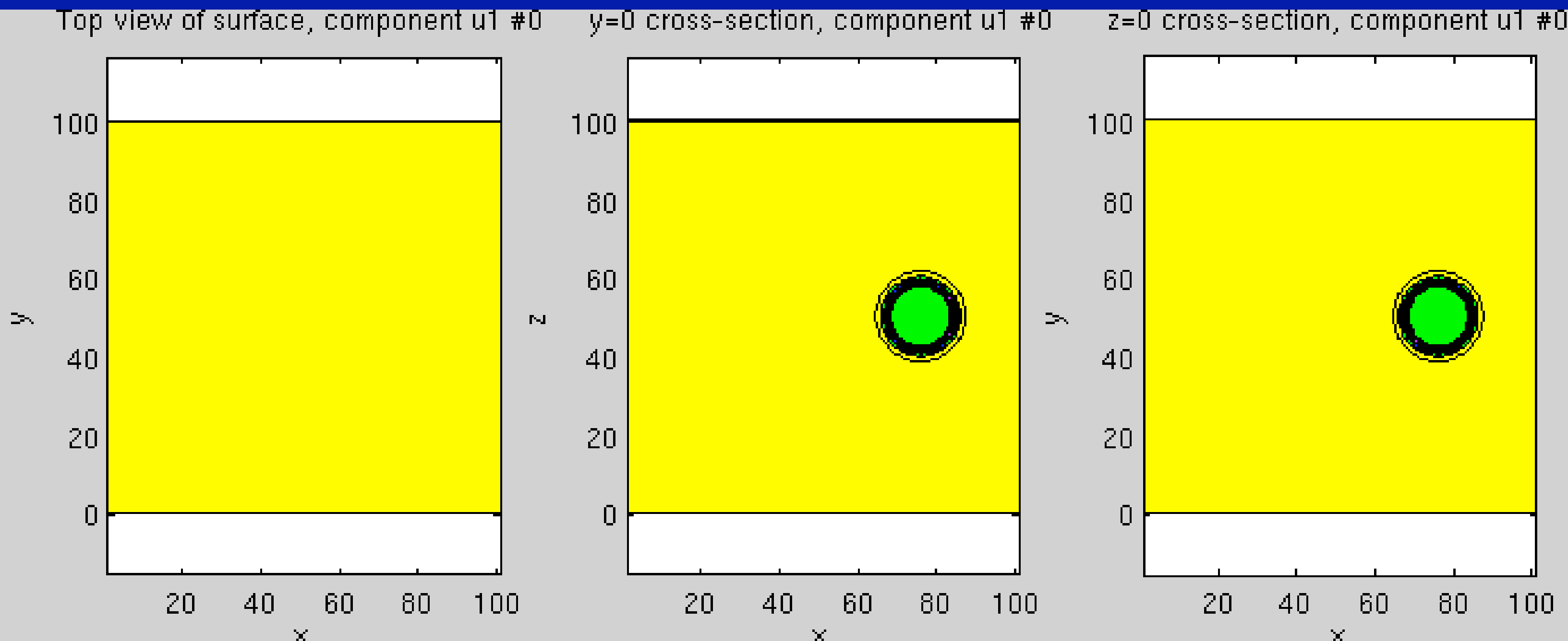


Refined calculation about 70 times faster **and uses** 5.5 times less memory

	Grid	Grid points	Processors	CPU [hours]
1 mesh	h = 50	1.24e8	984	0.445 x 984 = 437.9
Refined mesh	h_1 = 50 h_2 = 100	2.27e7	32	0.197 x 32 = 6.3

Embedded Boundary Method for Topography

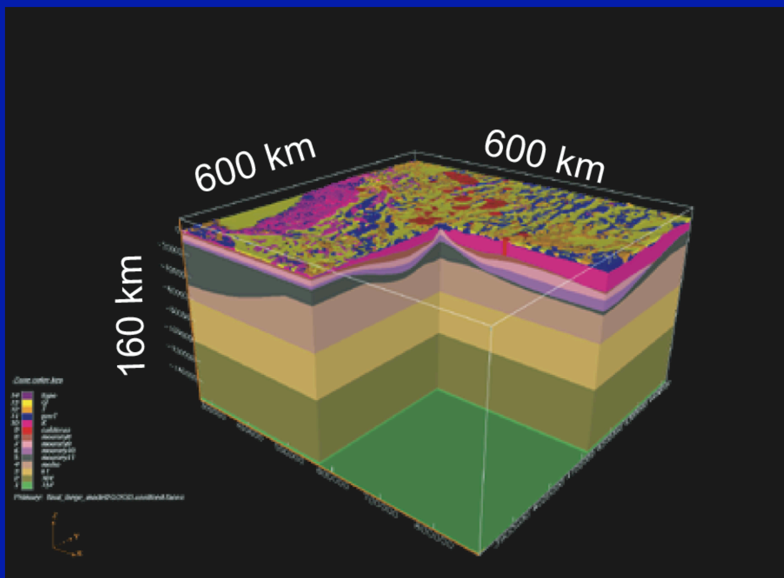
2D slices

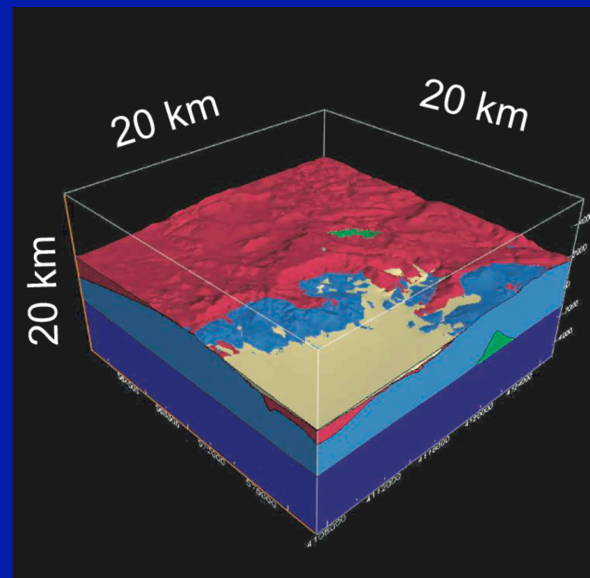


3D sphere response to point force

- Cartesian w/ embedded boundary method for stress-free bc
- Includes all cases of topography geometry

Handling 3D Models: EarthVision to Etree





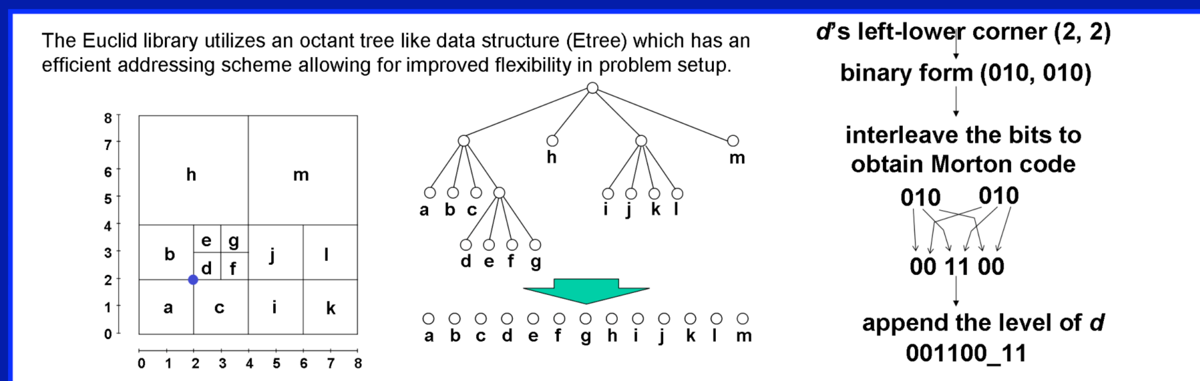
EarthVision
Geologic
Models

Lithology ->

Material properties ->

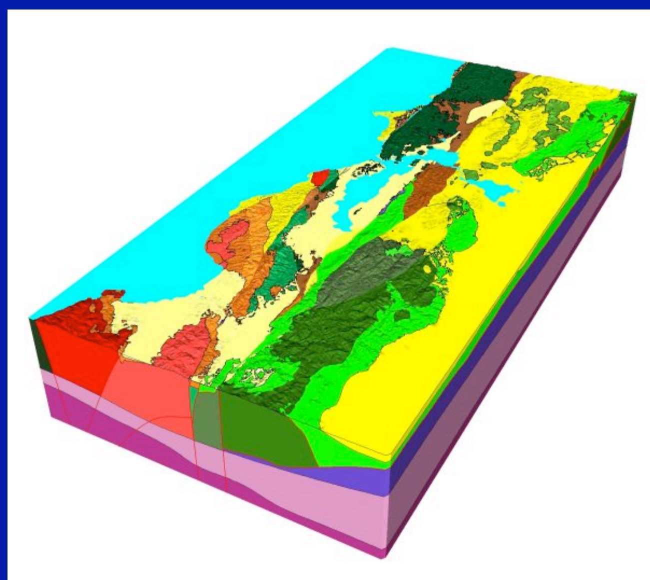
Etree file ->

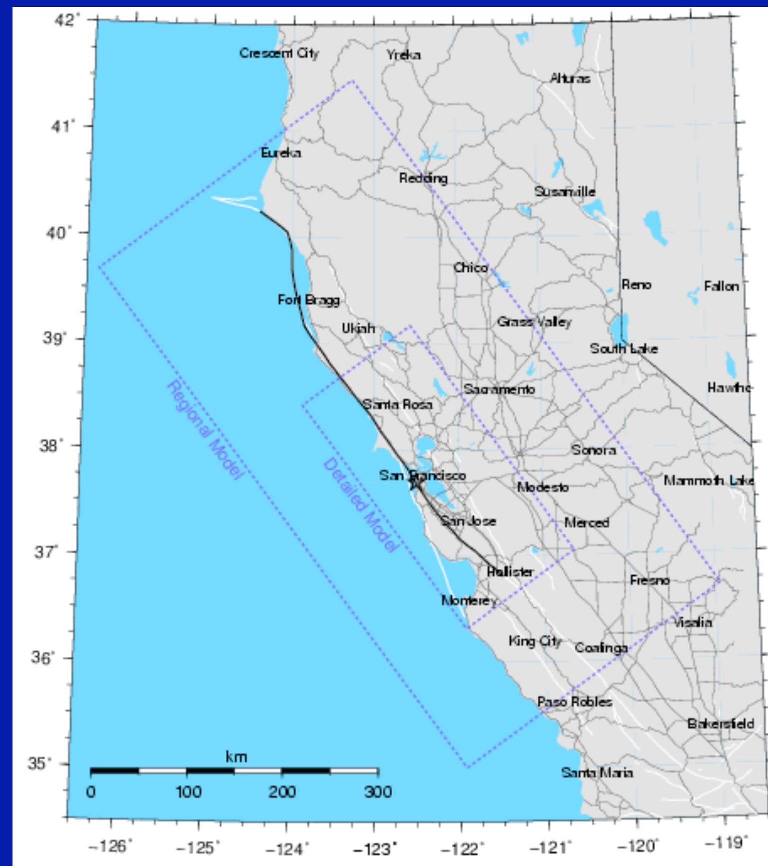
Wave propagation



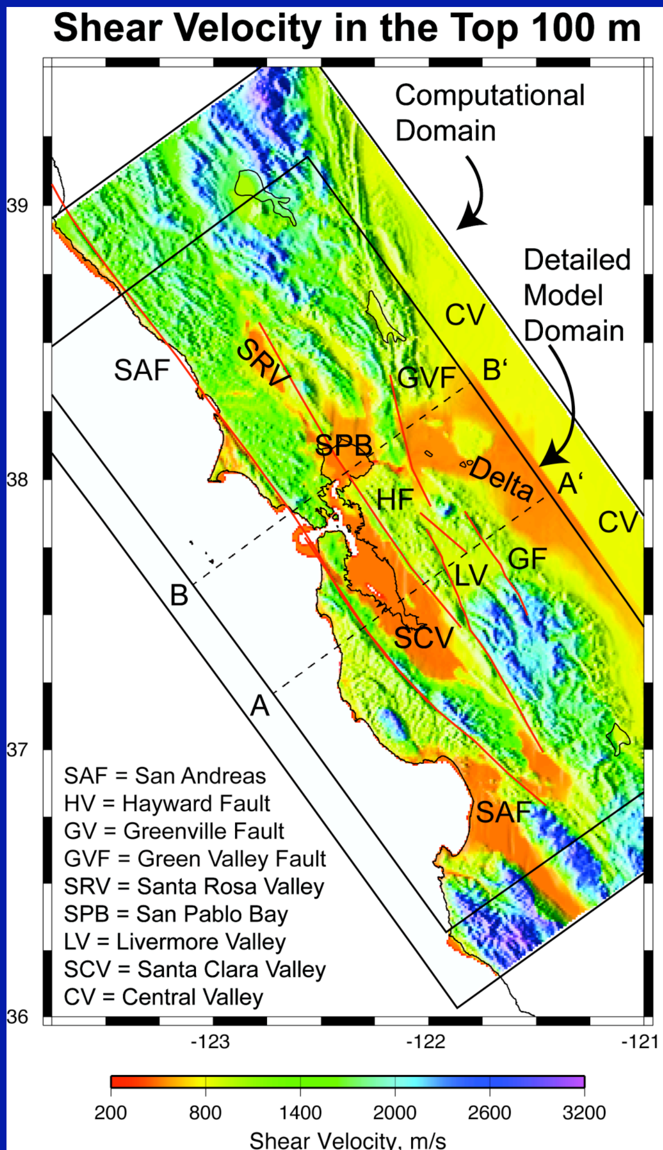
3D Model for the San Francisco Bay Area and Northern CA

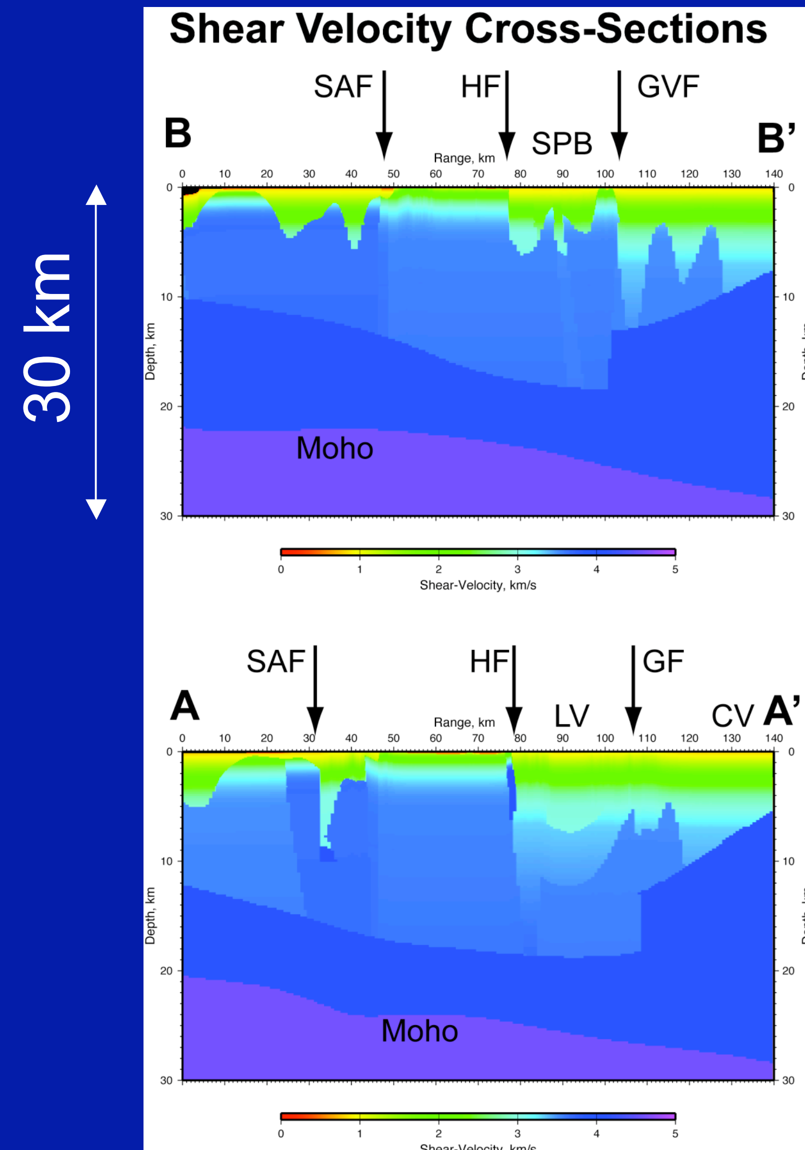
- USGS developed model of SF region
- We performed simulations of moderate earthquakes were used to validate the model
- We performed large simulations of the 1906 earthquake





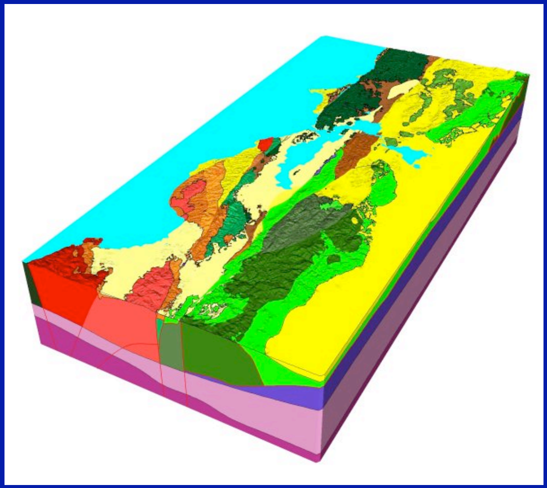
SF Bay Area Geology is Complex



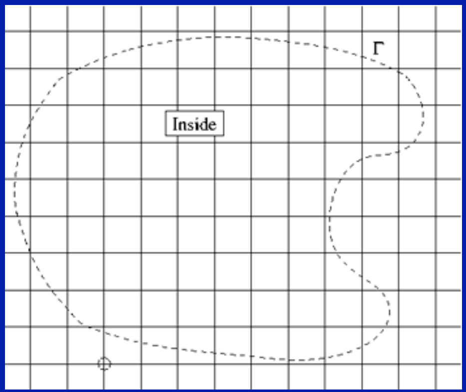


Pieces For Earthquake Ground Motion Modeling

Etree Model(s)
(USGS or other)



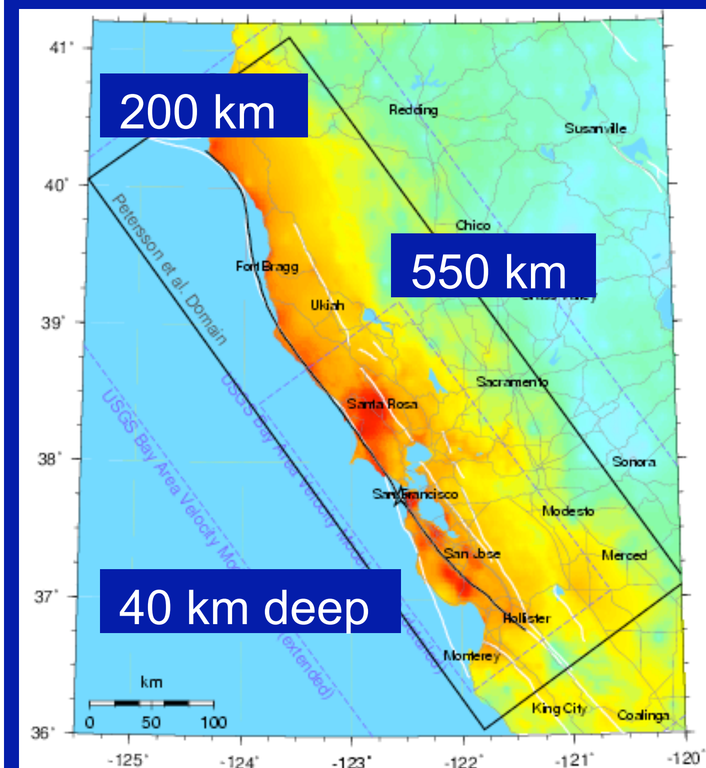
WPP Code



Livermore Computing
LINUX parallel machines
Thunder - 22 Tflop, 4096 CPU's
Zeus - 11 Tflop, 2304 CPU's
Thunder GC 50,000 CPU-hours/week
Weekend DAT ~ 65,000 CPU-hours

Scaling Up to Big Problems

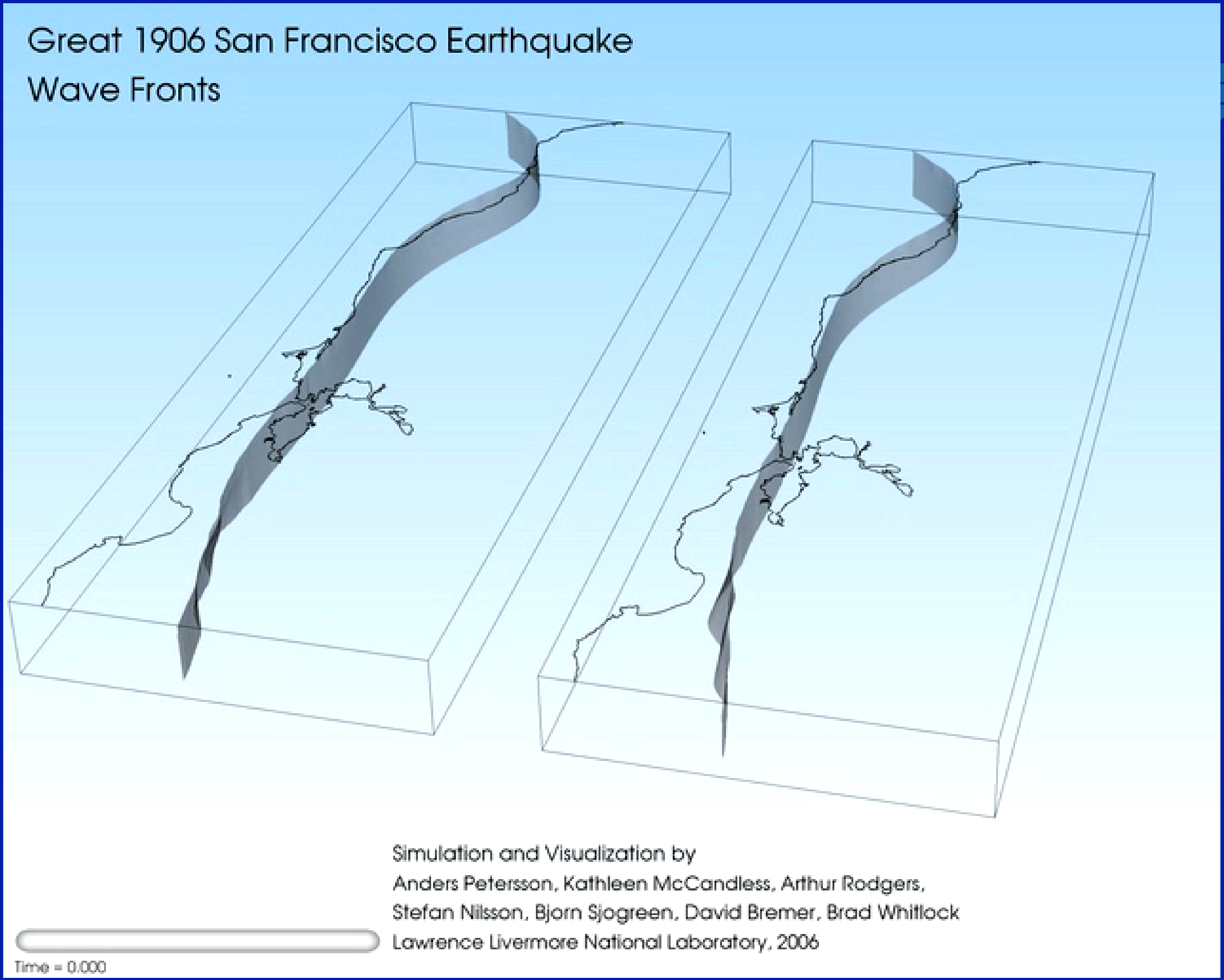
- Seismic modeling requires significant computer resources
  – You won’t run any significant 1906 simulations on your workstation!



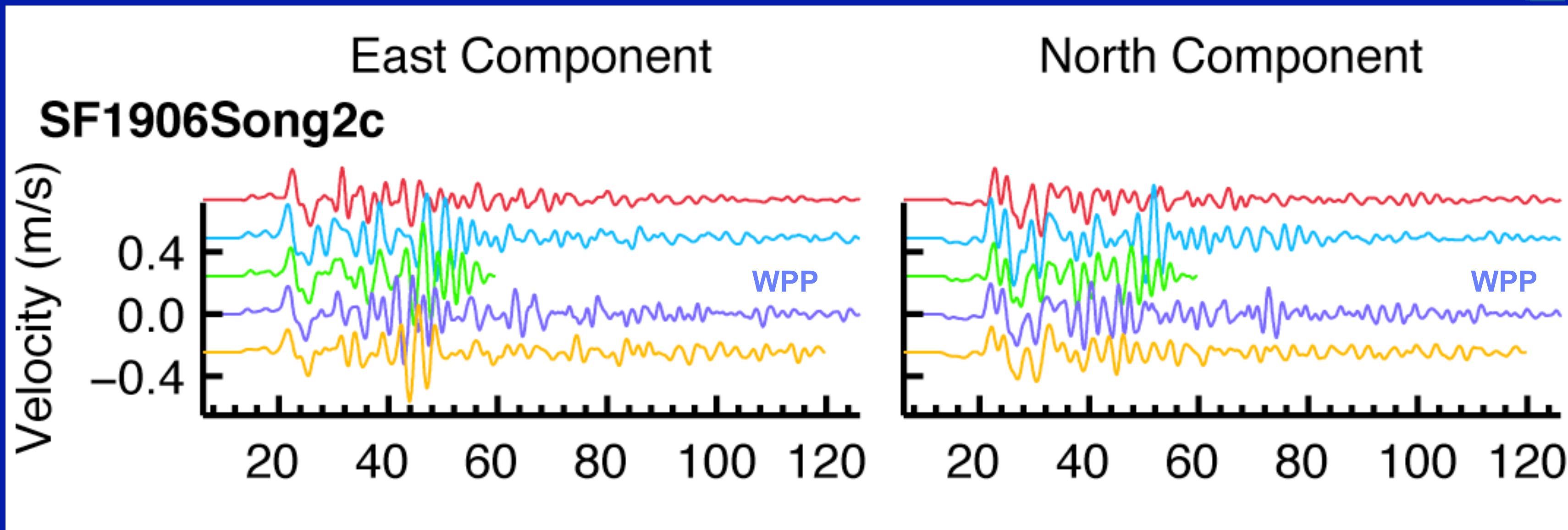
Simulating 300 seconds on 1024 processors on MCR with the WPP code:

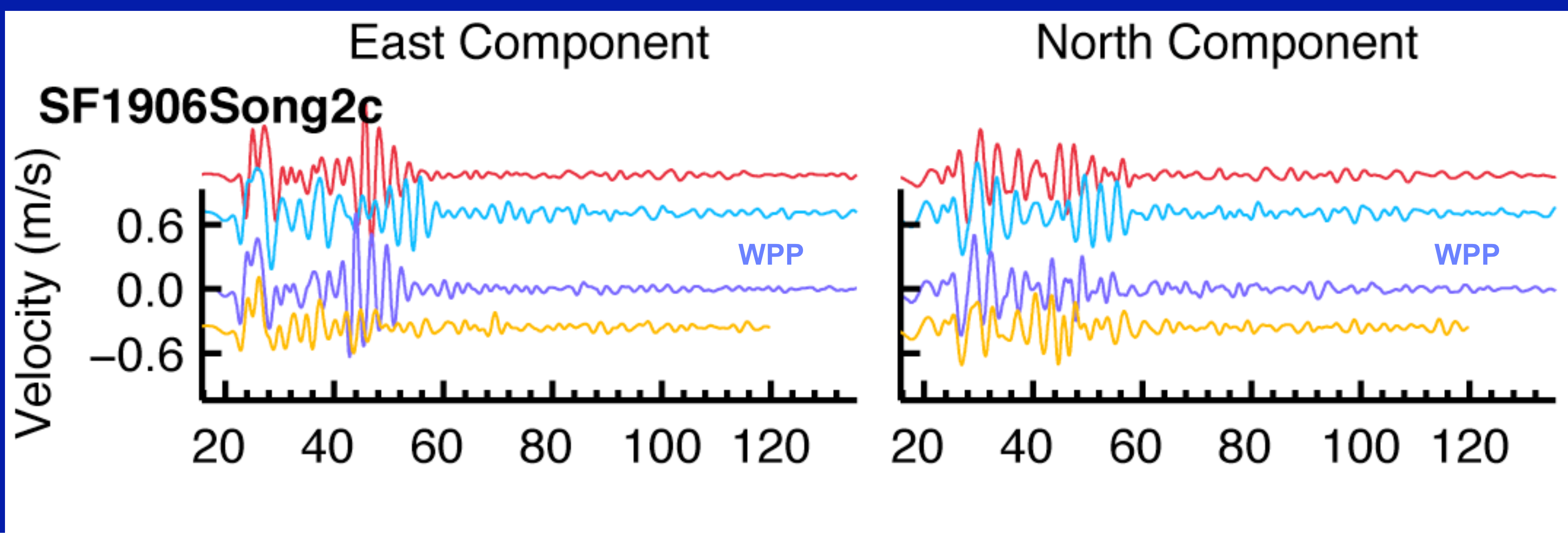
freq	Grid size	# grid points	Time step	# time steps	CPU [h]
0.2	250	256e6	2.2e-2	13,600	2
0.4	125	2e9	1.1e-2	27,300	26
0.5	100	4e9	8.7e-3	34,500	67
1.0	50	32e9	4.4e-3	68,200	1,061

MCR: 2304 proc Linux cluster 7.6 Tflop/s on Linpack benchmark


Great 1906 San Francisco Earthquake
Wave Fronts
Simulation and Visualization by
Anders Petersson, Kathleen McCandless, Arthur Rodgers,
Stefan Nilsson, Bjorn Sjogreen, David Bremer, Brad Whitlock
Lawrence Livermore National Laboratory, 2006
Time = 0.000

SF1906 Waveform Comparison





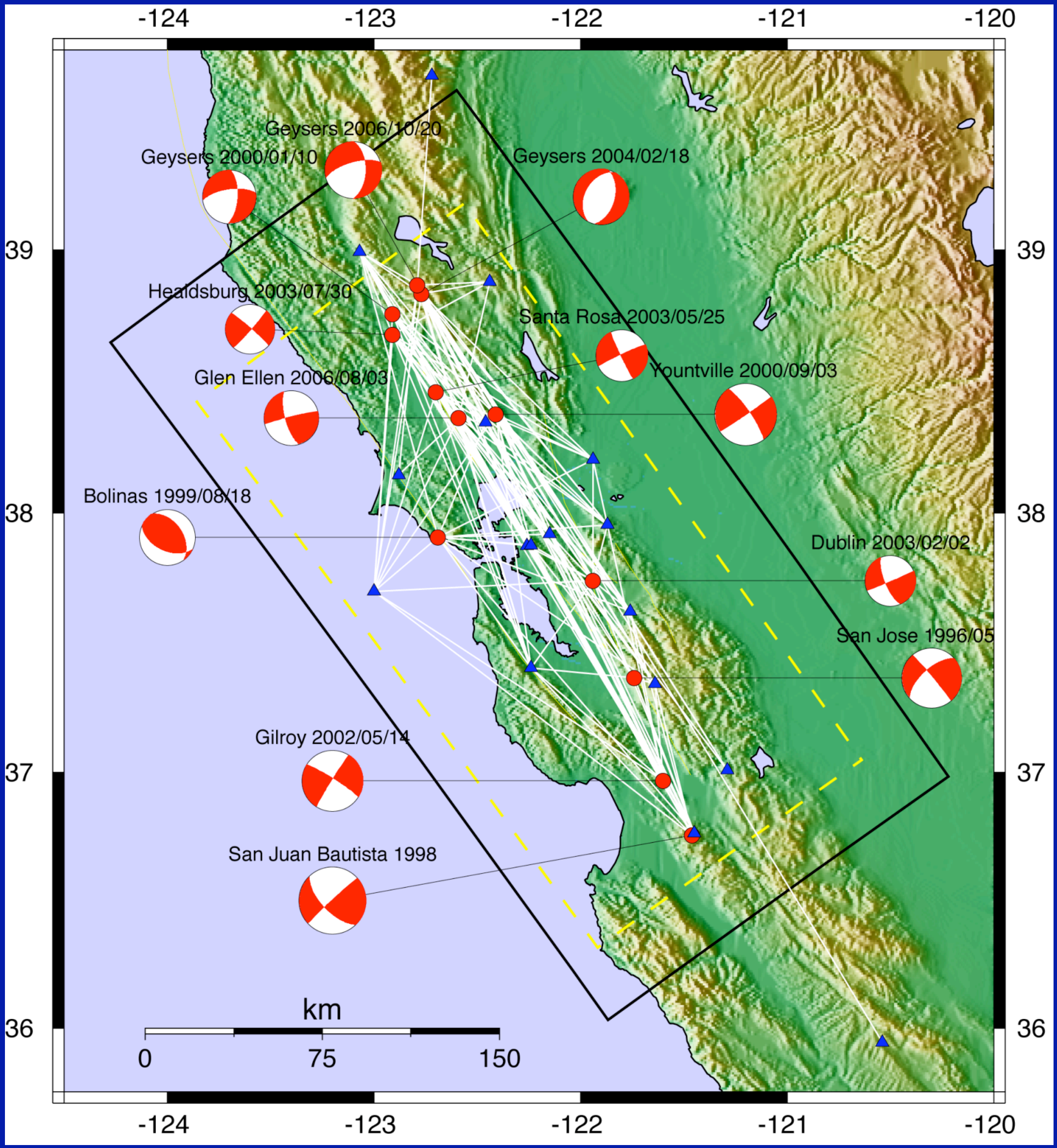
Moderate Earthquakes Allow Us To Test the USGS Model

Moderate (M_W 4-5) earthquakes are useful for evaluating velocity model

12 events (circles)
15 stations (triangles)

Coverage uneven, many paths along Hayward-Rodgers Creek Fault

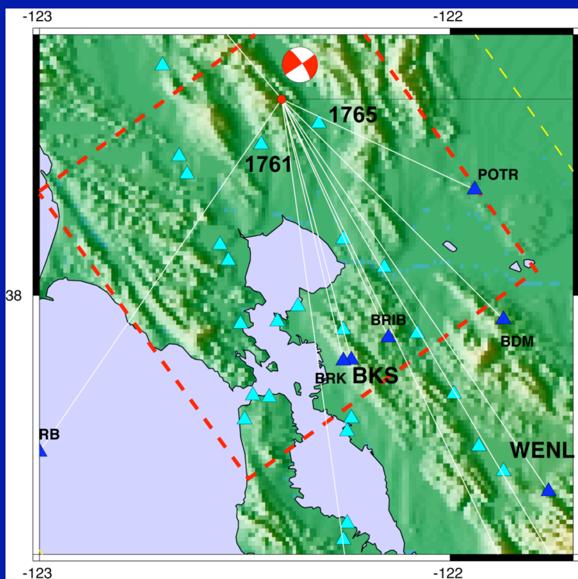
Events, BB Stations & Paths

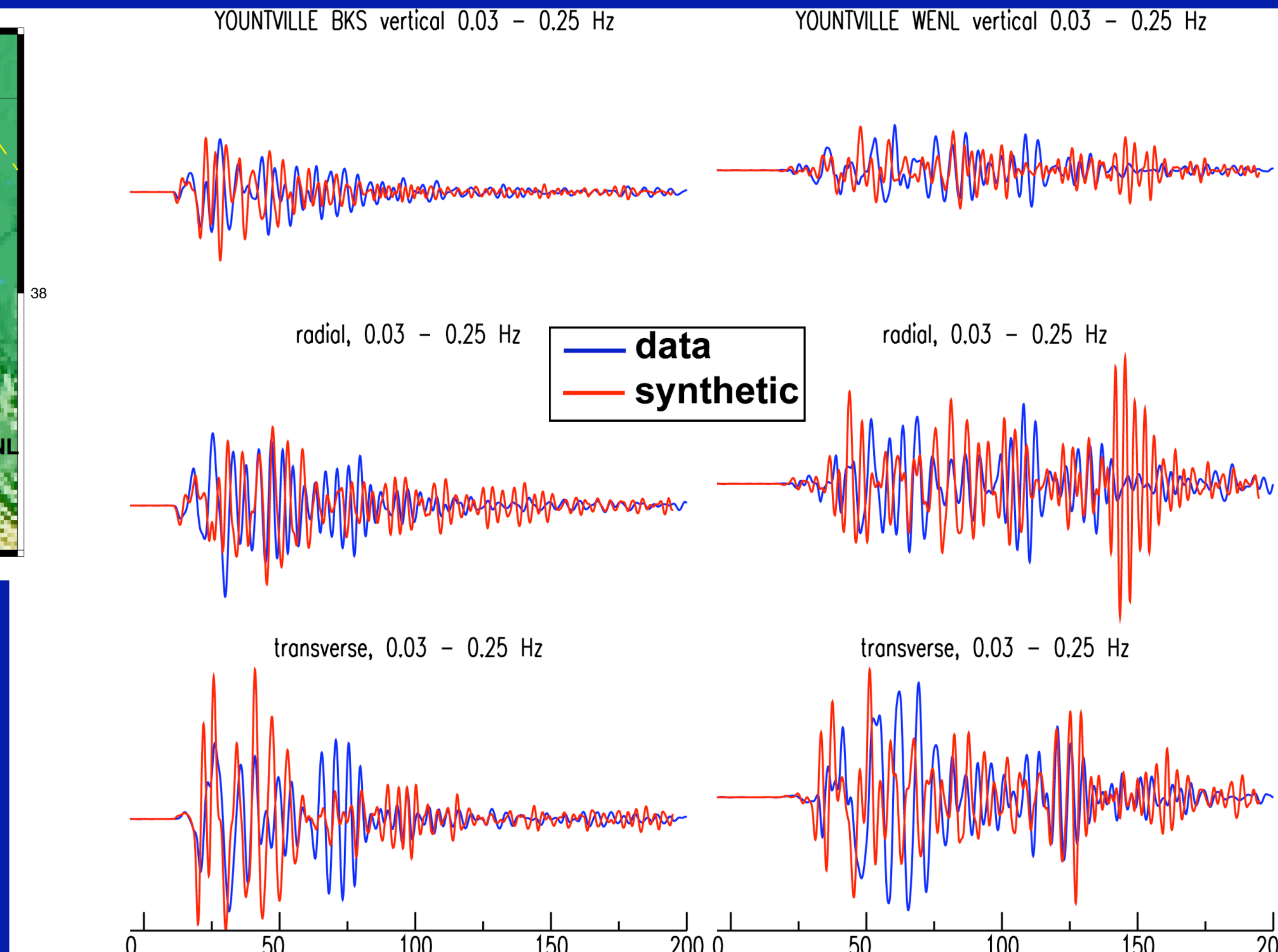


2000/09/03 Yountville Earthquake Broadband (BDSN) Stations

red = higher res. domain

BKS - Berkeley **WENL - Livermore**

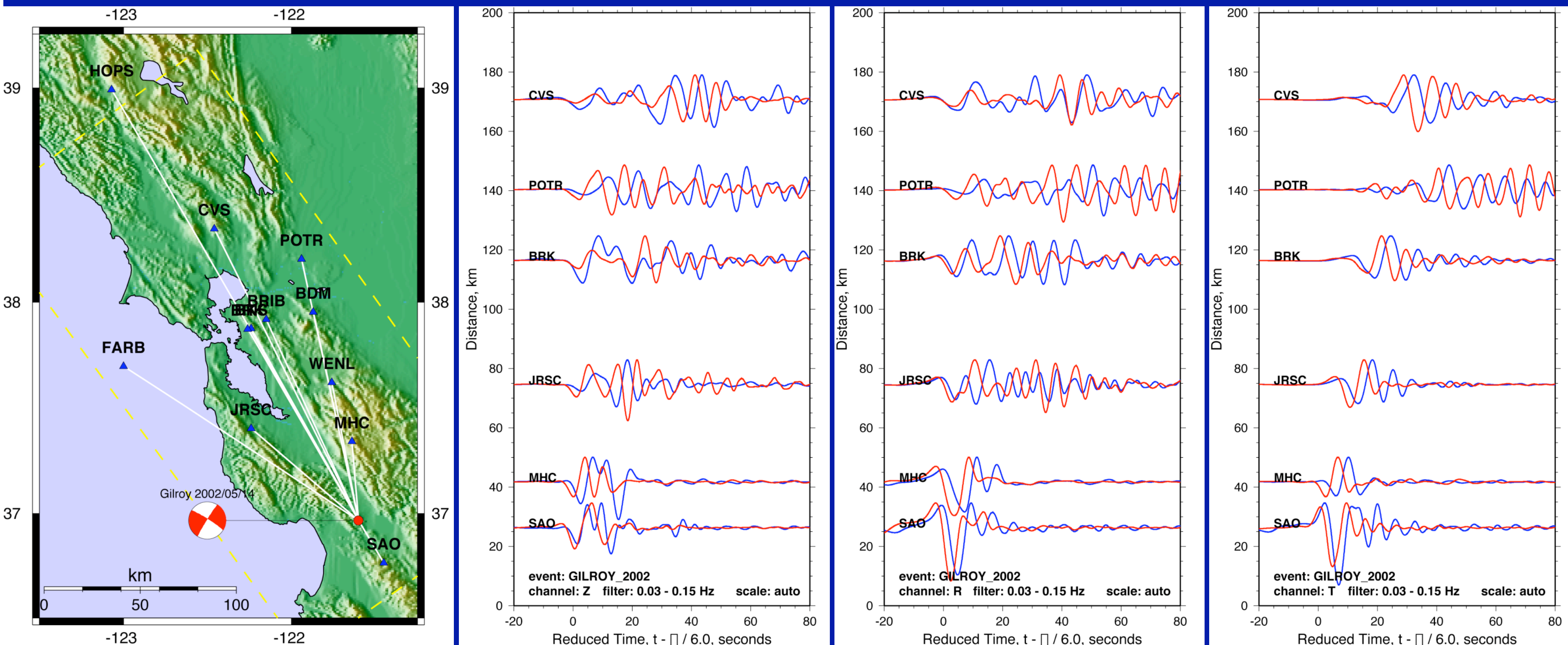




Absolute timing and amplitude

2002/05/14 Gilroy Earthquake Broadband (BDSN) Stations

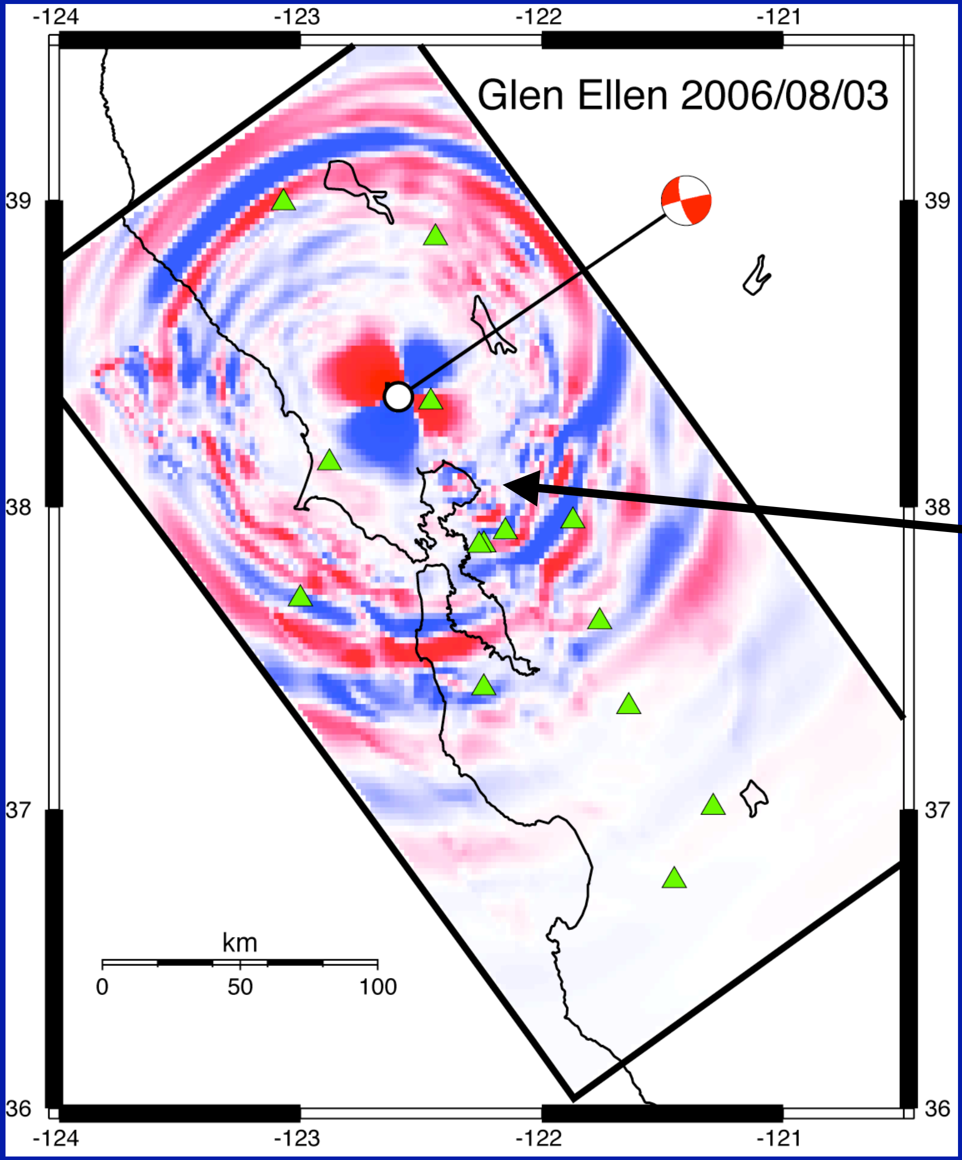
Vertical Radial Transverse



Frequencies = 0.03-0.15 Hz
Periods = 7-33 seconds

Delays increase with distance …

Aug. 3 2006, Glen Ellen Earthquake

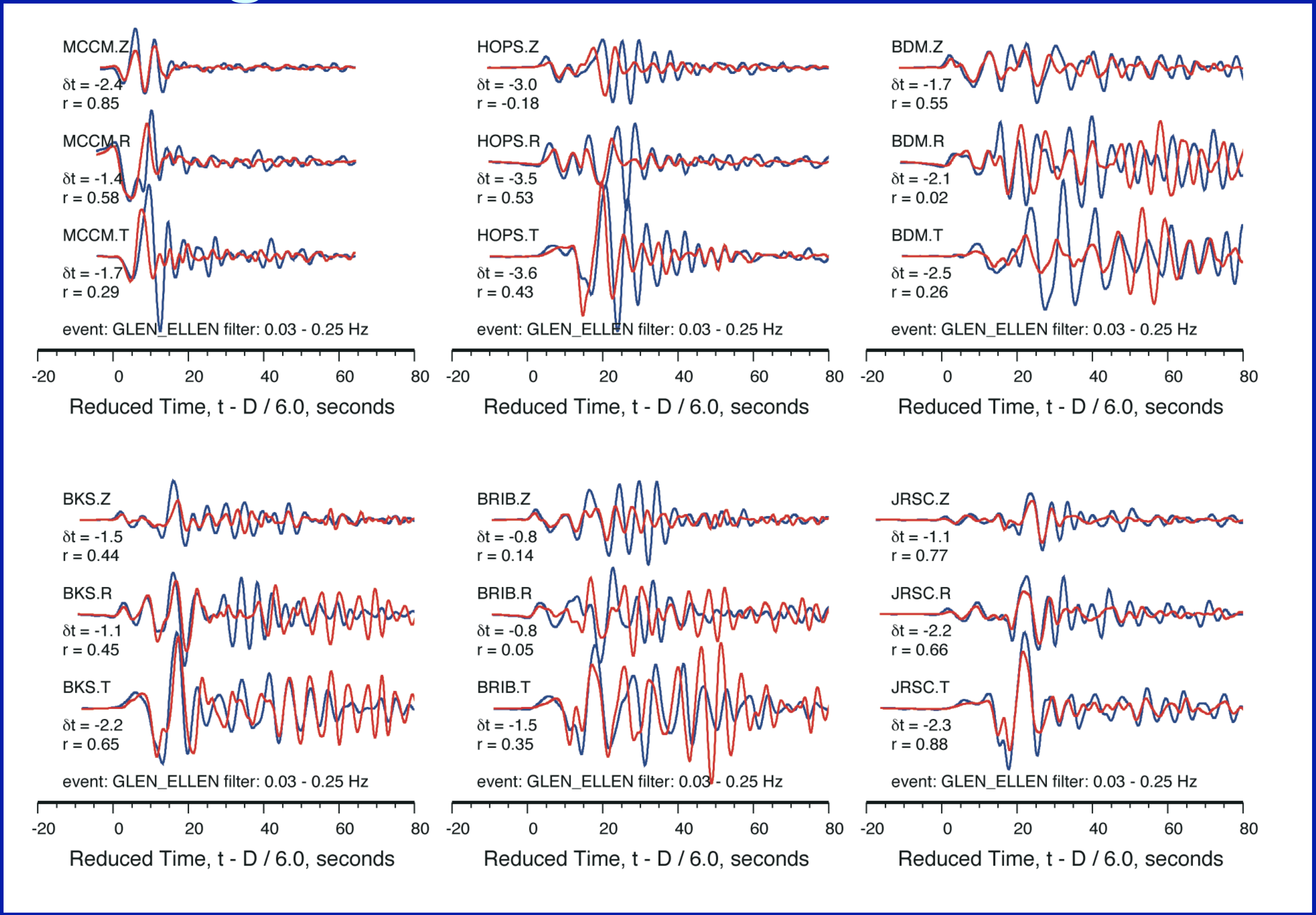


Snapshot of vertical displacement

Note distortion of wavefronts

San Pablo Bay generates surface wave coda

Waveform Fits for August 3 2006, Glen Ellen

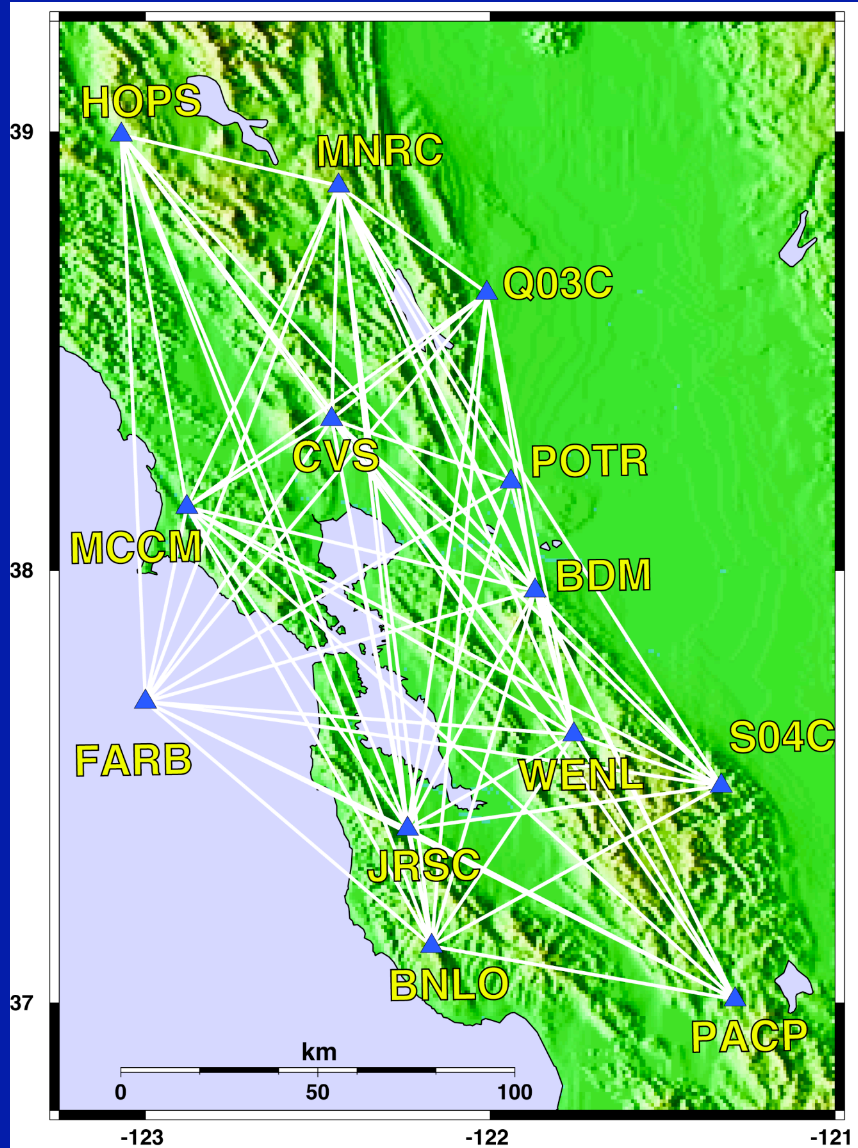


Green's Functions From Ambient Noise Provide New Constraints on Model

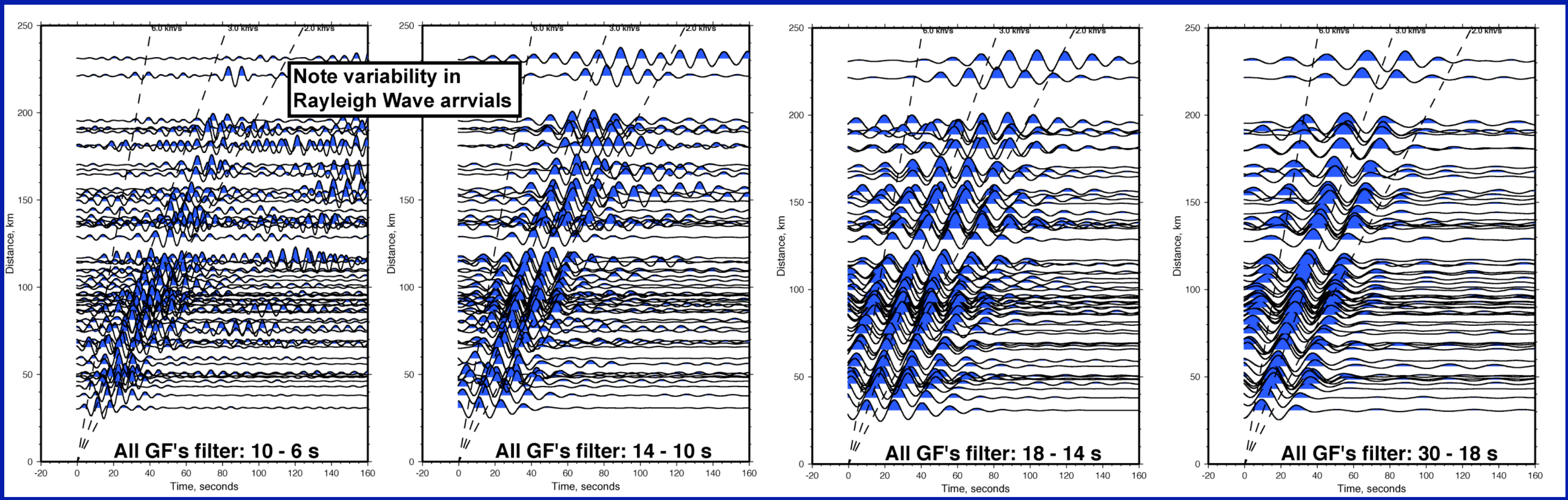
Empirical GF's provide more balanced path coverage of the SF Bay Area.

Vertical-to-vertical component cross-correlations between stations provided by Morgan Moschetti and Mike Ritzwoller (University of Colorado, Boulder).

Part of an NSF-Earthscope project to estimate lithospheric structure across the western US.



Empirical GF's in Four Period Bands

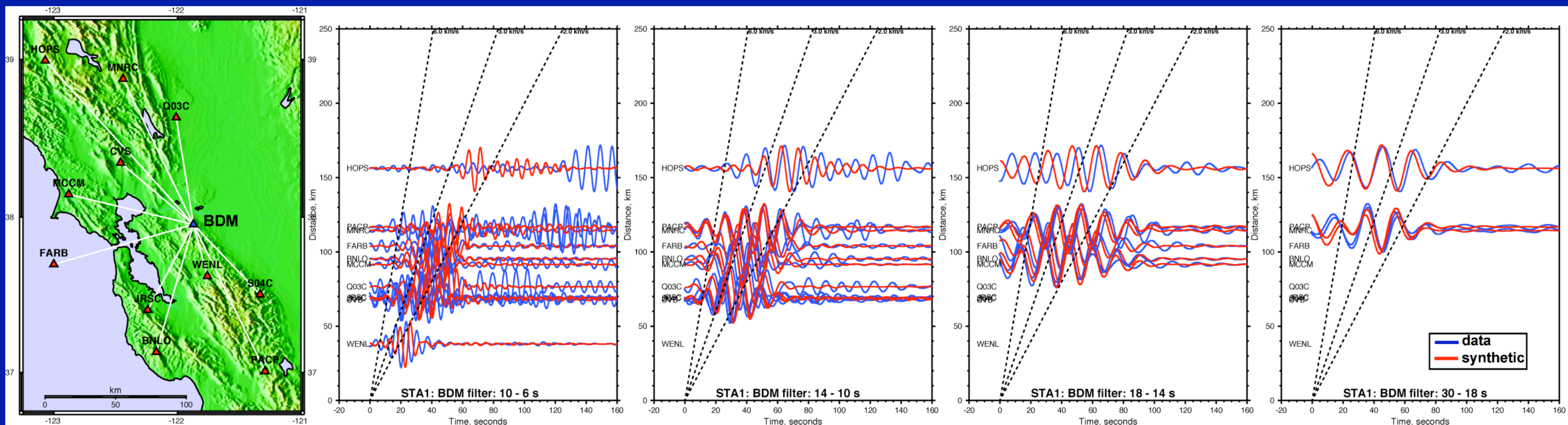


GF's for all available inter-station pairs plotted as record section.

Rayleigh waves are clearly observed, but phase is variable.
Noise appears to be variable as well.

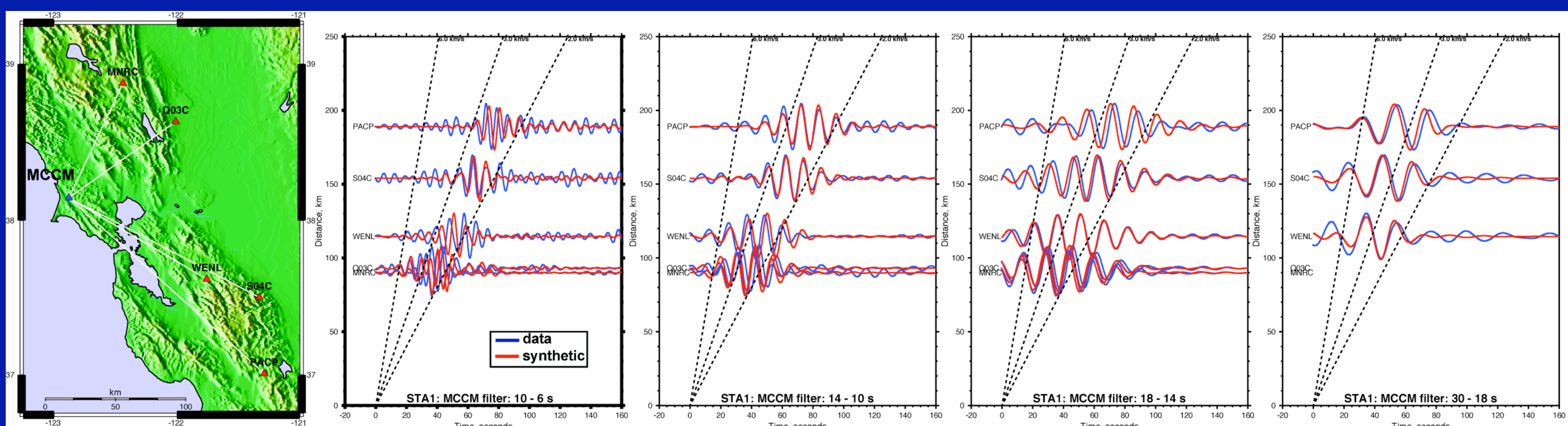
We Modeled GF's With WPP and the USGS 3D Model

BDM



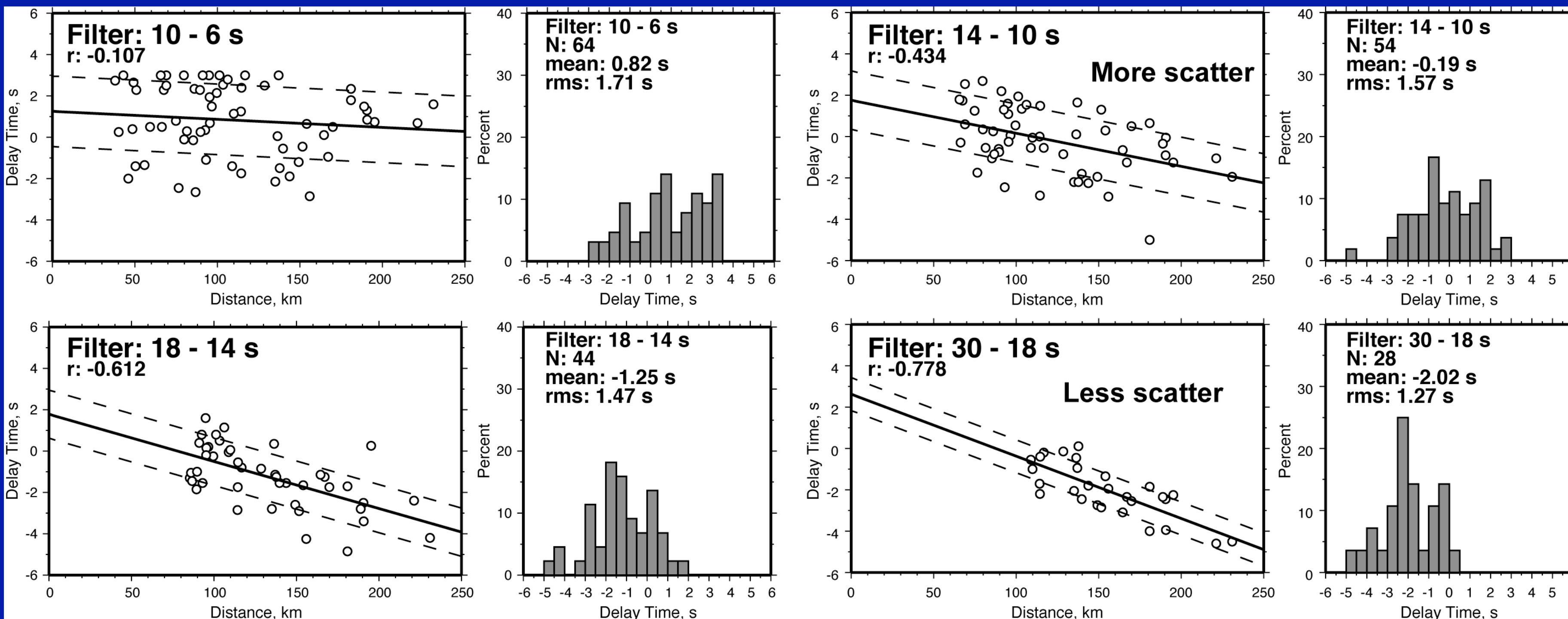
MCCM

6-10 s   10-14 s   14-18 s   18-30 s



Note: require at least three wavelengths

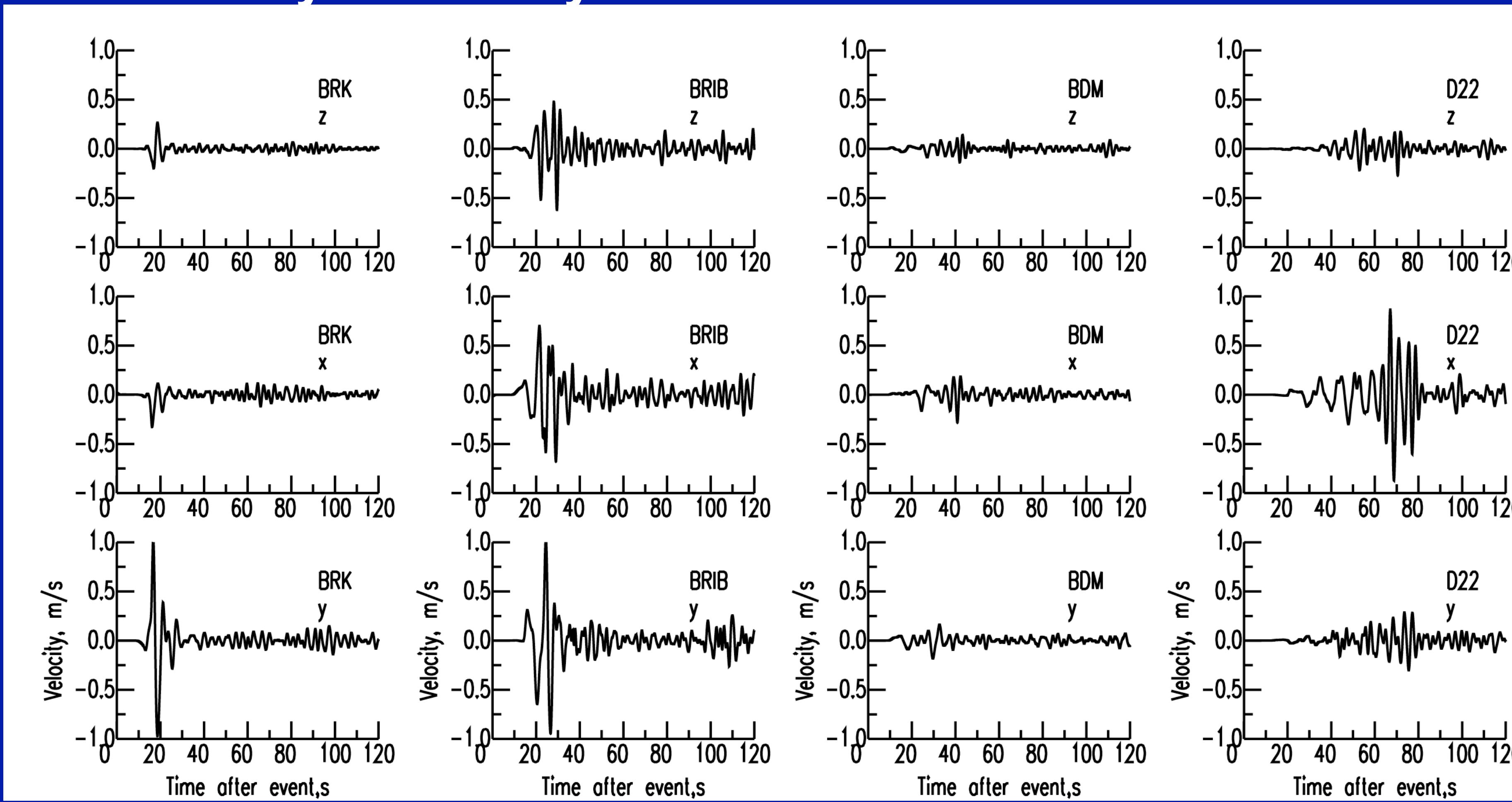
Phase Delays Between Observed and Modeled GF's Show Systematics



The delays decrease with distance suggesting USGS 3D model is too fast, consistent with earthquake observations. Scatter provides path-specific constraints on structure.

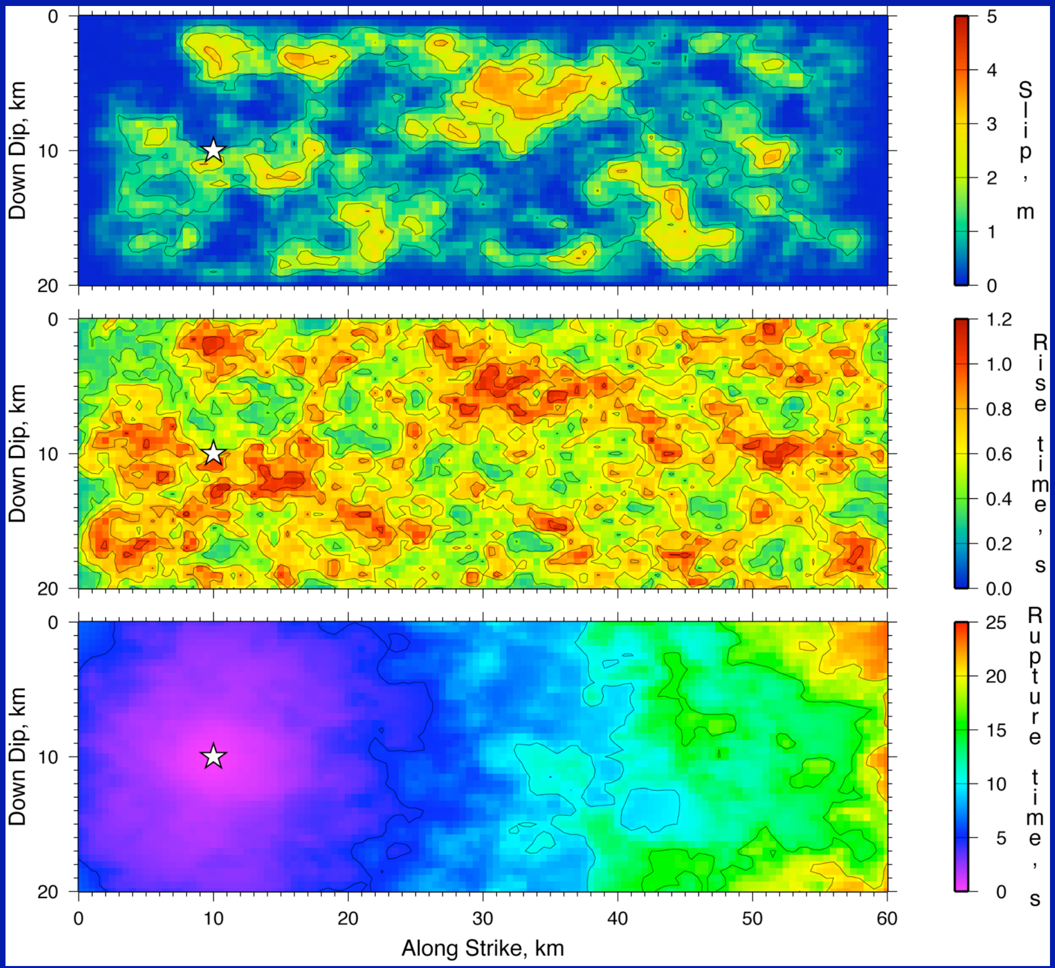
Ground Motions For M_W 7.0 Hayward Fault Scenario

Berkeley   Lafayette   Mt Diablo   Delta



Future Effort - Consider Stochastic Rupture Models

Following Liu, Archuleta and Hartzell (2006) pseudodynamic rupture models generated stochastically with correlated slip, rise time, rupture velocity and rake

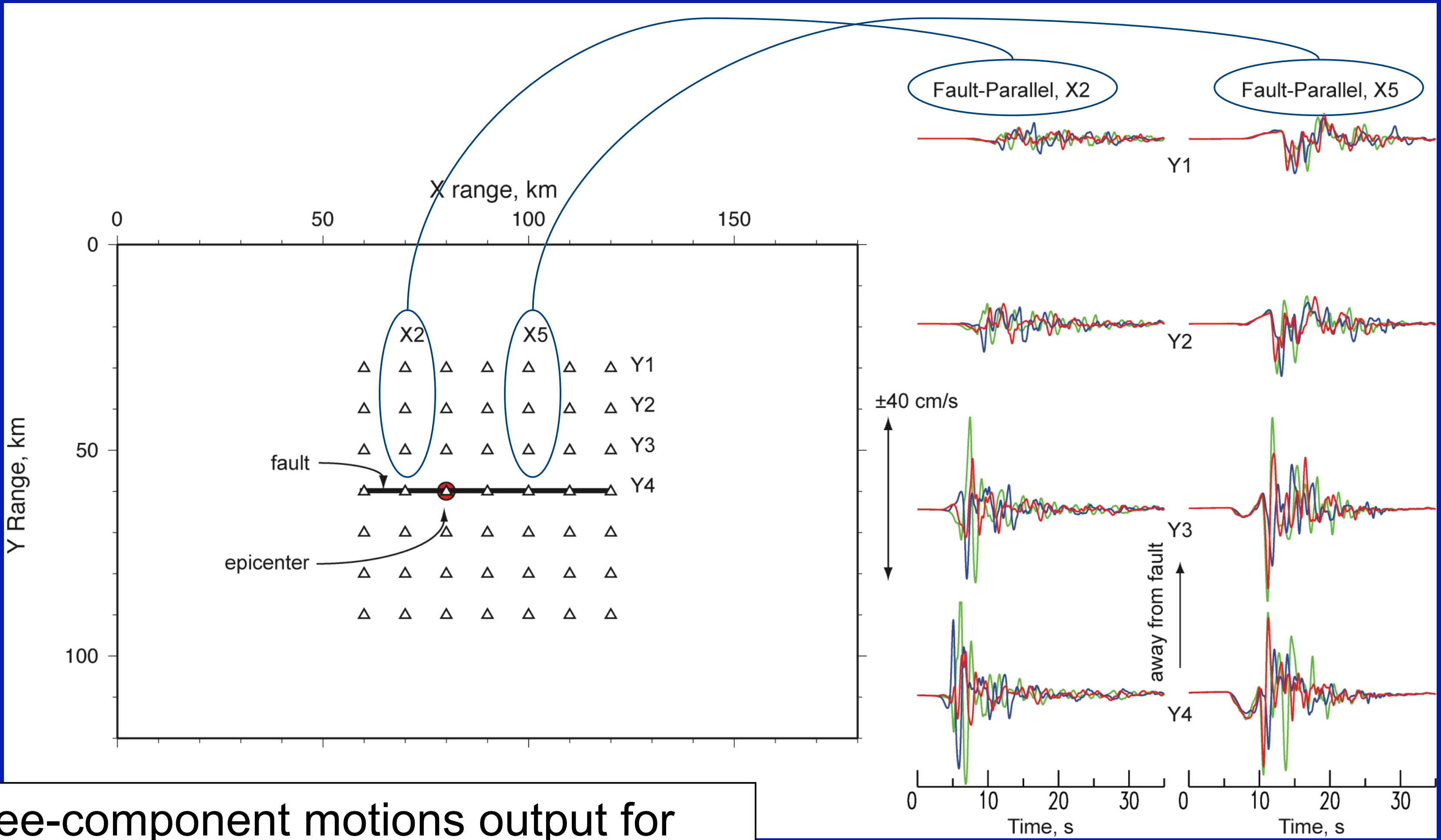


Hypocenter at star
$M_W = 7.0$
L = 60 km; H = 20 km

Correlation structure of **slip** based on empirical relations on M_0

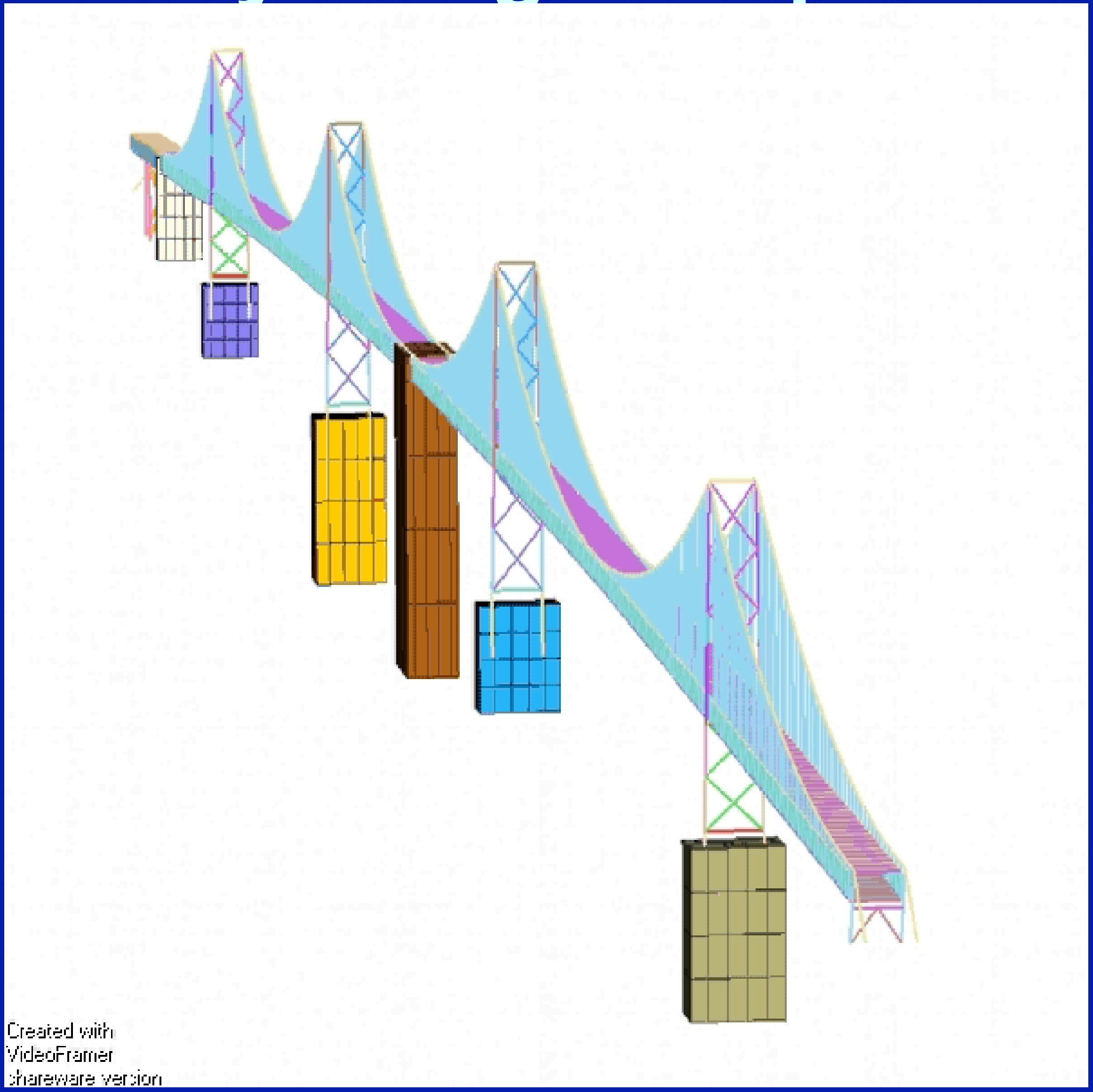
Remainder from based on relationships between slip, rise time, rupture velocity and rake

Ground Motions For Three Stochastic Rupture Models



Three-component motions output for near-source region.
These calculations valid to 1 Hz.

M_W 7.0 Hayward Fault
SF Bay Bridge Response



Development Plans

- Complete current development
  - Mesh refinement & attenuation (later in 2007)
  - Topography & PML (early 2008)
- Domain Reduction/Representation Theorem
  - Pass motions from non-linear (hydrodynamic) code to WPP (explosion modeling)
  - Introduce plane-wave to 3D structure in WPP
  - Pass motions from WPP to 1D (ω-k, Cagniard) codes
  - Pass motions from WPP to non-FE code (GNEP & YMP)
    - Include soil/structure interaction

  - **Please download and use the code!**