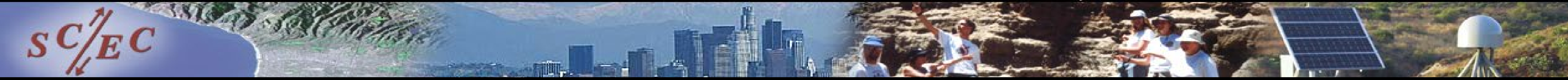
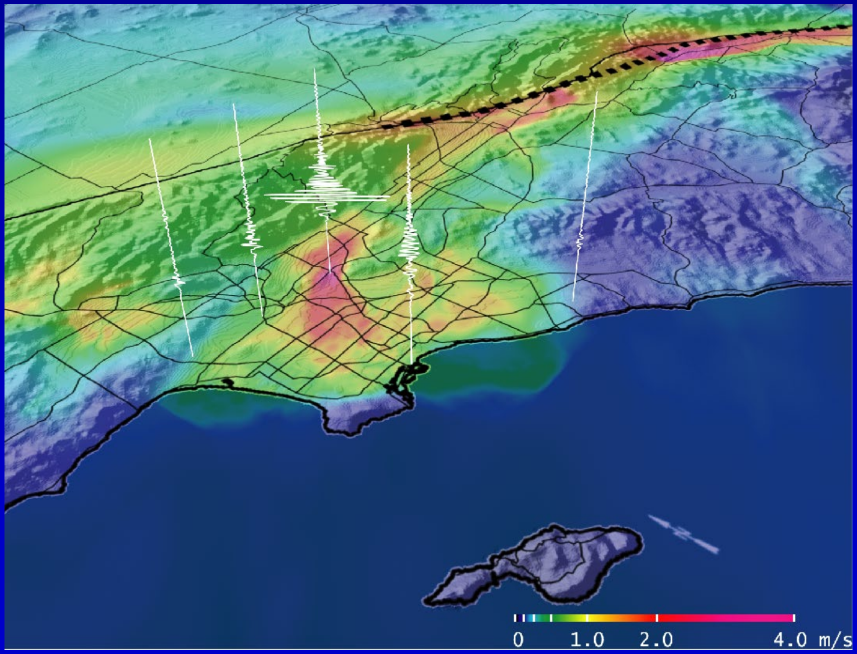
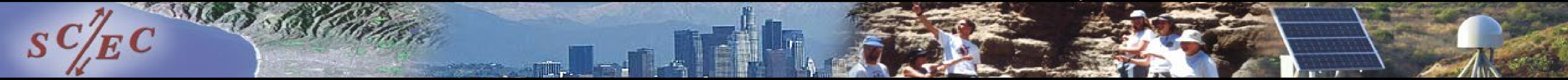
SOUTHERN CALIFORNIA EARTHQUAKE CENTER



SCEC Community Modeling Environment (SCEC/CME) - Earthquake Wave Propagation Simulations

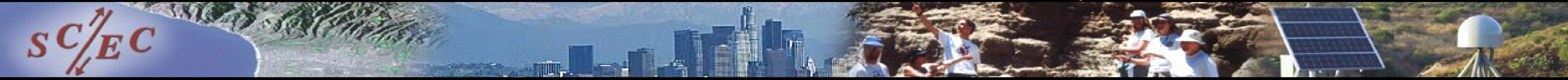


Philip Maechling
CIG/IRIS
Computational Seismology Workshop
8 June 2005



SCEC Earthquake Wave Propagation

- SCEC
- Example Simulations
  - TeraShake
  - Puente Hills
  - Fréchet Kernels
- Community Modeling Environment (SCEC/CME)
  - Workflows
  - Interchangeable Components
  - Data Management



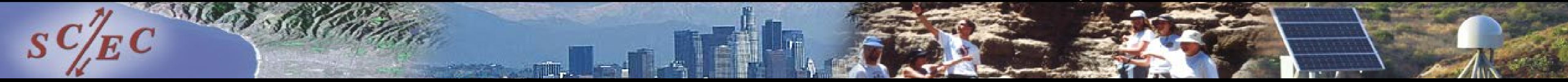
Southern California Earthquake Center

Core Institutions

California Institute of Technology
Columbia University
Harvard University
Massachusetts Institute of Technology
San Diego State University
Stanford University
U.S. Geological Survey (3 offices)
University of California, Los Angeles
University of California, San Diego
University of California, Santa Barbara
University of Nevada, Reno
University of Southern California (lead)

- Consortium of 14 core institutions and 26 other participating organizations, founded as an NSF STC in 1991, and re-funded in 2001 for 5 additional years.
- Co-funded by NSF and USGS under the National Earthquake Hazards Reduction Program (NEHRP)
- Mission:
  - Gather all kinds of data on earthquakes in Southern California
  - Integrate information into a comprehensive, physics-based understanding of earthquake phenomena
  - Communicate understanding to end-users and the general public to increase earthquake awareness, reduce economic losses, and save lives

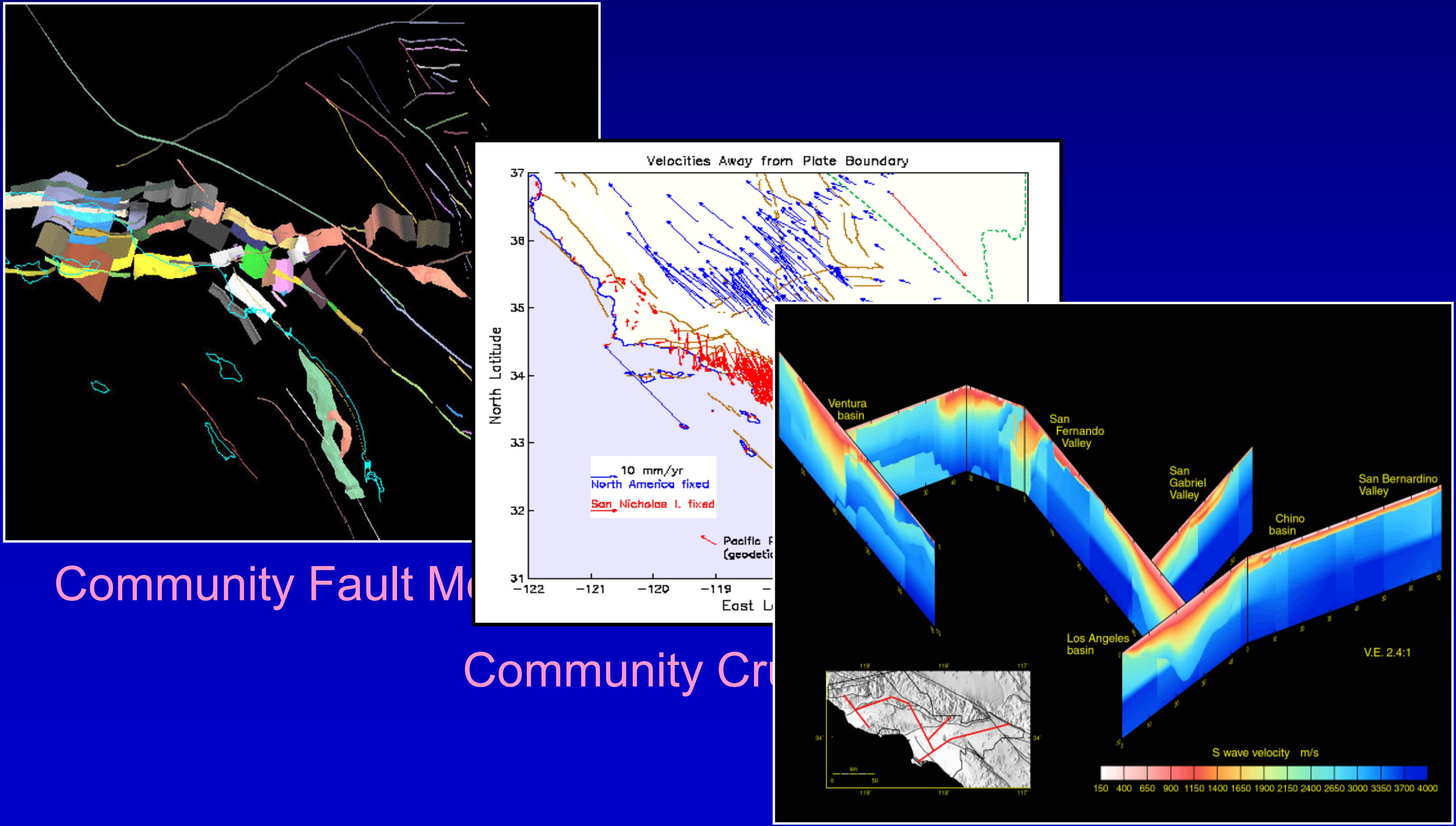
http://www.scec.org



SCEC Earthquake Wave Propagation

- SCEC Science Mission
  - – Gather information About earthquakes
  - – Integrate into a physics-based understanding
  - – Communicate understanding to community

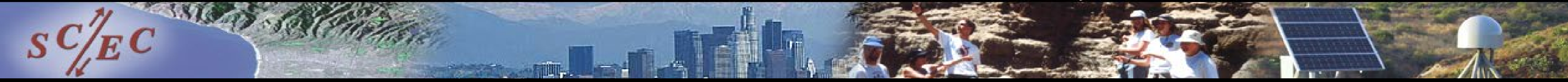
Development of SCEC Geophysical Models



Community Fault M

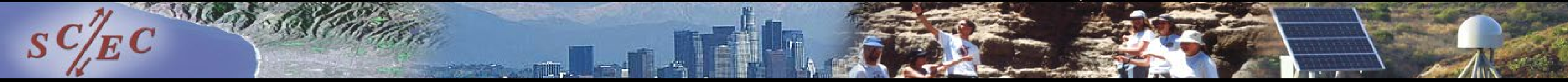
Community Cr

Community Velocity Model (CVM.3.0)



PEER/SCEC Project Team

- Jacobo Bielak (CMU)
- Steven Day (SDSU)
- Doug Dreger (UCB)
- Robert Graves (URS)
- Shawn Larsen (LLNL)
- Kim Olsen (UCSB)
- Arben Pitarka (URS)



Introduction

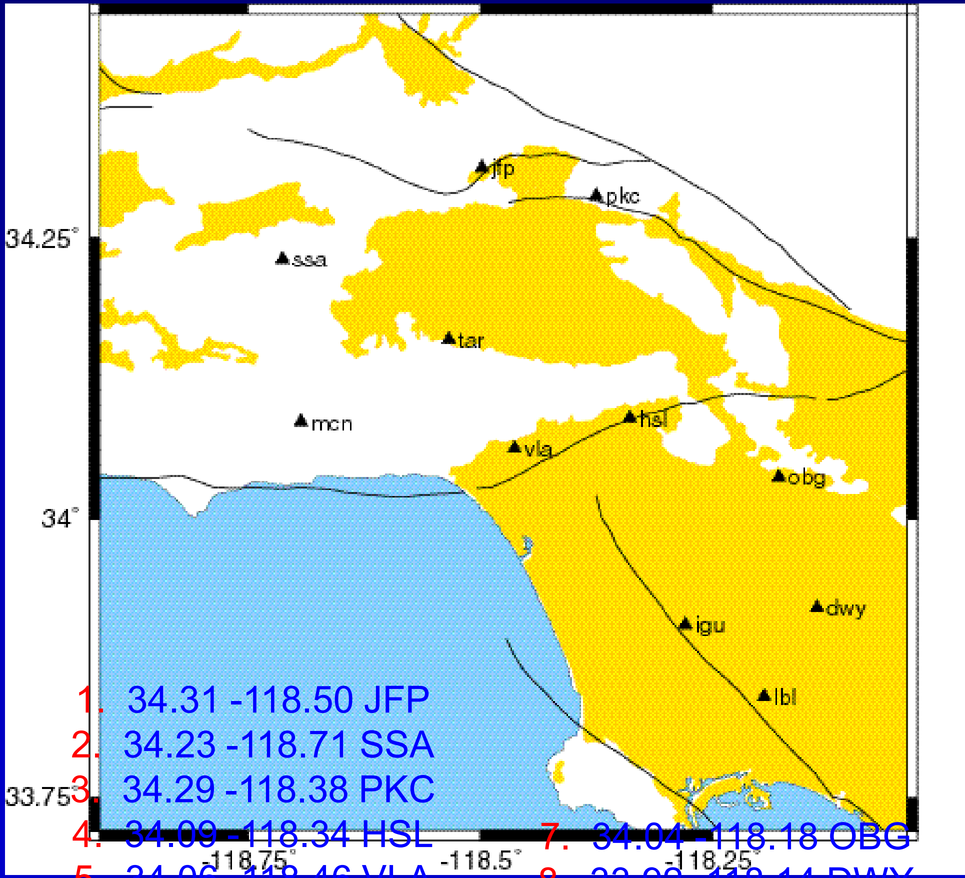
- Project Objectives
  - Test 3D ground motion simulation codes (“verification”)
  - Test efficacy of 3D ground motion modeling (“validation”)
  - Coordinated execution of 3D ground motion simulations for realistic sources in realistic basin environments
  - Development of practical engineering rules for correcting ground motion estimates for basin effects

Code Testing

- Simplified source and structure
  - Point dislocation, uniform halfspace
  - Point dislocation, uniform halfspace (large domain)
  - Point dislocation, layer over halfspace
  - Propagating strike slip, layer over halfspace
  - Propagating thrust, layer over halfspace
  - Point dislocation, anelastic layer over halfspace
- Simple source, realistic structure
  - Point dislocation, SCEC CVM Version 2
  - Point dislocation, modified SCEC CVM Version 2
- Realistic source and structure: Northridge E.Q.

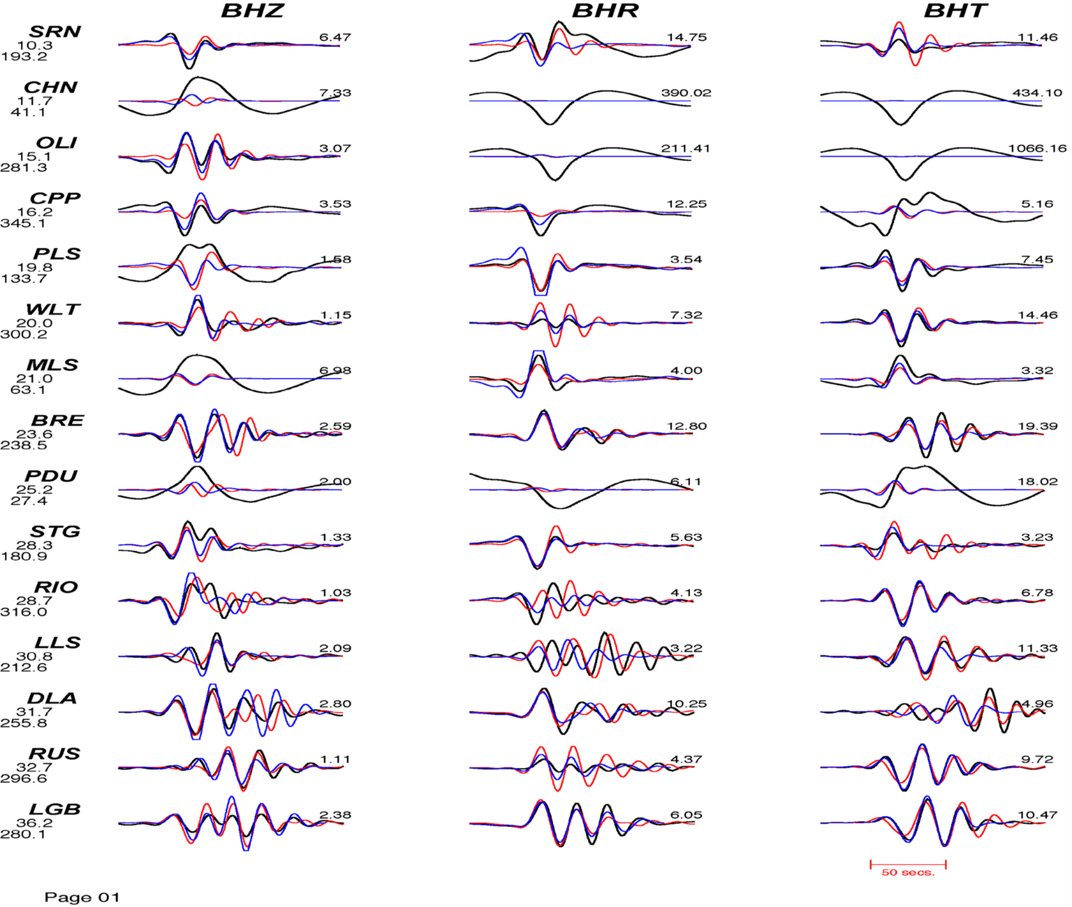
Example Verification Exercise -Northridge Simulation

- Wald et al source
- ~ 80 km x 80 km region
- 0 - 0.5 Hz
- SCEC CVM Version 2
- Elastic case ("NOR.2")
- Anelastic case ("NOR.1")



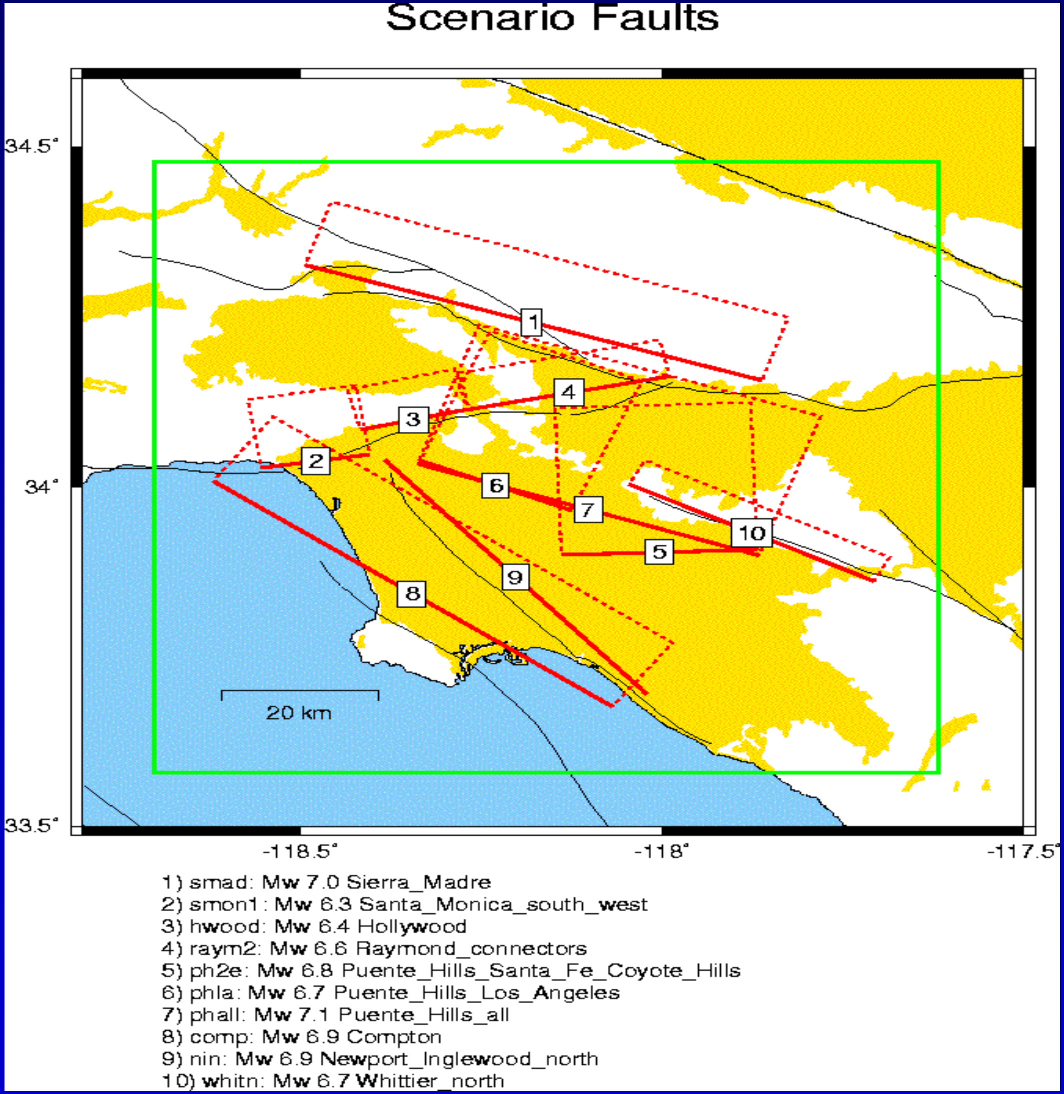
1.	34.31	-118.50	JFP
2.	34.23	-118.71	SSA
3.	34.29	-118.38	PKC
4.	34.09	-118.34	HSL
5.	34.06	-118.46	VLA
6.	33.90	-118.28	IGU
7.	34.04	-118.18	OBG
8.	33.92	-118.14	DWY
9.	34.16	-118.53	TAR
10.	34.09	-118.69	MCN
11.	33.84	-118.19	LBL

Validation Exercises for AWM Codes



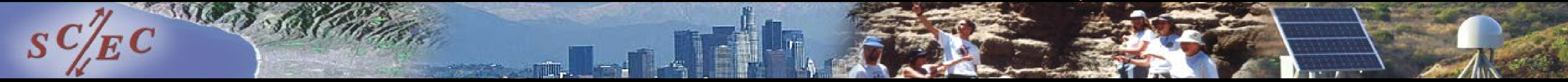
Comparisons for 09/03/02 Yorba Linda Earthquake
Data in black, SCEC CVM (FD) in blue, Harvard model (SEM) in red

Scenario Earthquake Catalog



Scenario Faults

1) smad: Mw 7.0 Sierra_Madre
2) smon1: Mw 6.3 Santa_Monica_south_west
3) hwood: Mw 6.4 Hollywood
4) raym2: Mw 6.6 Raymond_connectors
5) ph2e: Mw 6.8 Puente_Hills_Santa_Fe_Coyote_Hills
6) phla: Mw 6.7 Puente_Hills_Los_Angeles
7) phall: Mw 7.1 Puente_Hills_all
8) comp: Mw 6.9 Compton
9) nin: Mw 6.9 Newport_Inglewood_north
10) whitn: Mw 6.7 Whittier_north



Earthquake Scenarios

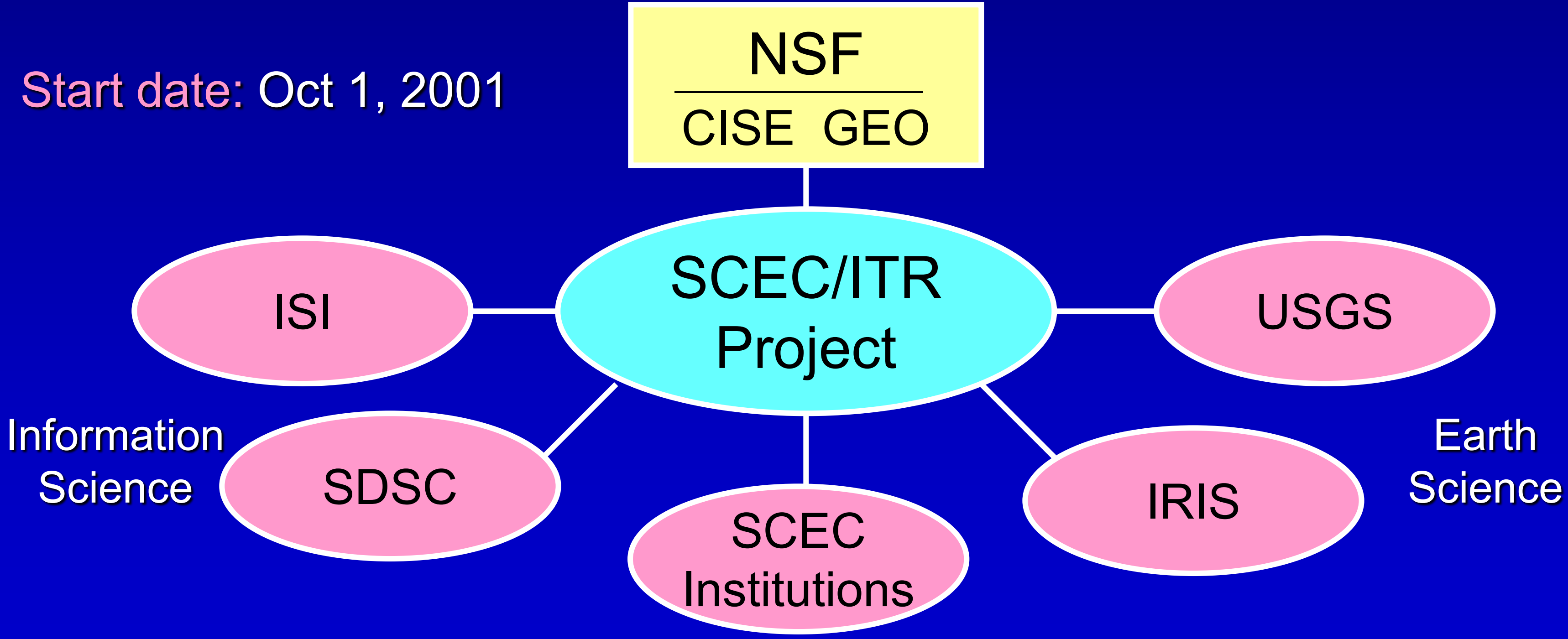
- ~100 L.A.-region earthquake scenarios
  - 8-10 faults
    10 rupture scenarios each
- ~10^8 elements per scenario
- Save velocity time histories at ~10^4 points
- Reduce to ~10 “Intensity measures”
  - Peak velocity
  - Response spectral ordinates

SCEC/CME Project

Goal: To develop a cyberinfrastructure that can support system-level earthquake science – the SCEC Community Modeling Environment (CME)

Support: 5-yr project funded by the NSF/ITR program under the CISE and Geoscience Directorates

Start date: Oct 1, 2001



NSF

CISE GEO

SCEC/ITR Project

ISI

USGS

Information Science

SDSC

SCEC Institutions

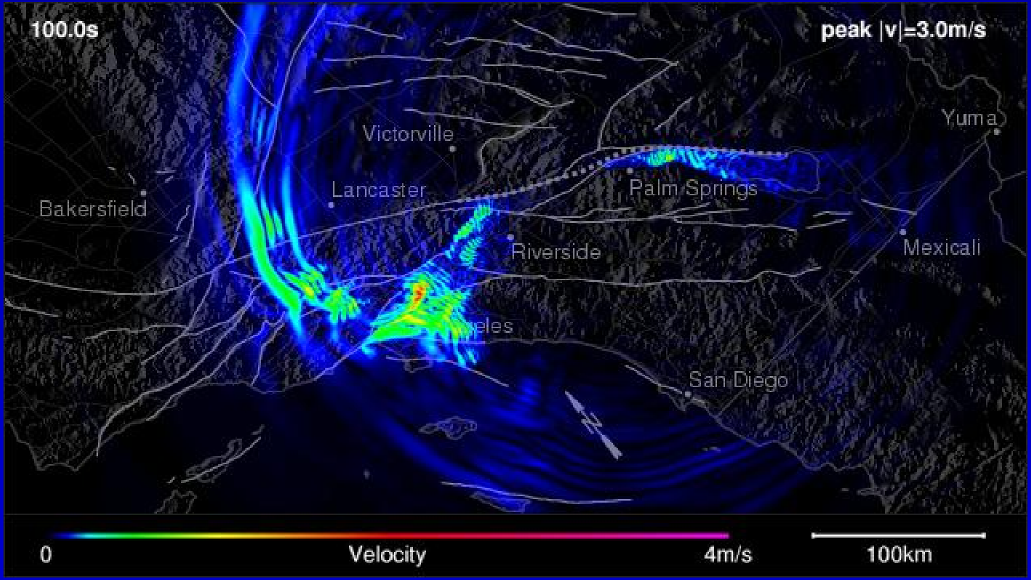
IRIS

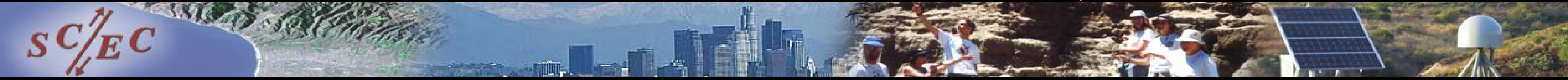
Earth Science

www.scec.org/cme

TeraShake Earthquake Simulations

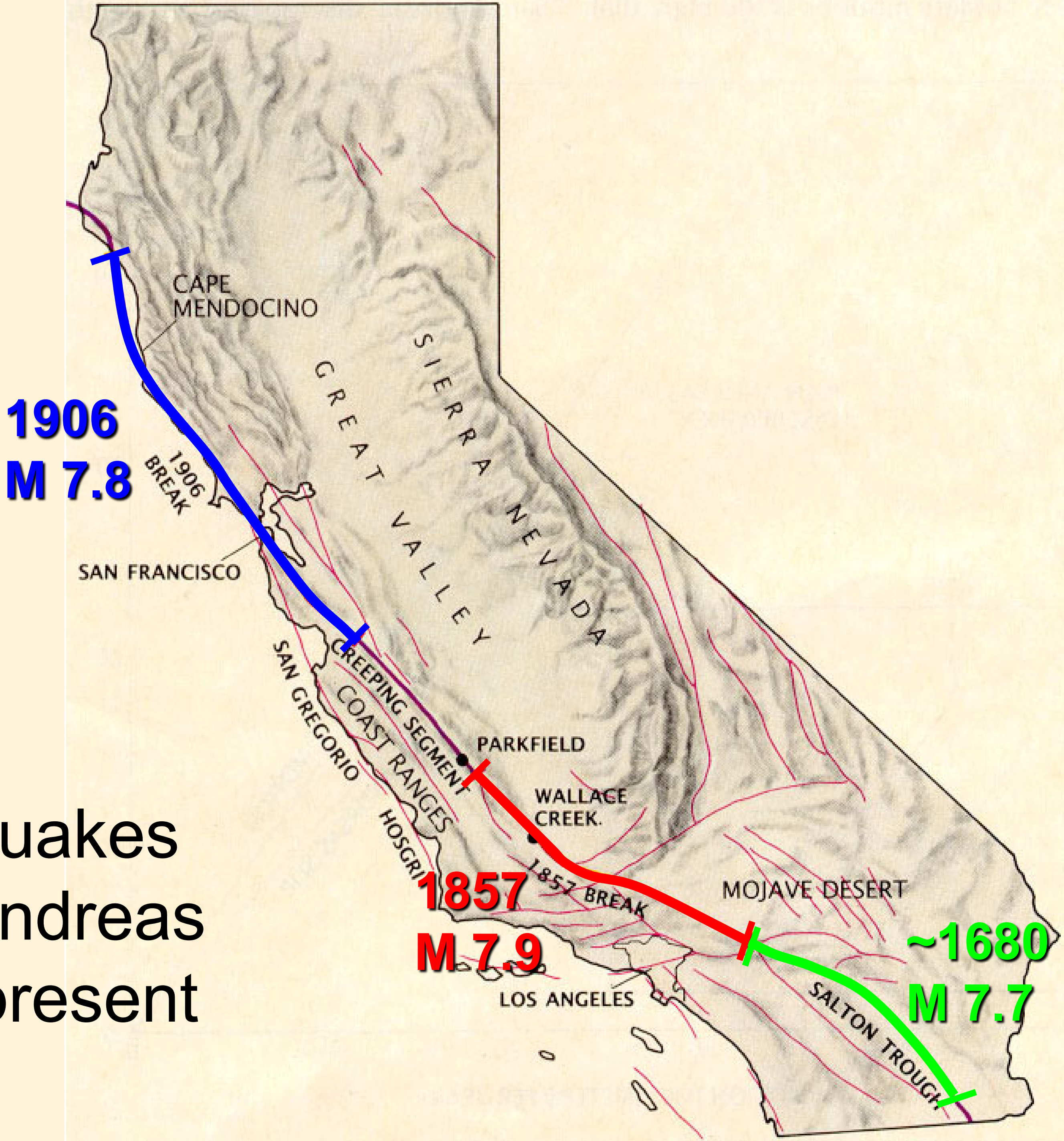
Kim Olsen, Steve Day, J. Bernard Minster
and the SCEC/CME Collaboration





33 researchers, 8 Institutions

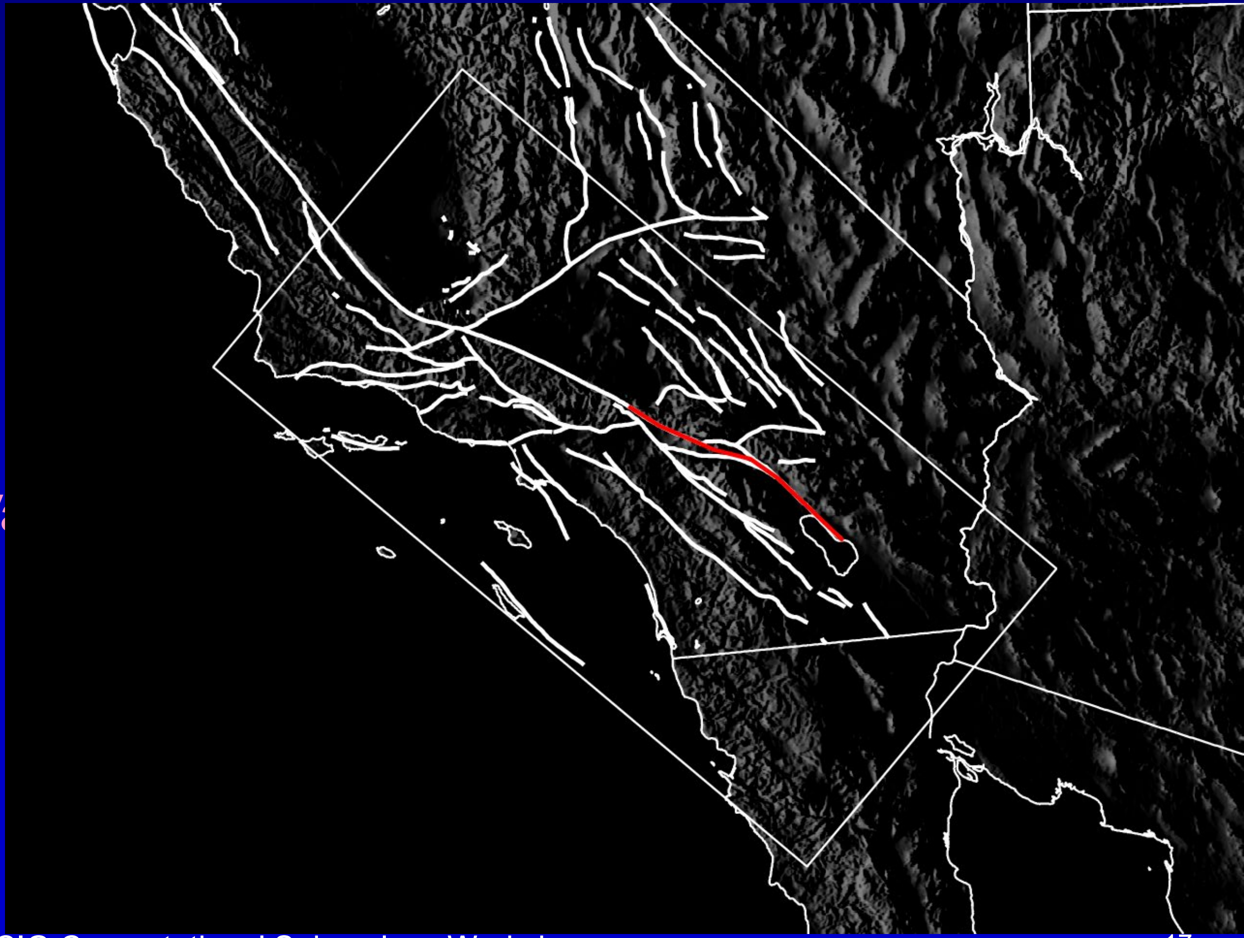
Southern California Earthquake Center
San Diego Supercomputer Center
Information Sciences Institute
Institute of Geophysics and Planetary Physics (UC)
University of Southern California
San Diego State University
University of California, Santa Barbara
Carnegie-Mellon University
EXonMobil



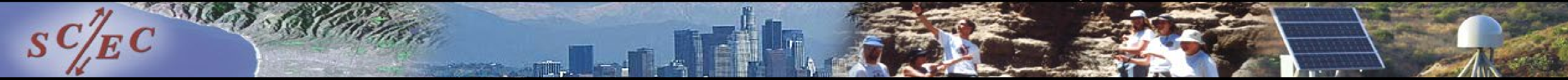
Major Earthquakes on the San Andreas Fault, 1680-present

TeraShake Simulation Area

- Rectangular region parallel to San Andreas fault containing:
  - Los Angeles,
  - San Diego,
  - Mexicali,
  - Tijuana,
  - Ventura Basin,
  - Fillmore,
  - Southern San Joaquin Va
  - Catalina Island,
  - Ensenada



- 600 x 300 x 80 km



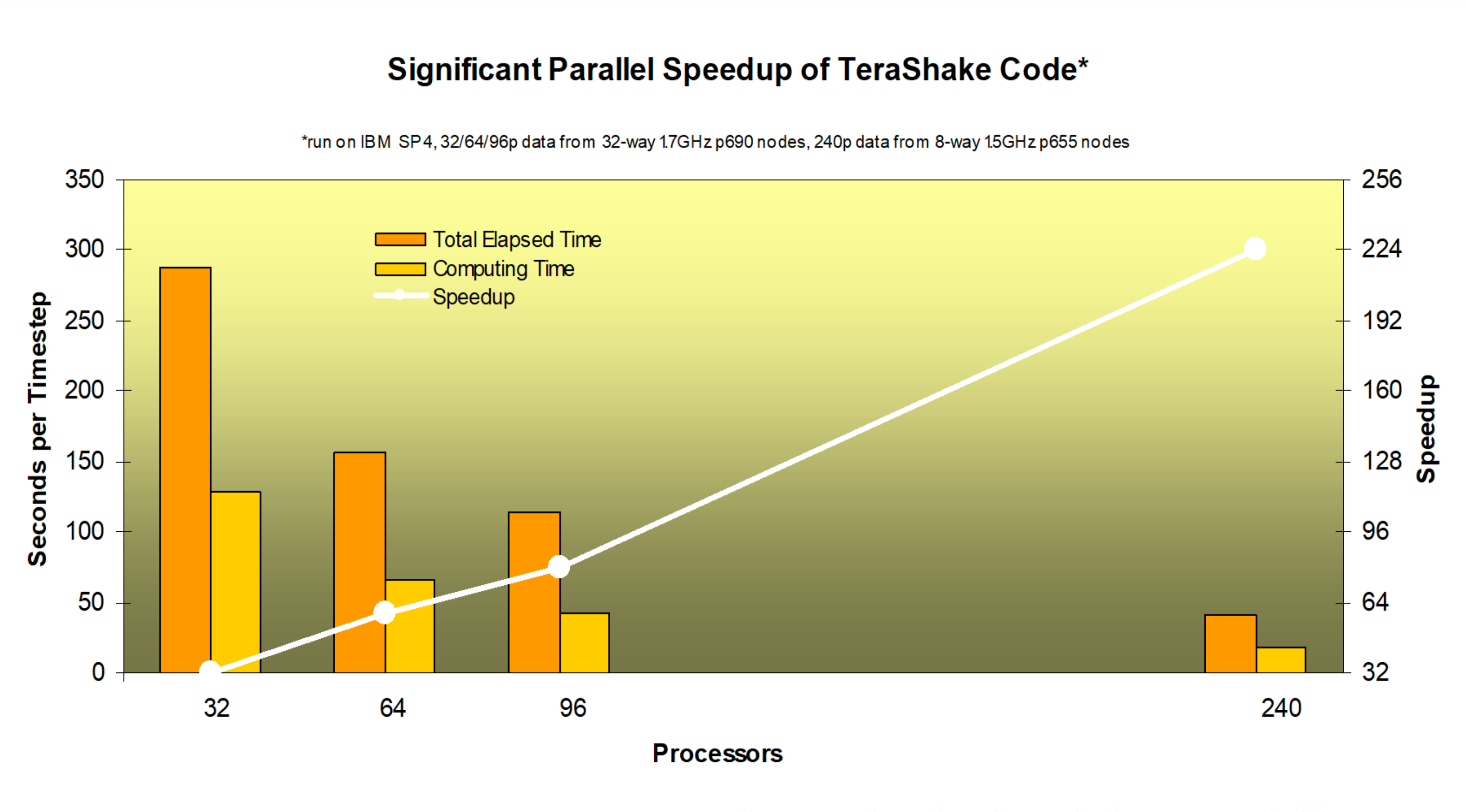
TeraShake Modeling Challenge

- Outer scale is large: ≥ 500km.
  - Fault rupture is several 100 km long.
  - Broad NOAM-PCFC plate boundary zone
  - Strong ground motions felt several 100 km away.
- **Use absorbing boundary conditions**
- Inner scale is small: ≤ 200m.
  - Physics of rupture scales of 1 m to 200 m.
  - Slow shear velocities in shallow soils: $\lambda < 200$ m
- **Impose a“floor” on shear velocities: ≤ 500m/s**
- **Restrict frequencies modeled: ≤ 0.5 Hz.**

TeraShake Earthquake Simulation

- Magnitude 7.7 earthquake on southern San Andreas
- Mesh of 1.8 Billion cubes, 200 m in dimension
- 0.011 sec time step, 20,000 time steps: 3 minute simulation
- Kinematic source (adapted from Denali): Cajon Creek to Bombay Beach
  - 60 sec source duration
  - 18,886 point sources, each 6,800 time steps in duration
- 240 processors on San Diego SuperComputer Center DataStar
- ~ 20,000 CPU hours, over approximately 5 days wall clock
- ~ 50 Terabytes of output (30 million floppies)

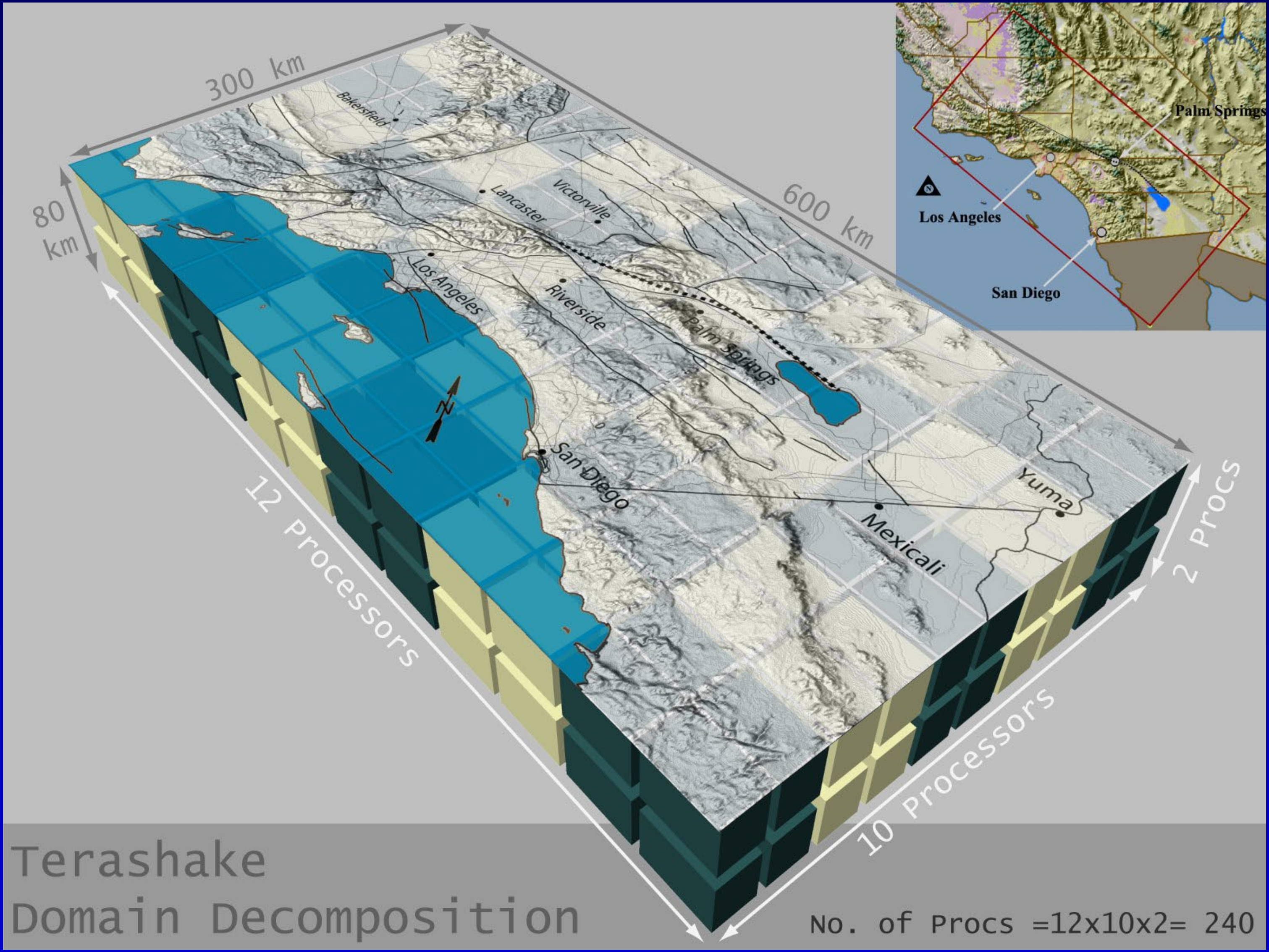
TeraShake Performance



Significant Parallel Speedup of TeraShake Code*

*run on IBM SP4, 32/64/96p data from 32-way 1.7GHz p690 nodes, 240p data from 8-way 1.5GHz p655 nodes

Source: Yifeng Cui, Scientific Computing, SDSC



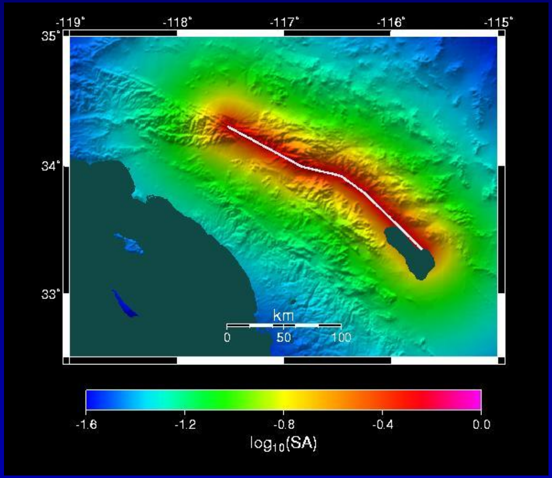
240 Processors

How do you get to 47 TBytes?

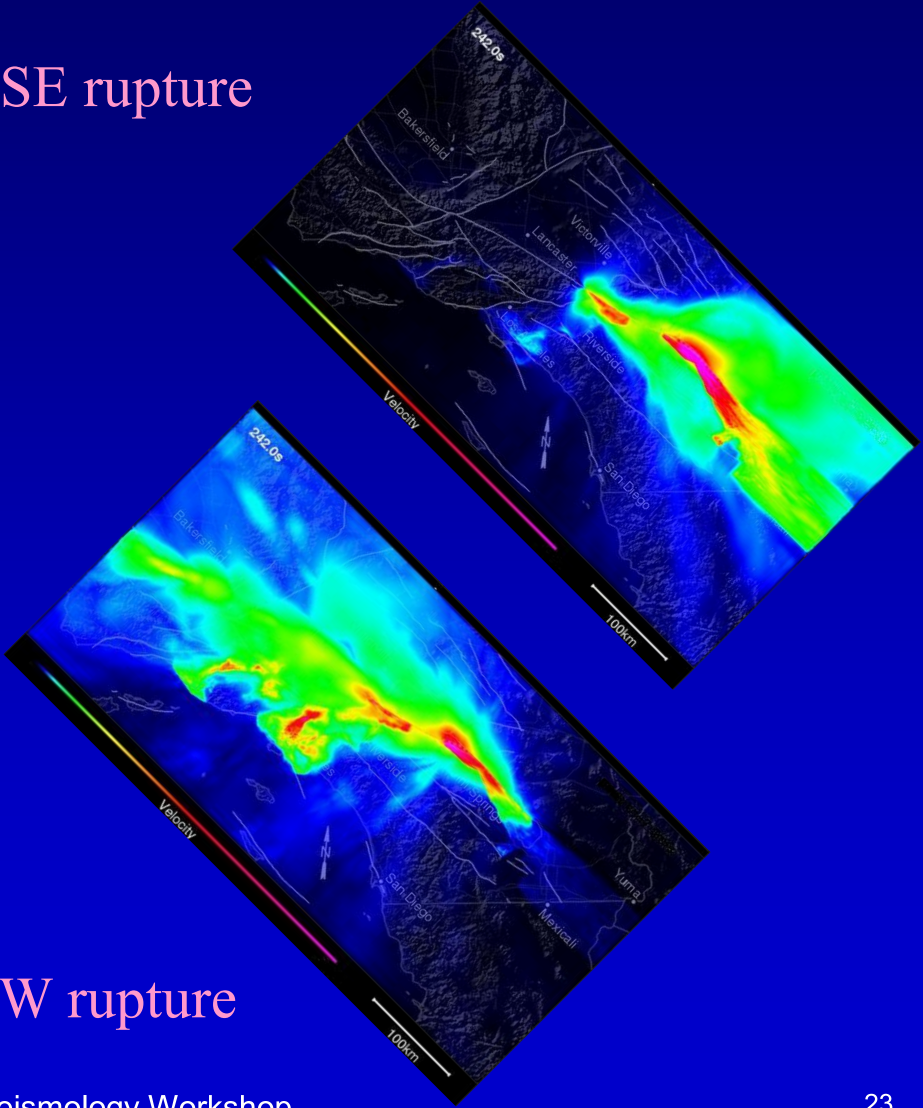
Full volume velocities every 10th time step	43.2
Full surface velocities every time step	1.1
Checkpoints (/restarts) every 1,000 steps	3.0
Doodahs (input files, etc)	0.1

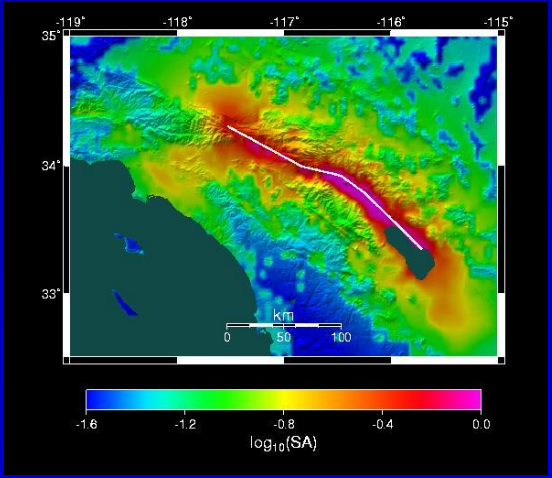
Total number of files: 150,000

TeraShake Peak Ground Velocity Maps



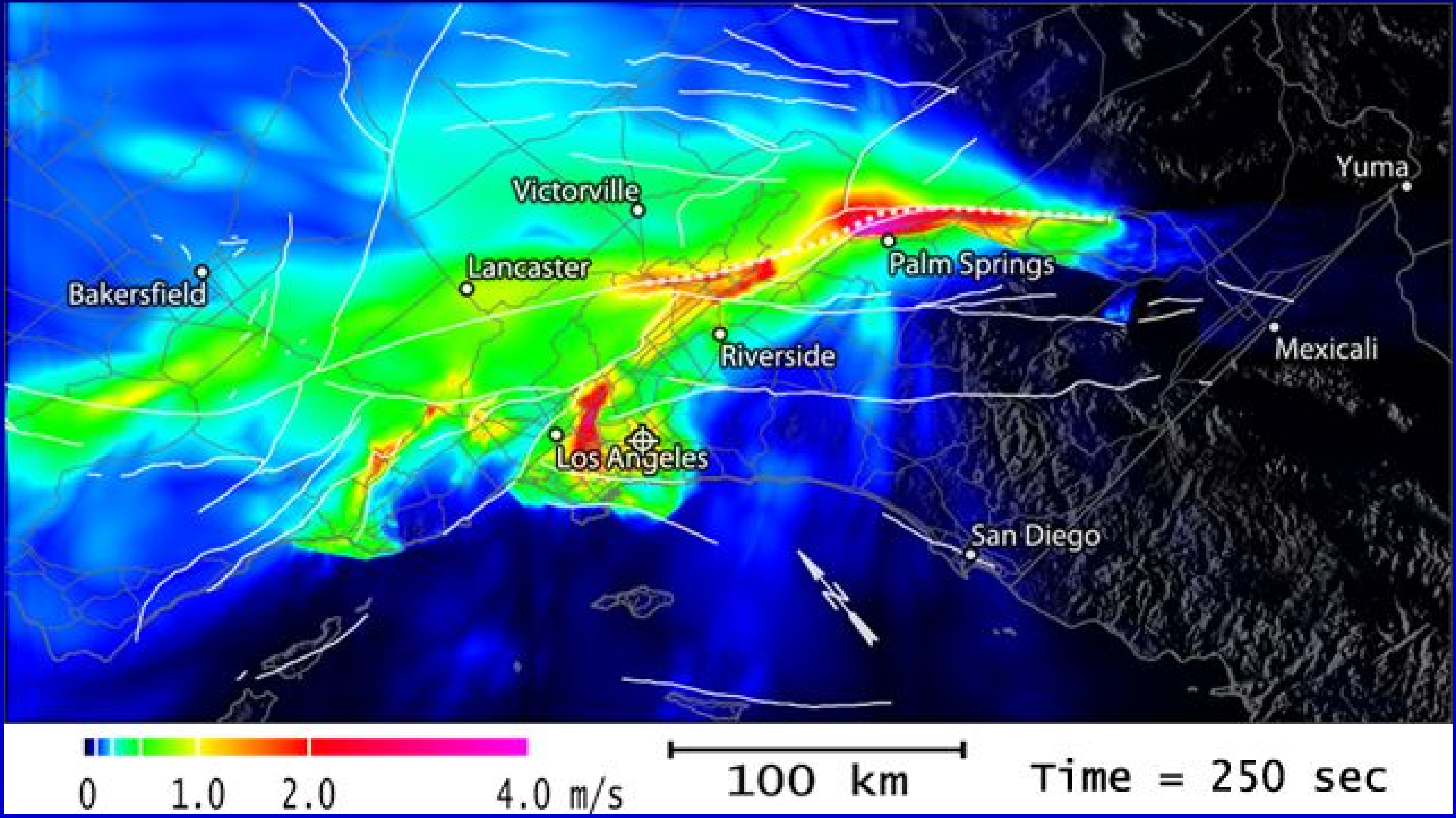
NW to SE rupture



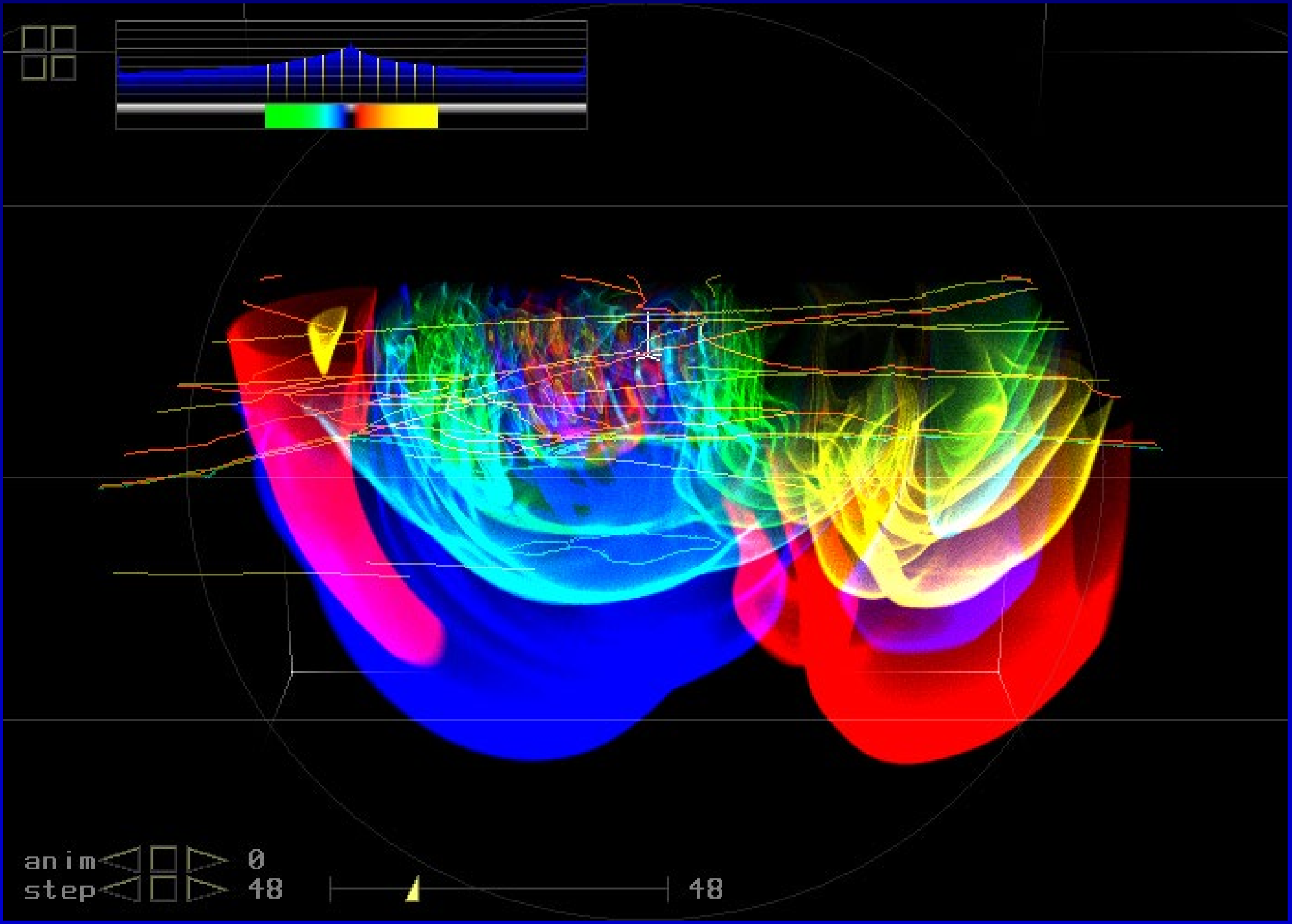


SE to NW rupture

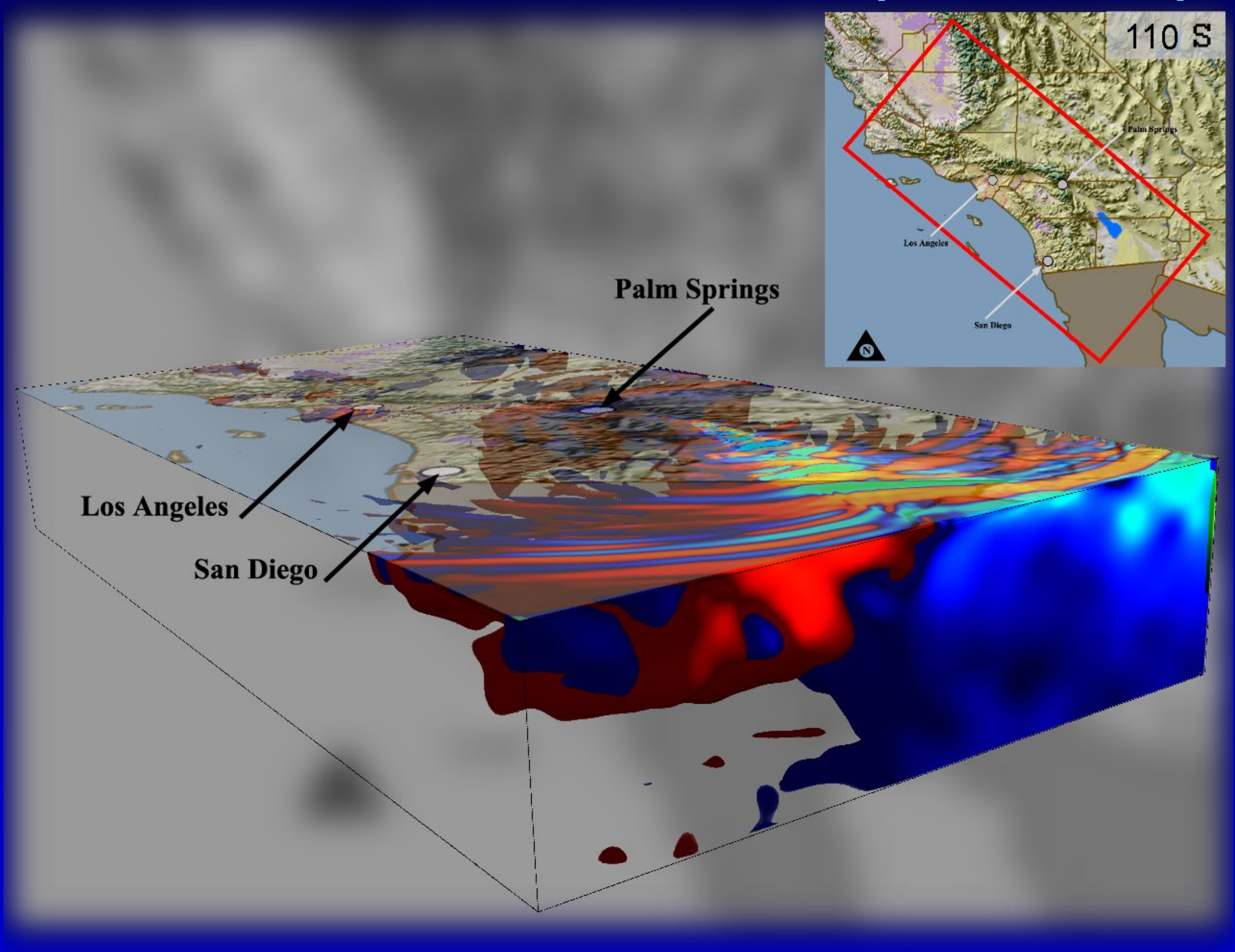
Terashake Simulation



Point Cloud 4D Visualization



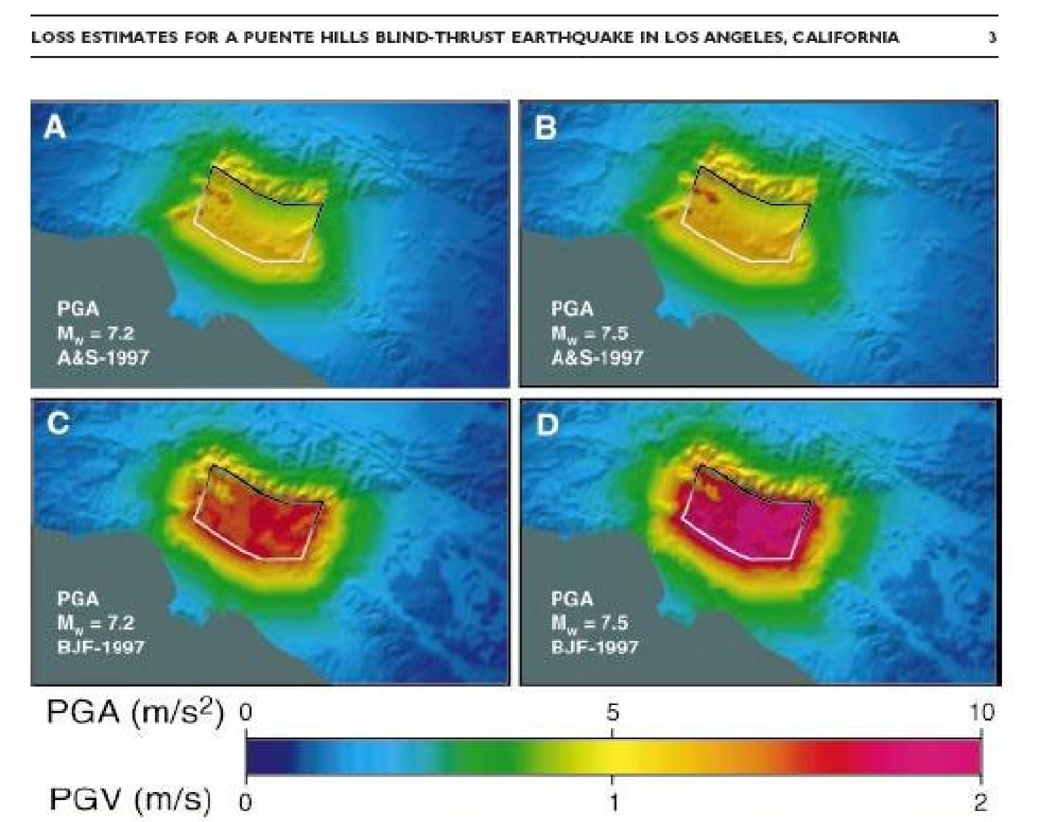
3D visualization (SDSC)



Puente Hills Faulte Earthquake Simulation

Robert Graves – URS and SCEC

Attenuation Relationship-based SHA



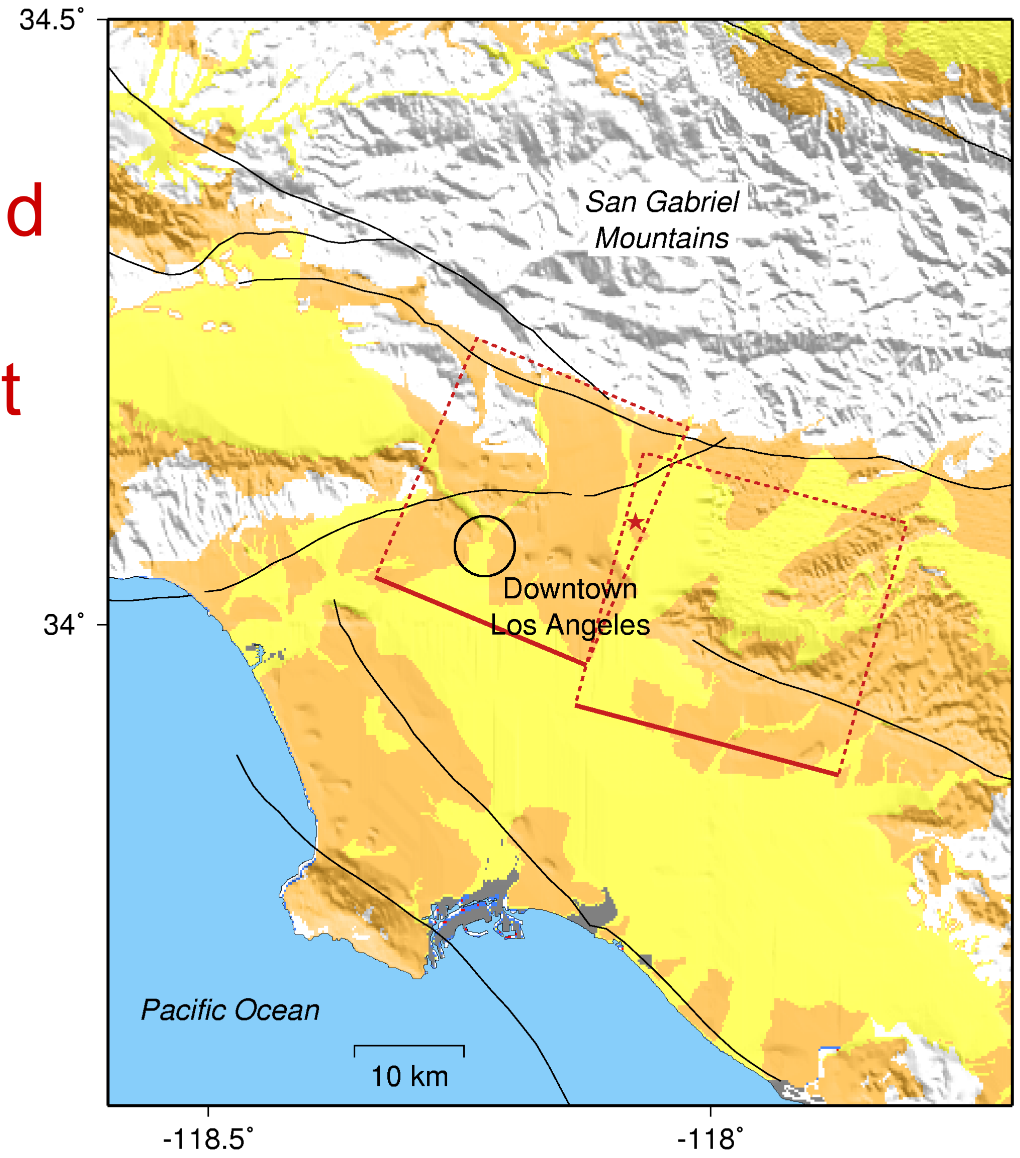
LOSS ESTIMATES FOR A PUENTE HILLS BLIND-THRUST EARTHQUAKE IN LOS ANGELES, CALIFORNIA 3

Abrahamson and Silva (1997)

Boore et al. (1997)

Attenuation Relationships produce significant differences in ground motion prediction

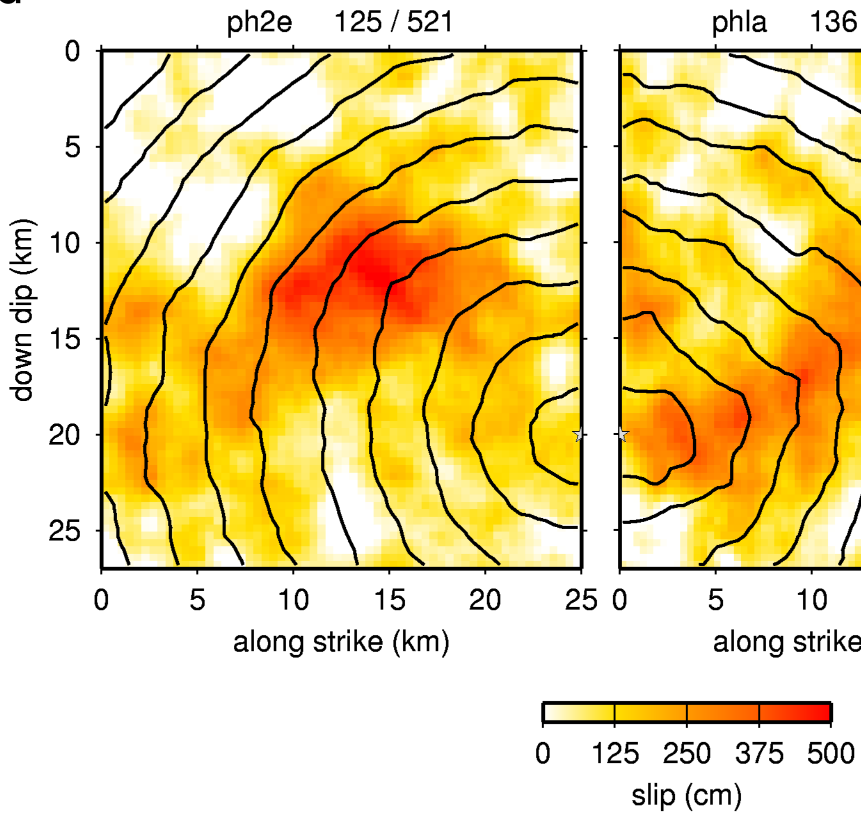
Fault location and geometry from Community Fault Model



- Coarse slip distribution and hypocenter initially specified
- Extend to fine-scale sampling using K^{-2} filter (e.g. Somerville et al., 1999)
- Rupture time derived from simple scaling formula

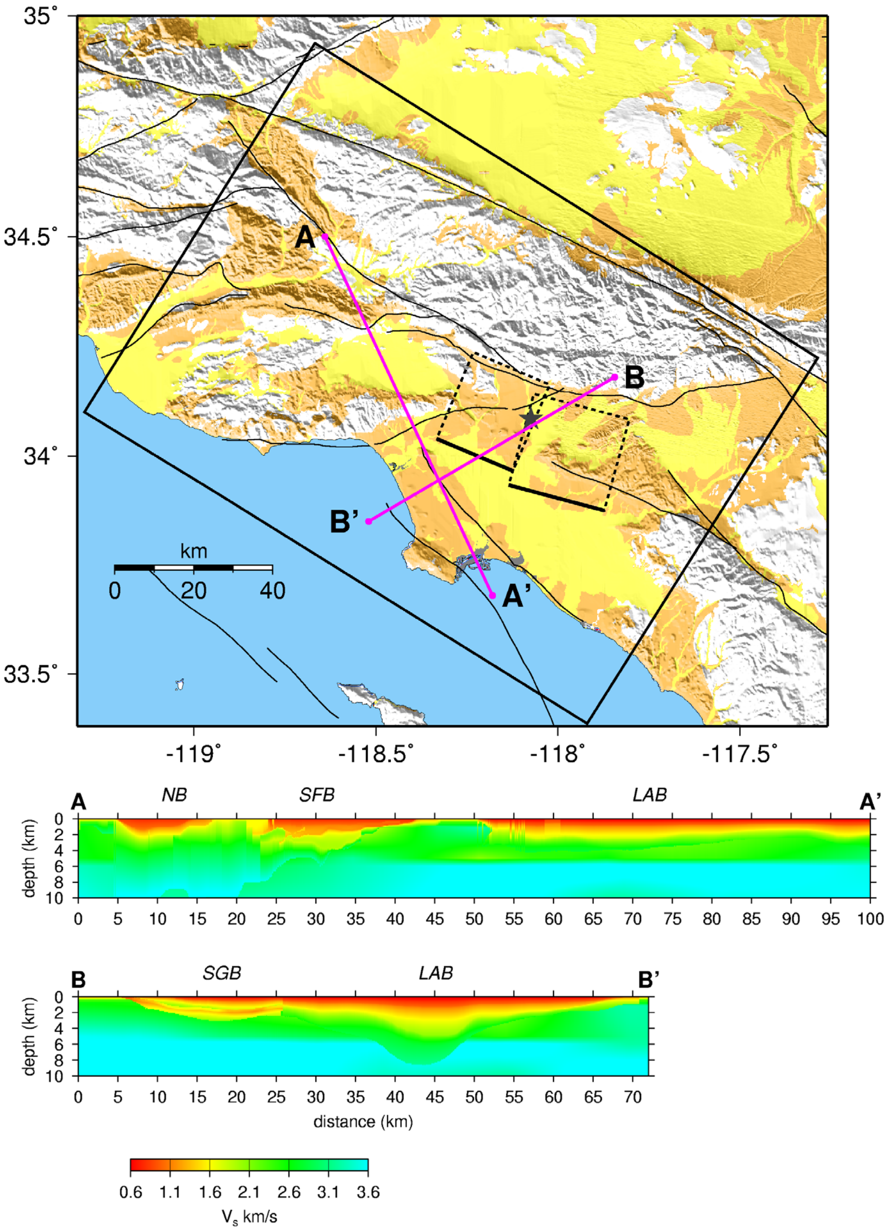
$$T_i = R / V_r - \delta t\ (slip)$$

$$V_r = \alpha V_s$$



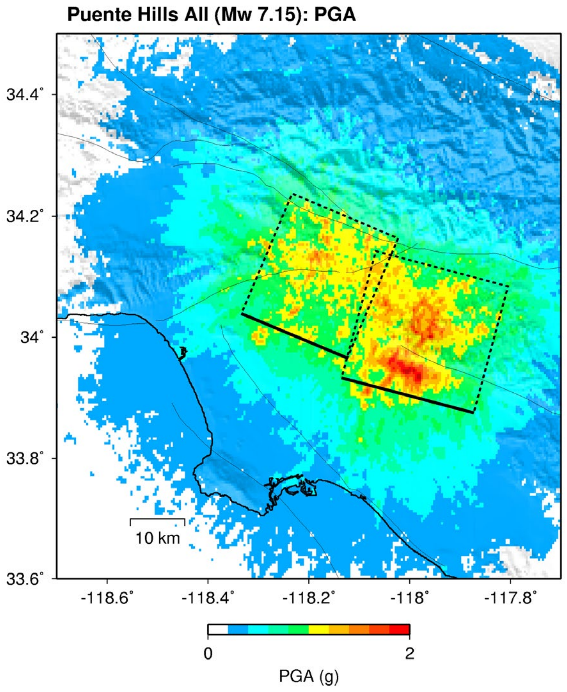
Model Region

- 150 km X 110 km X 45 km
- SCEC Community Velocity Model (3D)
- 380 X 10^6 node FD grid (h=125 m)
- Broadband (0-10 Hz) output at 66,000 sites

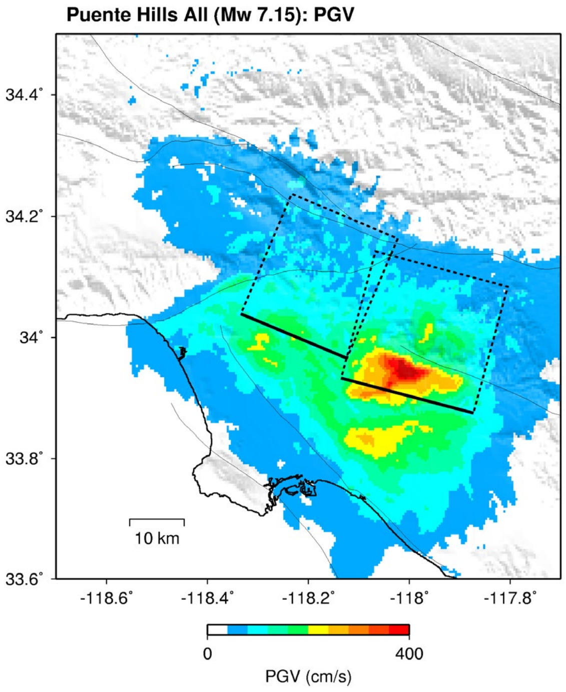


Ground Motion Maps

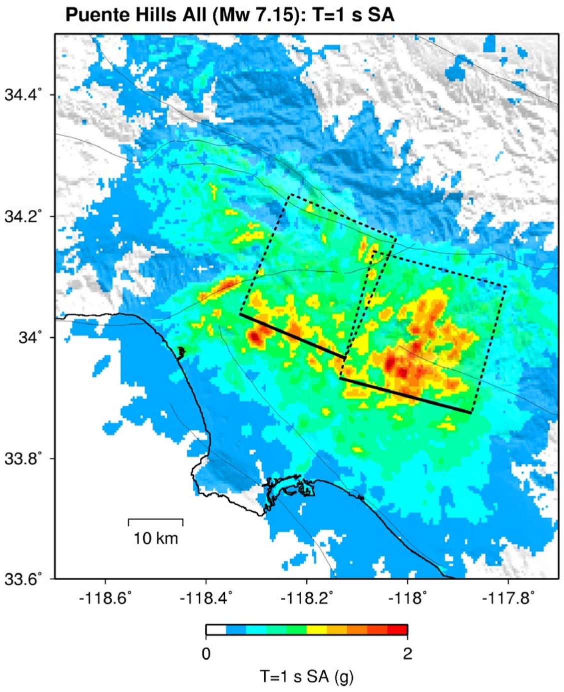
PGA



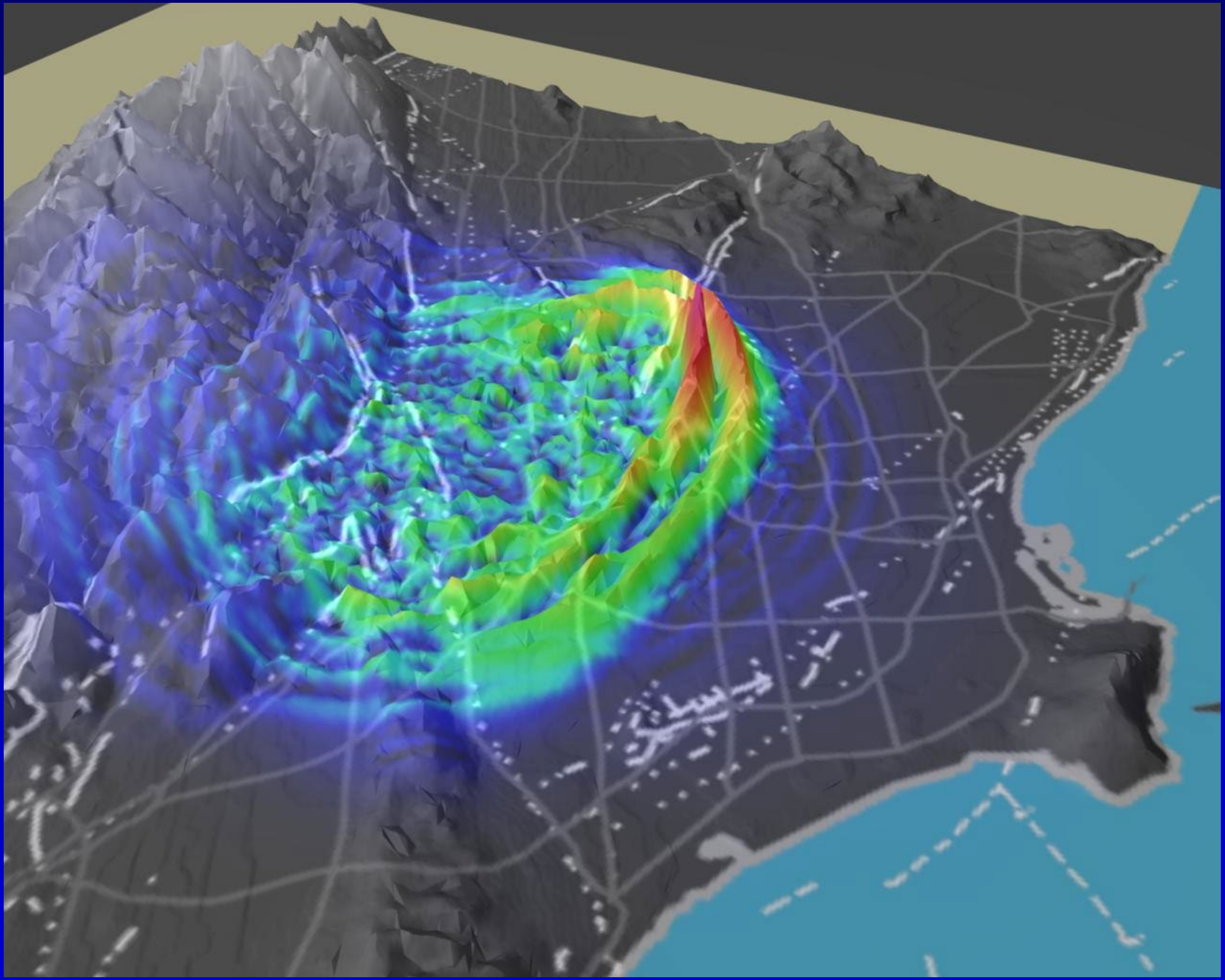
PGV



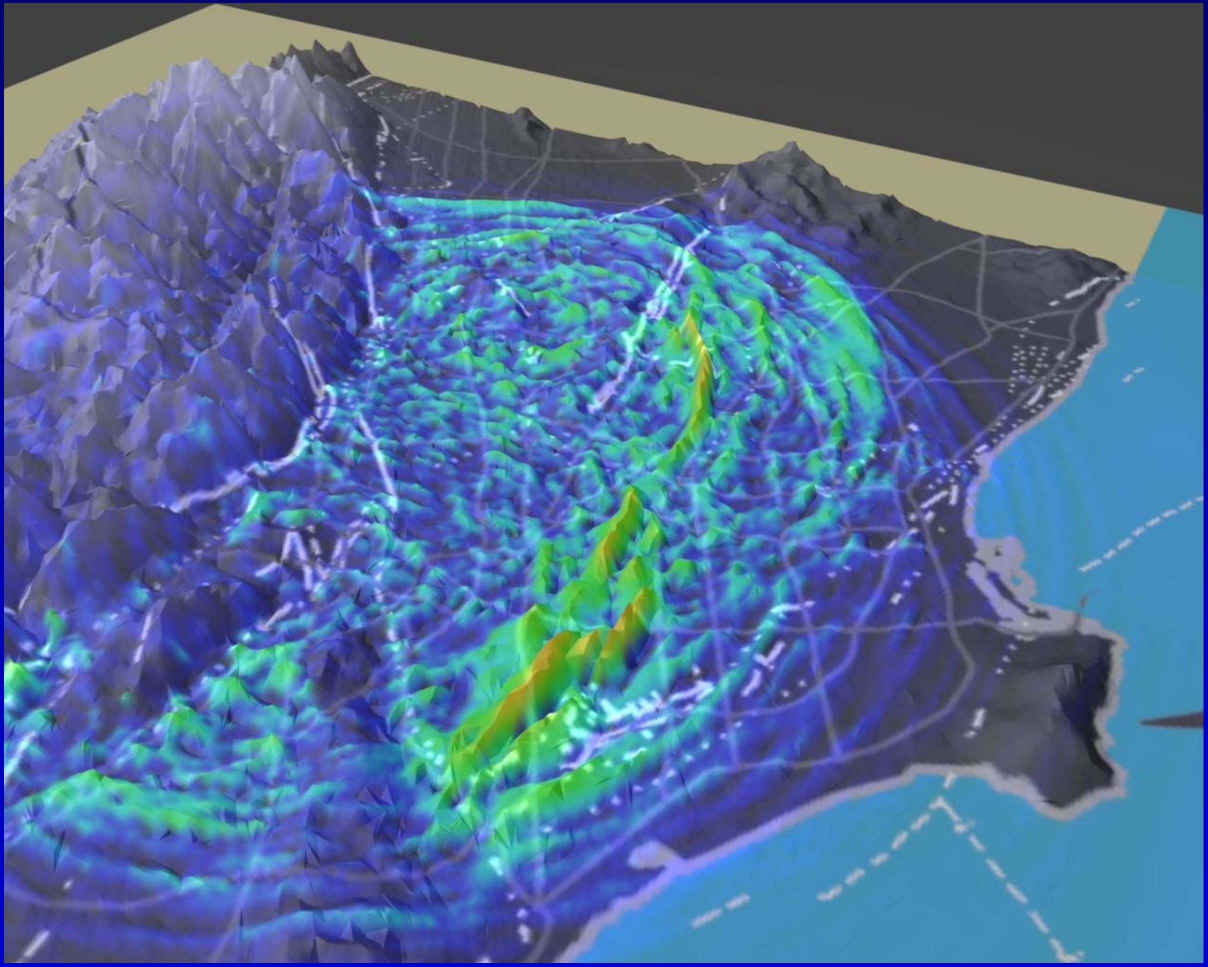
1 sec SA

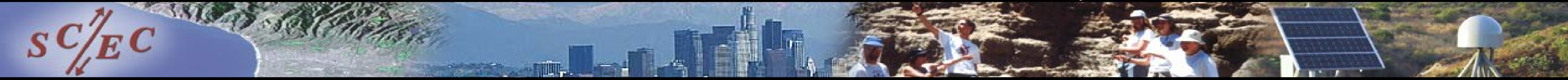


Puente Hills Simulation



Puente Hills Simulation



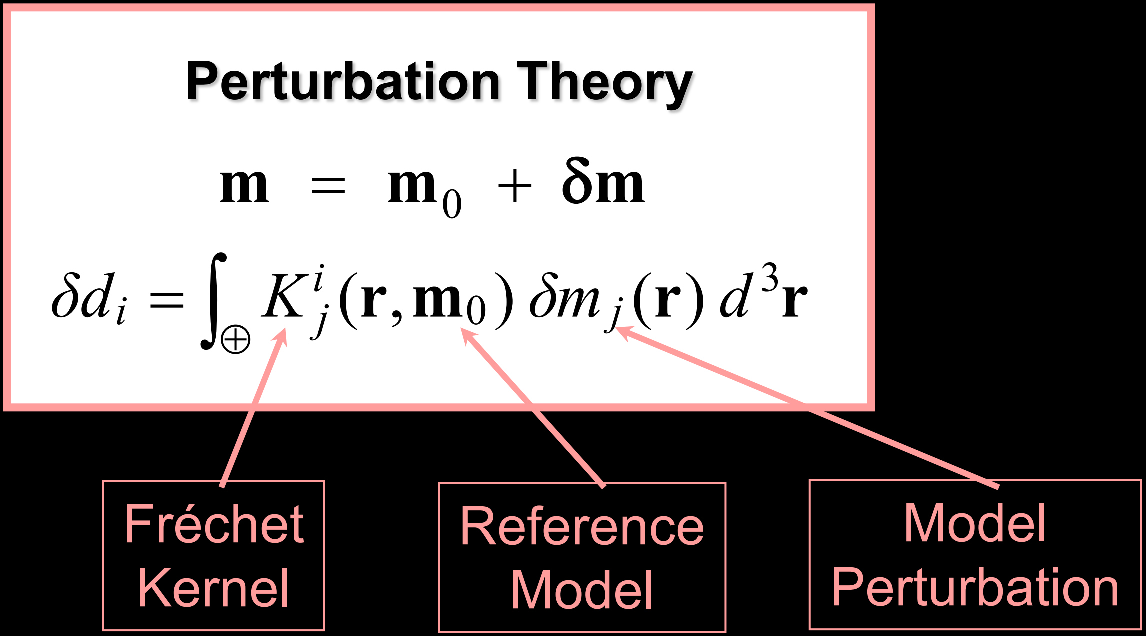


Fréchet Kernels

Li Zhao, Po Chen, Tom Jordan –
USC and SCEC

Imaging Earth Structure

Li Zhao (USC), Po Chen (USC),
Thomas H. Jordan (USC) & Kim B. Olsen (SDSU)



Perturbation Theory

$$\mathbf{m} = \mathbf{m}_0 + \delta\mathbf{m}$$

$$\delta d_i = \int_\oplus K^i_j(\mathbf{r},\mathbf{m}_0)\,\delta m_j(\mathbf{r})\,d^3\mathbf{r}$$

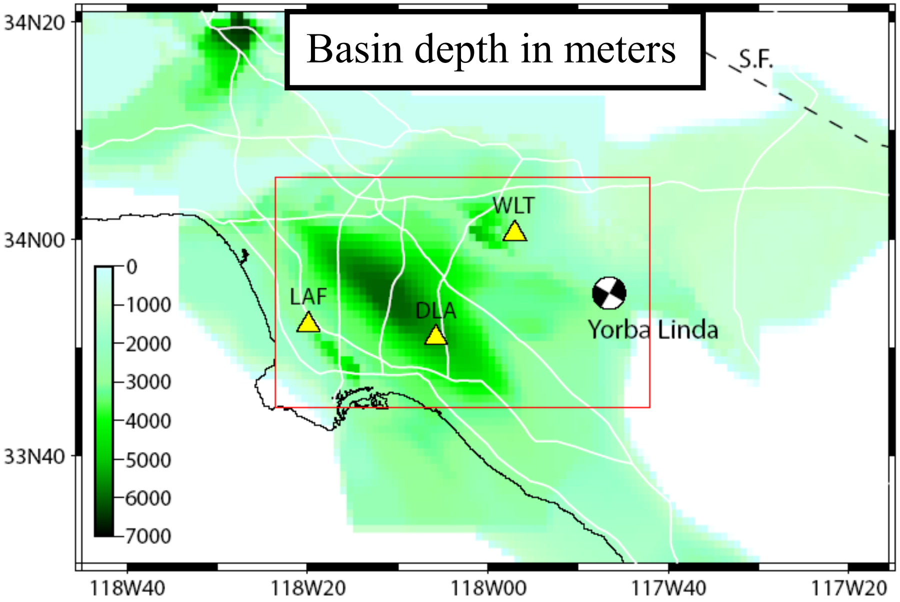
Fréchet Kernel

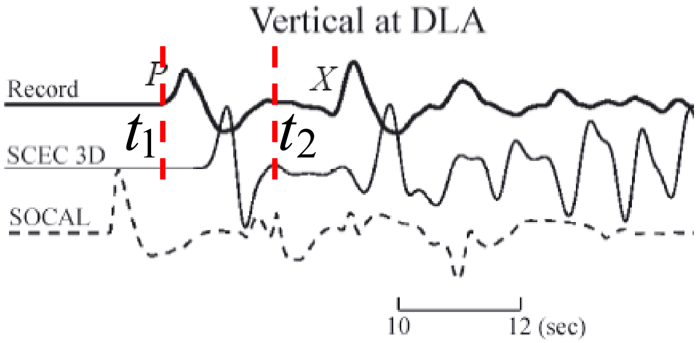
Reference Model

Model Perturbation

Given a dataset $\delta\mathbf{d}$, we compute the structural sensitivity (Fréchet kernel) *K* of each datum on a spatial grid in order to invert for the structural perturbation $\delta\mathbf{m}$.

Yorba Linda to DLA

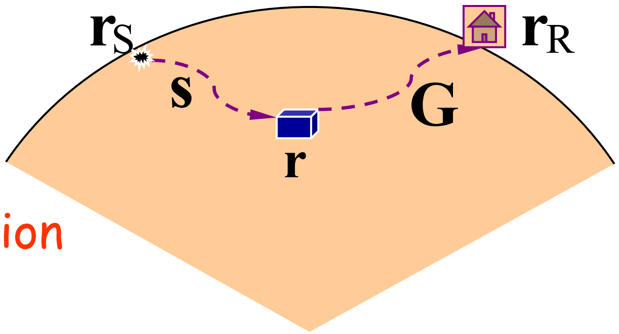




$$\delta T_\alpha = \int_\oplus K_\alpha^T(\mathbf{r})\,\delta\alpha(\mathbf{r})\,d\mathbf{r},$$

$$K_\alpha^T(\mathbf{r}) = -\frac{1}{P}\int_{t_1}^{t_2} 2\rho\alpha\dot{\mathbf{s}}(t)\cdot\int_0^t [(\nabla\cdot\mathbf{G}^{\mathrm{T}})(\nabla\cdot\mathbf{s})]\,d\tau\,dt,$$

Three wave fields & a 3D integral



$\dot{\mathbf{s}}(t):\ \ \mathbf{s}(\mathbf{r}_\mathrm{R},t;\mathbf{r}_\mathrm{S})$

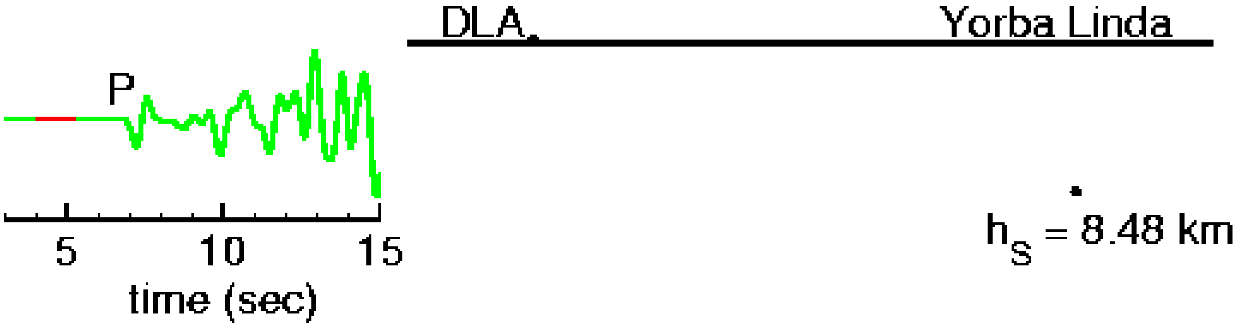
$\mathbf{s}:\ \ \mathbf{s}(\mathbf{r},\tau;\mathbf{r}_\mathrm{S})$

1 numerical simulation

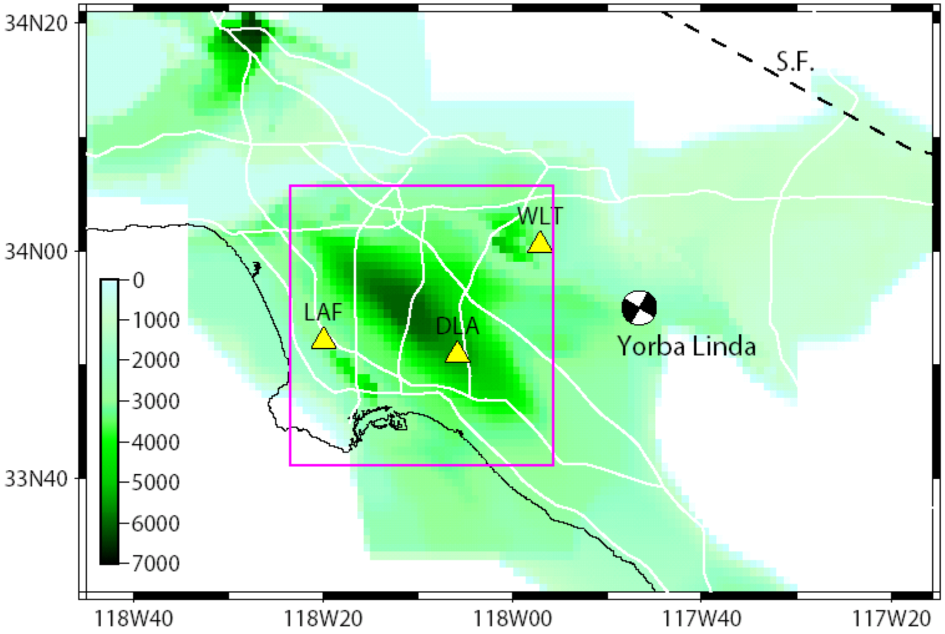
$\mathbf{G}:\ \ \mathbf{G}(\mathbf{r}_\mathrm{R},t;\mathbf{r},\tau)$ 3 numerical simulations

- ~2.5 M spatial grid points, 4000 time steps.
- For each source-station pair: three wavefields ~20GB; kernels ~2GB (3x3x10x20MB).
- 10 hours (wall-clock time) on 8-processor (750MHz) shared memory machine.

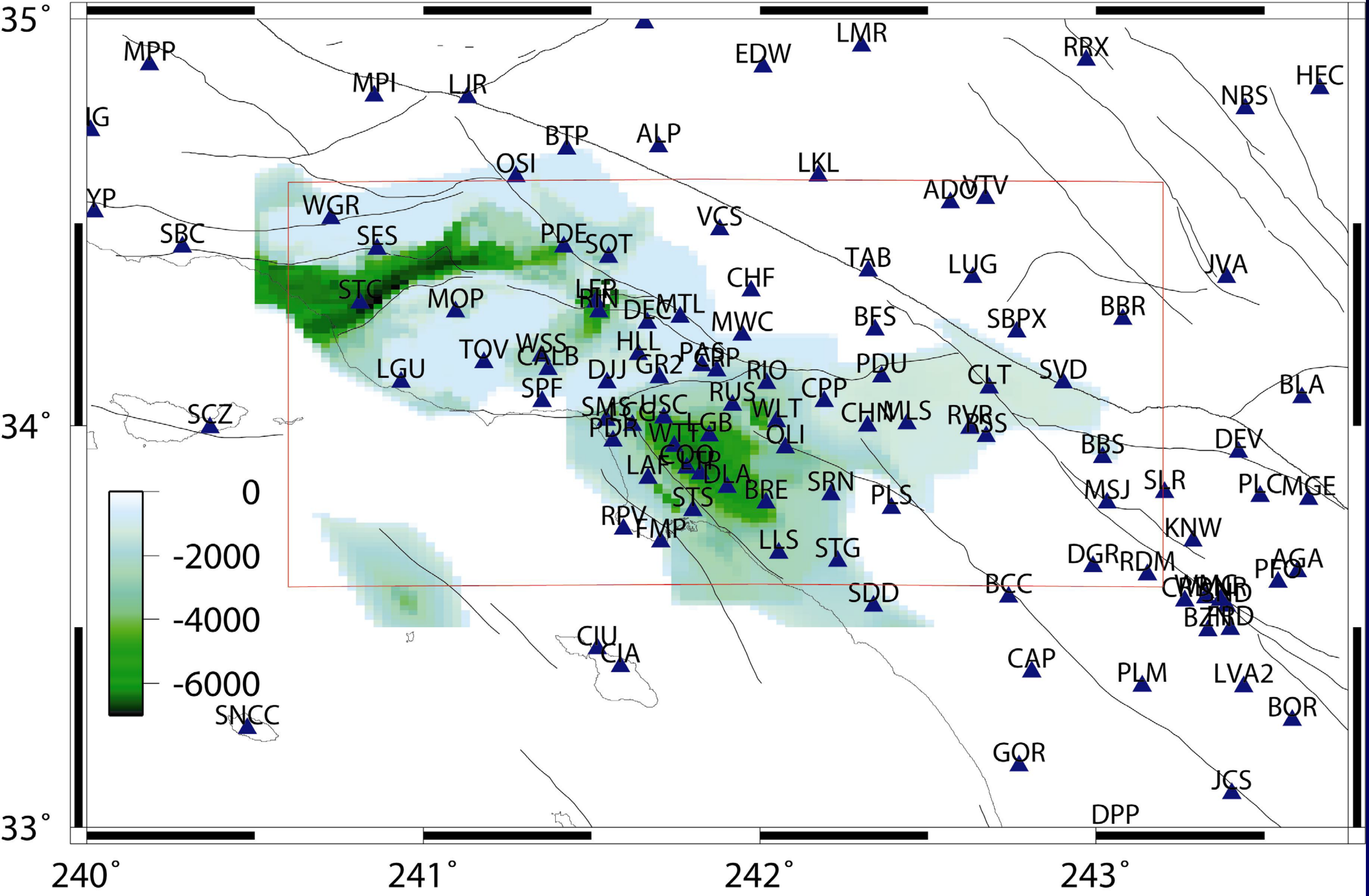
Yorba Linda to DLA delay time sensitivity to *P*-wave speed



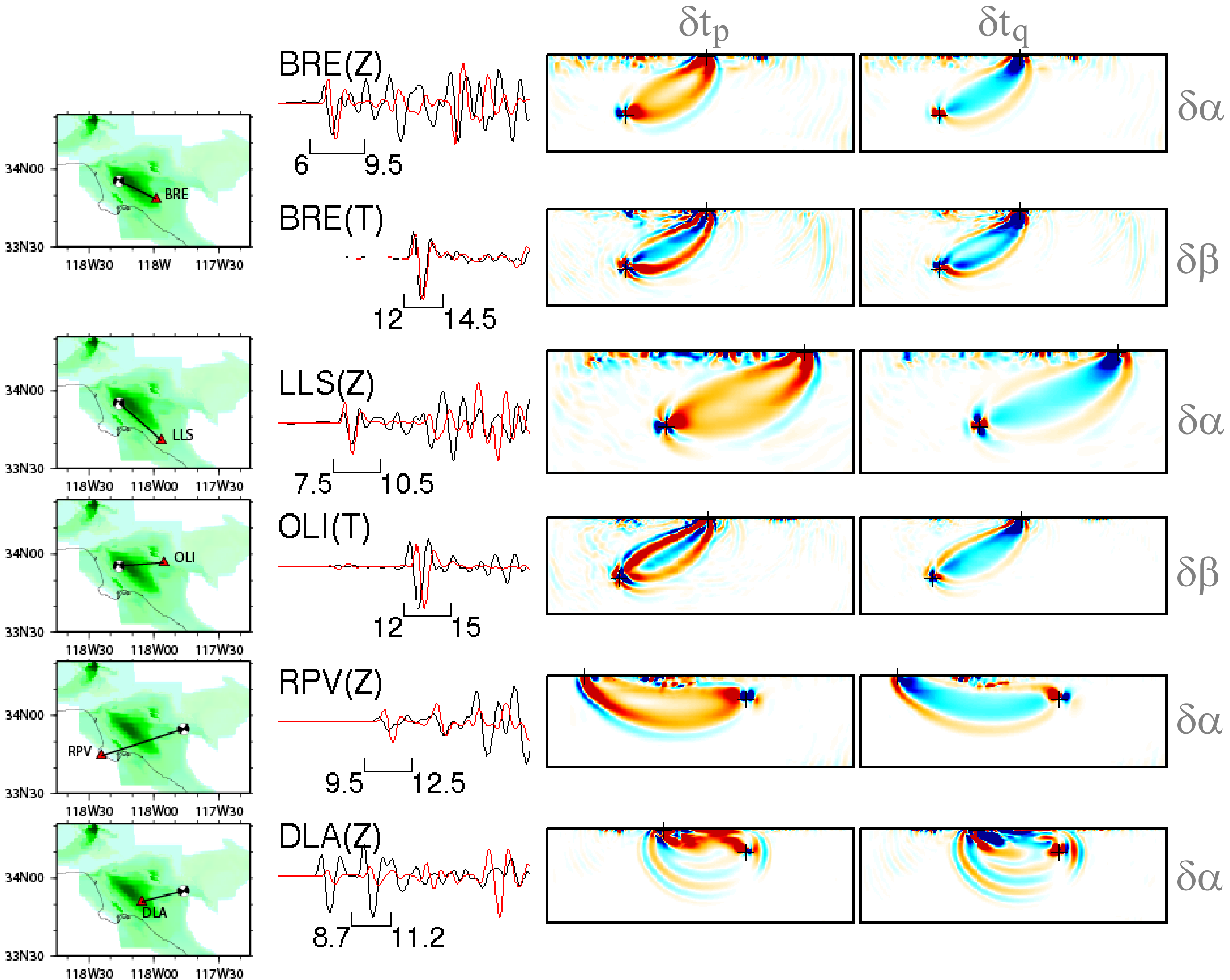
W–E component, SCEC CVM v3.0



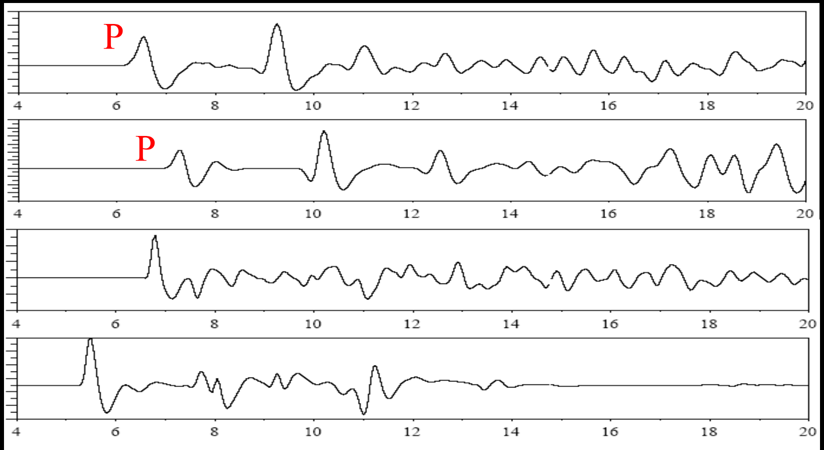
Stations in our RGT database



3-D Fréchet Kernels in 3-D Basin Model



3D visualization of Yorba Linda to DLA *P*-wave kernel

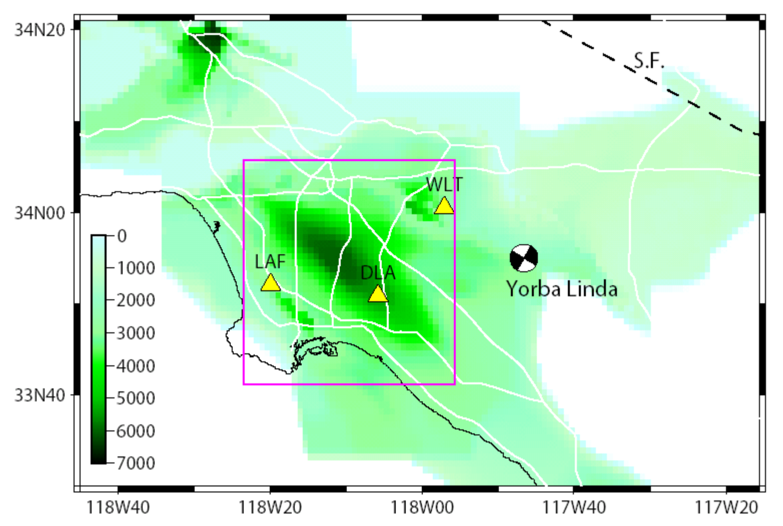


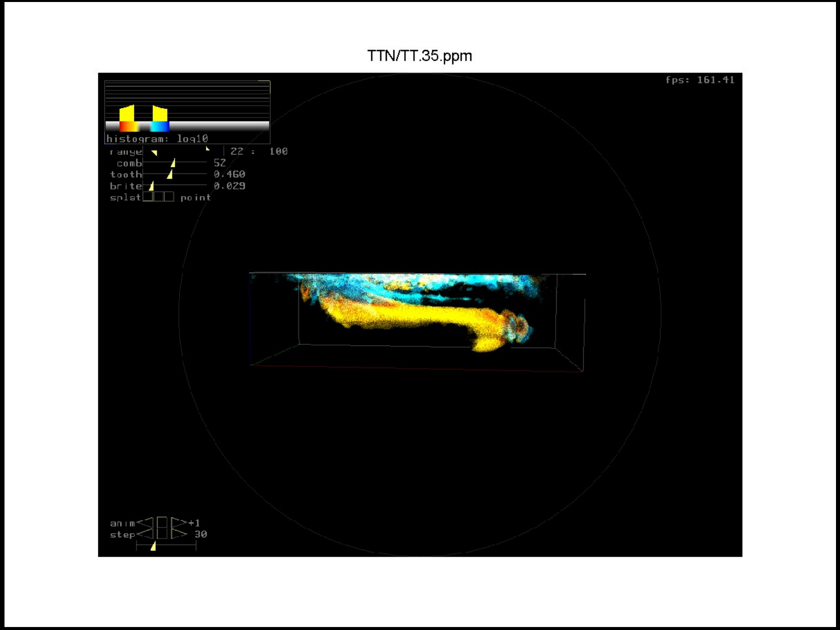
RECORD

SCEC 3D

SCEC 1D

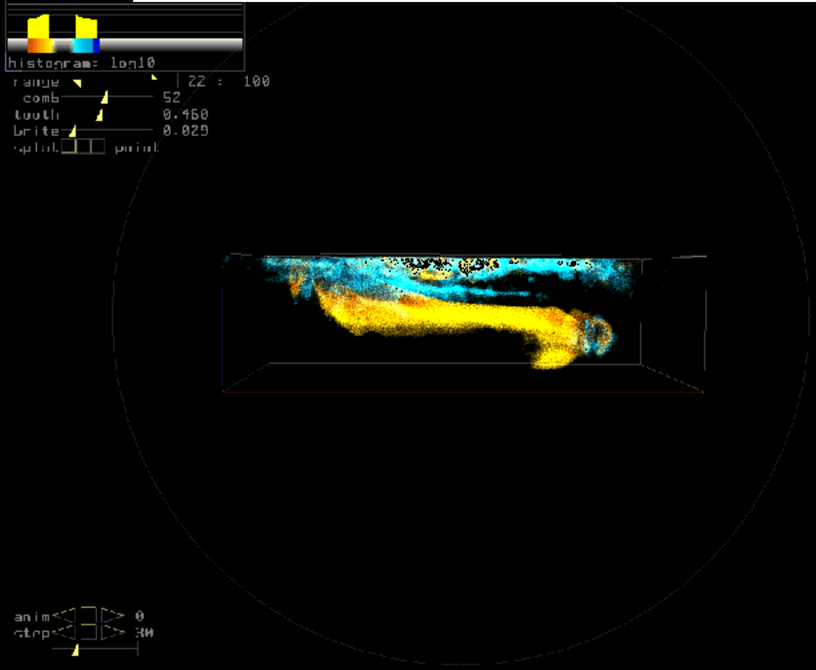
SOCAL





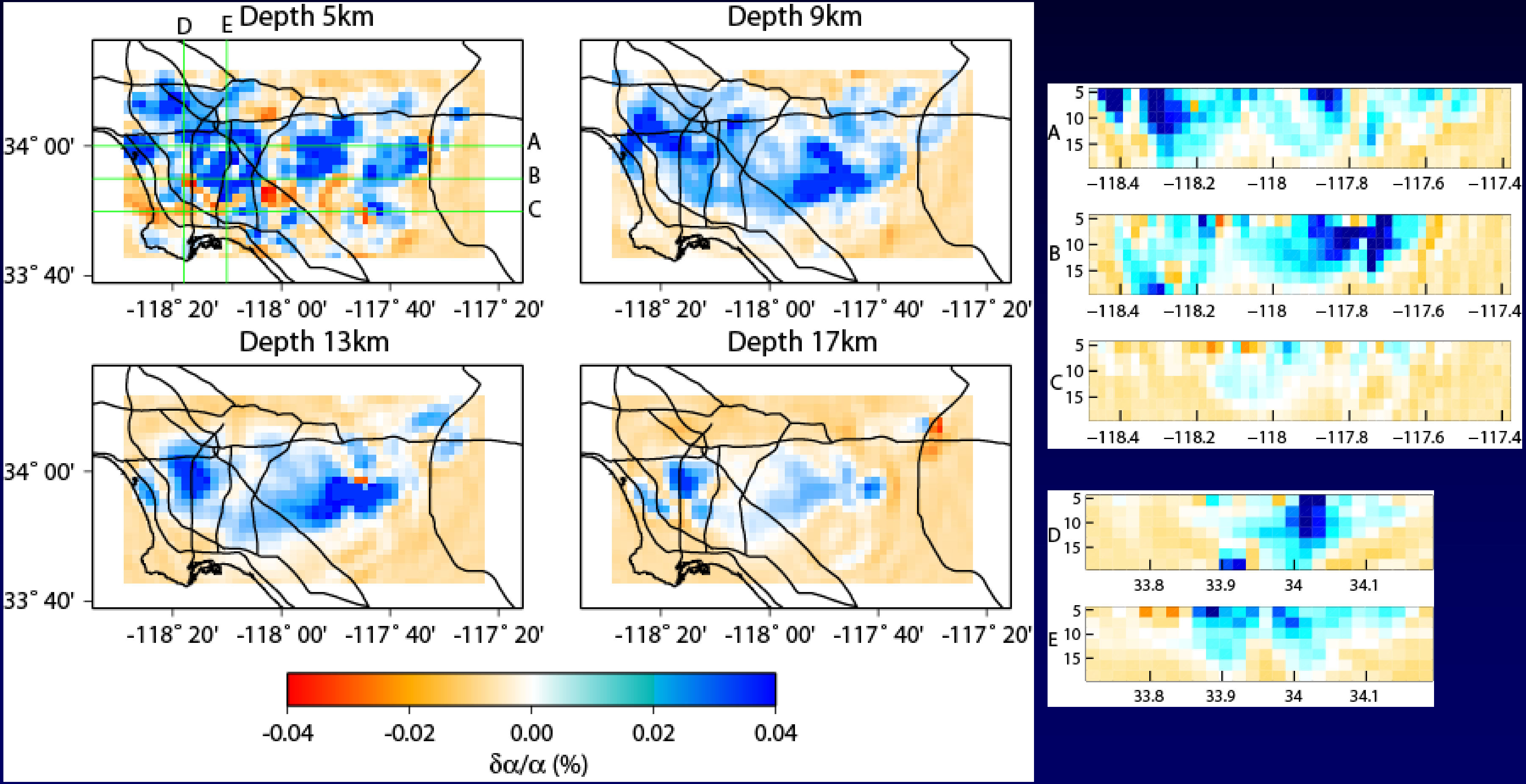
TTN/TT.35.ppm

```
fps: 161.41
histogram: log10
range          22 : 100
comb           52
tooth          0.460
brite          0.029
splat          point
anim           +1
step           30
```



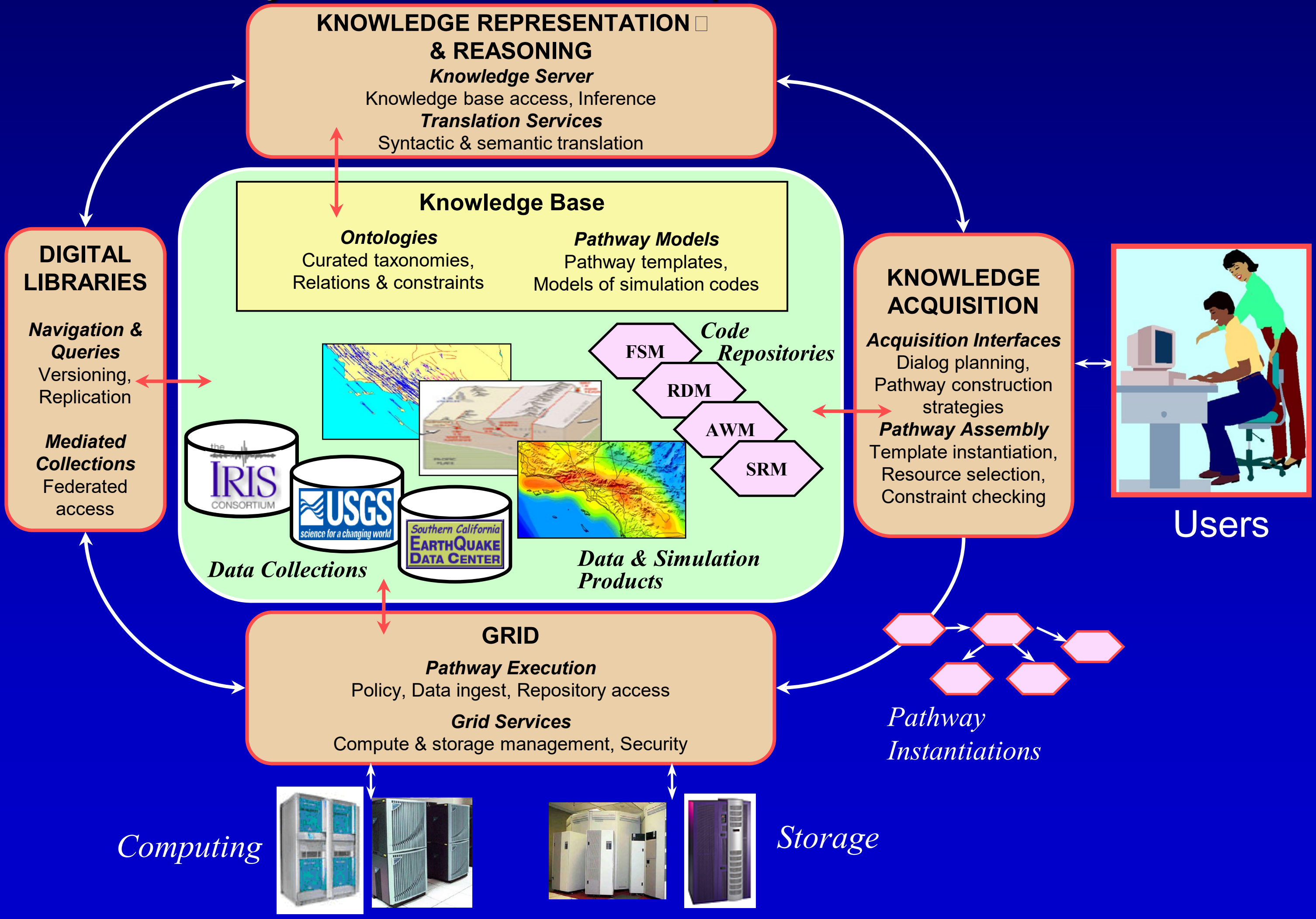
```
histogram: log10
range          22 : 100
comb           52
tooth          0.460
brite          0.029
splat          point
anim           0
step           30
```

Full 3-D Tomography Model (Preliminary)



SCEC Collaboratory

for system-level earthquake science



KNOWLEDGE REPRESENTATION & REASONING
Knowledge Server
Knowledge base access, Inference
Translation Services
Syntactic & semantic translation

Knowledge Base
Ontologies
Curated taxonomies, Relations & constraints
Pathway Models
Pathway templates, Models of simulation codes

Code Repositories

Data Collections

Data & Simulation Products

DIGITAL LIBRARIES
Navigation & Queries
Versioning, Replication
Mediated Collections
Federated access

KNOWLEDGE ACQUISITION
Acquisition Interfaces
Dialog planning, Pathway construction strategies
Pathway Assembly
Template instantiation, Resource selection, Constraint checking

Users

GRID
Pathway Execution
Policy, Data ingest, Repository access
Grid Services
Compute & storage management, Security

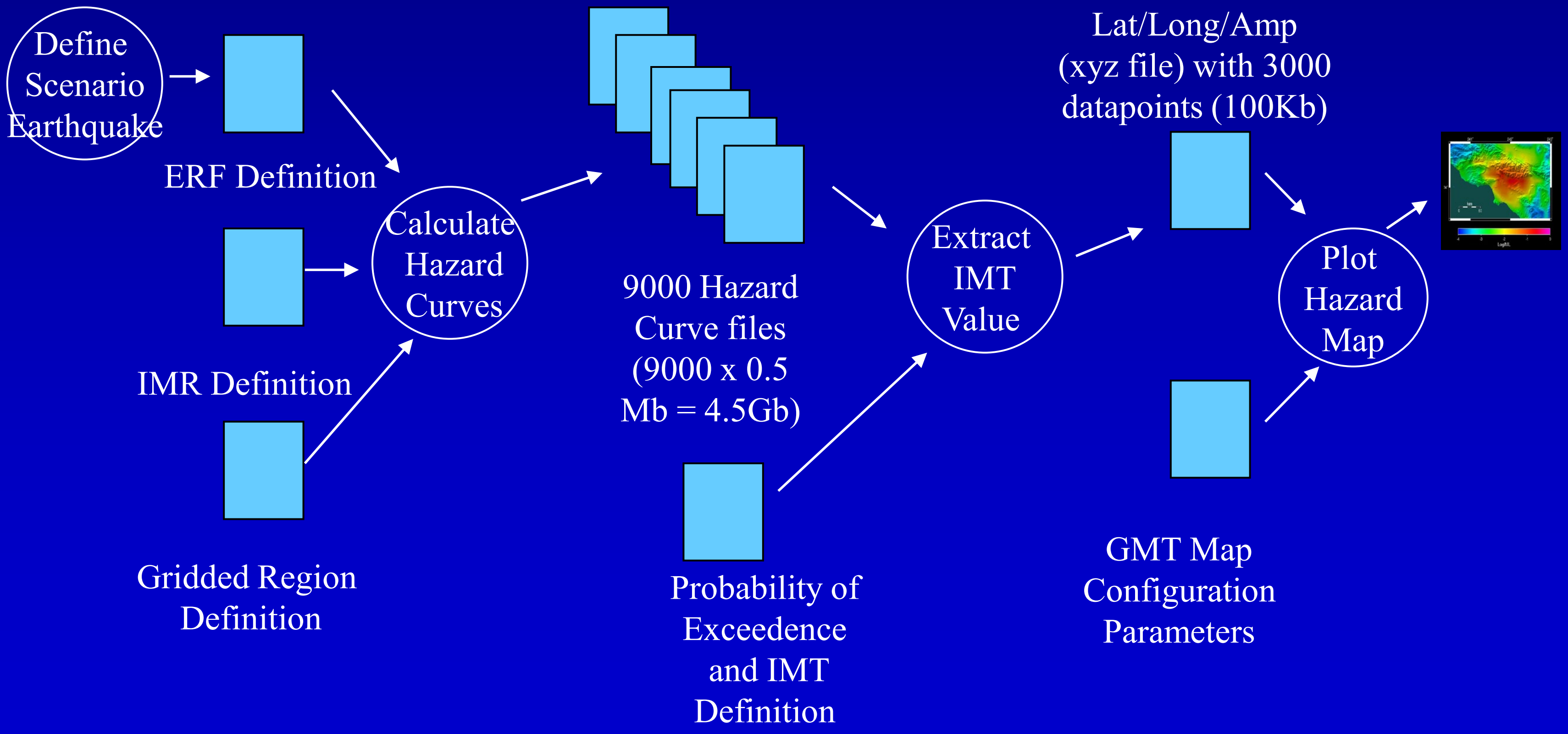
Pathway Instantiations

Computing

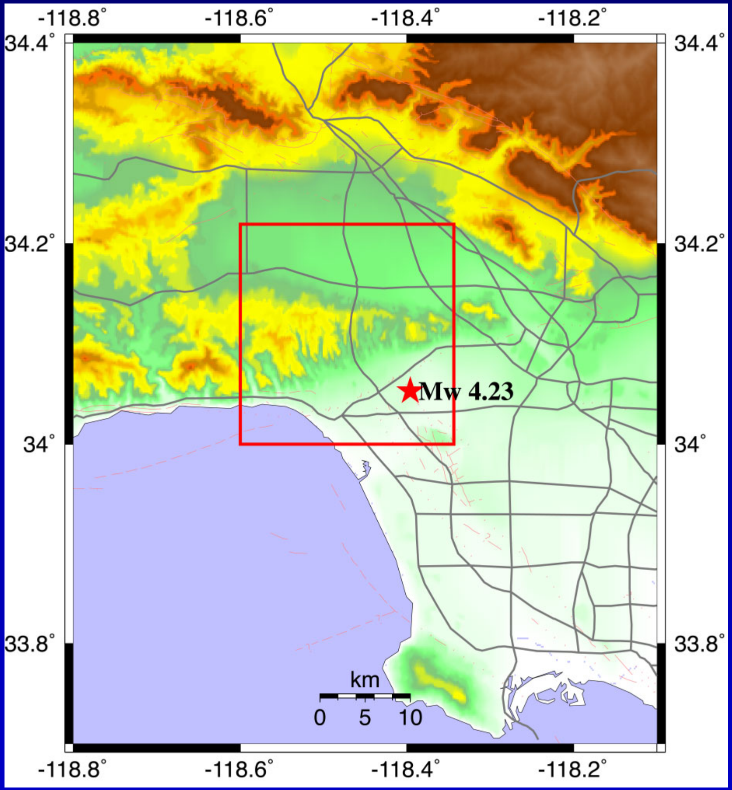
Storage

SCEC/CME Computational Pathway Construction

A SCEC/CME capability is to construct and run a series of SHA computations known as a computational pathway.



Wave Propagation Simulation showing Earthquake Waves Propagating Through a Geological Volume



Hollywood EQ - Mw 4.23, 6.98 depth
24x24x12 km region (160x160x80 nodes)
(Δx=150 m)

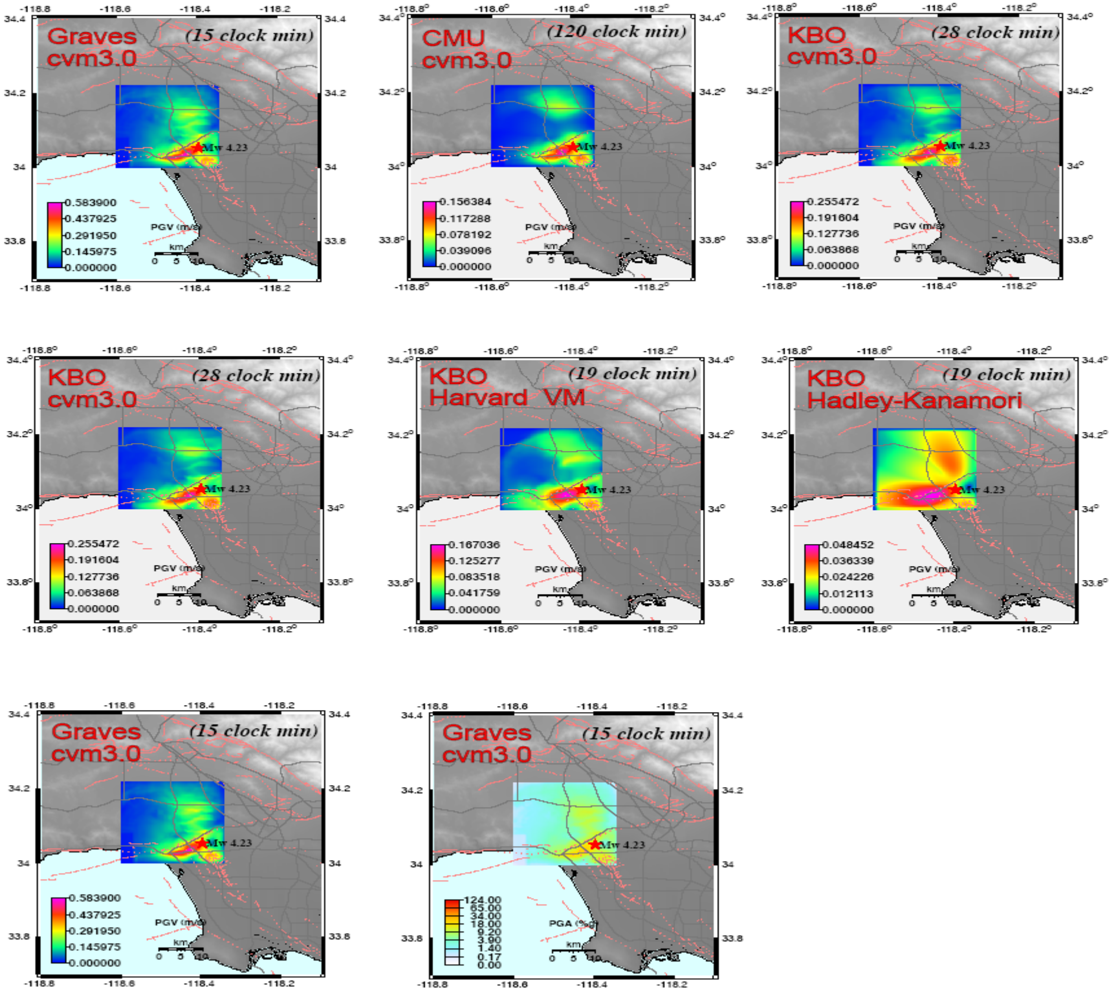
SCEC Collaboratory

for system-level earthquake science

Different AWM modeling codes

Different velocity models

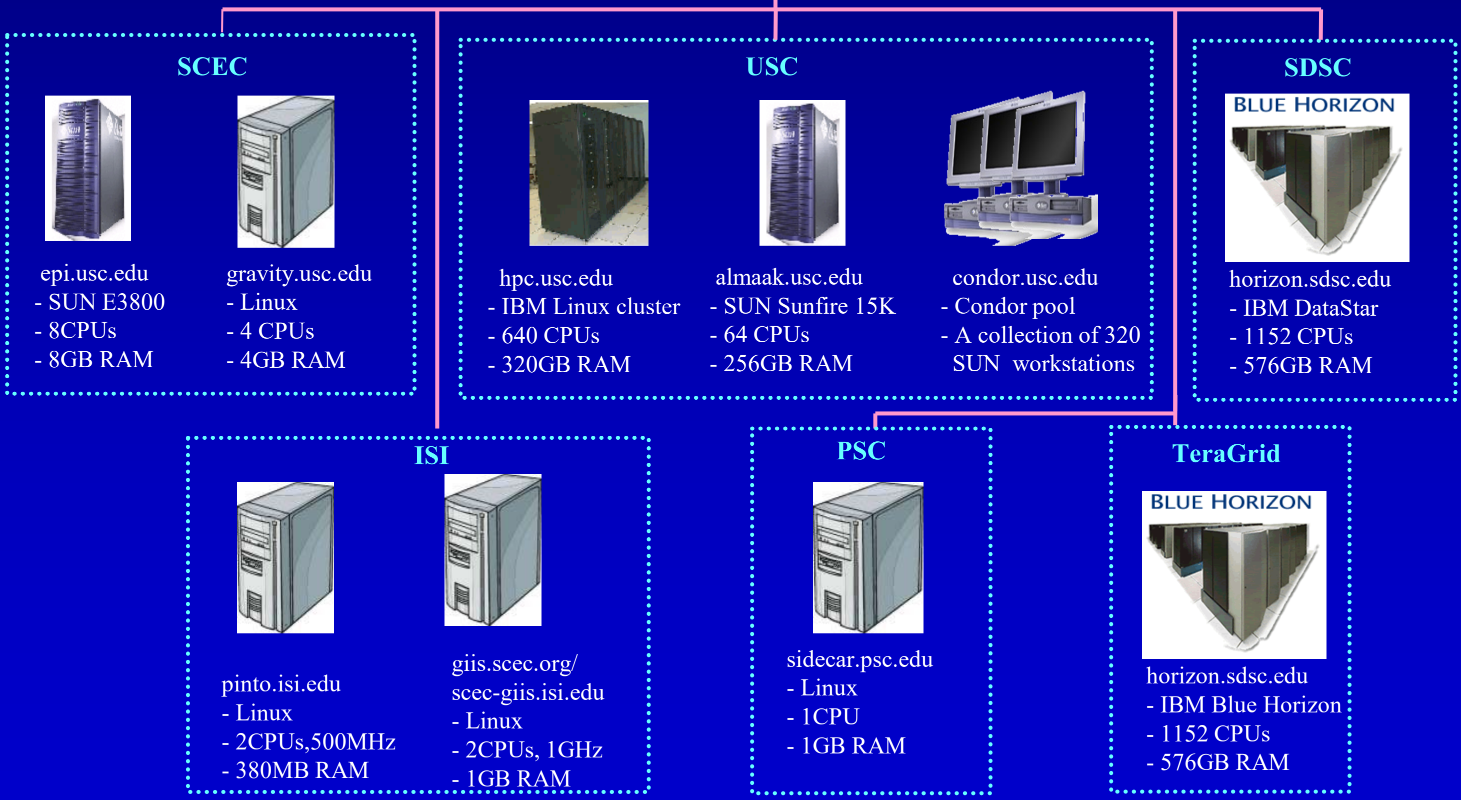
Different output products



Establishment of SCEC Grid Infrastructure

SCEC/CME has established grid-based connectivity, job-scheduling, and user and host authentication between SCEC, USC, ISI, SDSC, PSC, and TeraGrid sites.

SCEC Grid Testbed



SCEC

epi.usc.edu
- SUN E3800
- 8CPUs
- 8GB RAM

gravity.usc.edu
- Linux
- 4 CPUs
- 4GB RAM

USC

hpc.usc.edu
- IBM Linux cluster
- 640 CPUs
- 320GB RAM

almaak.usc.edu
- SUN Sunfire 15K
- 64 CPUs
- 256GB RAM

condor.usc.edu
- Condor pool
- A collection of 320 SUN workstations

SDSC

horizon.sdsc.edu
- IBM DataStar
- 1152 CPUs
- 576GB RAM

ISI

pinto.isi.edu
- Linux
- 2CPUs,500MHz
- 380MB RAM

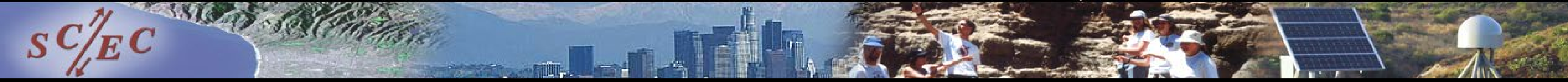
giis.scec.org/
scec-giis.isi.edu
- Linux
- 2CPUs, 1GHz
- 1GB RAM

PSC

sidecar.psc.edu
- Linux
- 1CPU
- 1GB RAM

TeraGrid

horizon.sdsc.edu
- IBM Blue Horizon
- 1152 CPUs
- 576GB RAM



Simulation and Data Access-based Metadata

Computation:

computation_platform=hpc.usc.edu computation_clocktime=24
computation_userprocs=48 computation_procs_plusminus=10
computation_platform_workdir=/tmphpc-00/maechlin/p2

Post-Processing:

postprocess_activity=pgv_map postprocess_results_files_exist=no
postprocess_results_host=gravity.usc.edu
postprocess_results_directory=/home/cmeutils/p2utils/postProcessing
postprocess_results_fileX=SSX3D postprocess_results_fileY=SSY3D
postprocess_results_fileZ=SSZ3D

Simulation:

simulation_codename=pmvl3d
simulation_tmax=20. simulation_out_timeskip=0.010
simulation_user_grid_dx=200. simulation_user_dt=0.010
simulation_minVs=500. simulation_poisson=0.27

Metadata System for Pathway 2

```
Sat Jan 24 06:38:21 PST 2004
#set_RegionInterest ...
region_velocitymodel=cvm3.0
region_depth_shallow=0.0
region_depth_deep=29800.0
region_origin_definition=lat_long
region_origin_latitude=33.58000
region_origin_longitude=-118.70000
region_origin_UTMeasting=342231.2
region_origin_UTMnorthing=3716883.6
region_surface_definition=bykm
rotation_angle=0.0
# opposite corner is usually the NorthEast corner
region_oppcorner_latitude=34.49012
region_oppcorner_longitude=-117.63136
region_oppcorner_UTMeasting=442031.2
region_oppcorner_UTMnorthing=3816683.6
region_lengtheast_km=99.800
region_lengthnorth_km=99.800
region_lengtheast_m=99800.0
region_lengthnorth_m=99800.0
```

```
Sat Jan 24 06:38:21 PST 2004
#code_resources ...
simulation_codeauthor=Kim_Olsen
simulation_codename=pmvl3d
simulation_codetype=FDuniform
simulation_language=fortran
simulation_memarch=MPI
simulation_indexorder=xyz
simulation_indexsign_x=1
simulation_indexsign_y=1
simulation_indexsign_z=1
```

```
Sat Jan 24 06:38:21 PST 2004
#simulation_info ...
simulation_minVs=500.0
simulation_poisson=0.27
simulation_stability_factor=0.480
simulation_tmax=80.000
simulation_dt=0.0100
simulation_timesamples=8001
simulation_user_dt=0.0100
```

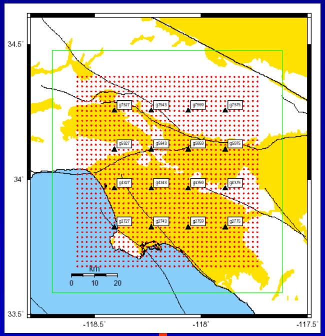
```
Sat Jan 24 06:38:21 PST 2004
#simulation_node_out ...
simulation_out_nodeXfirst=51
simulation_out_nodeXlast=451
simulation_out_nodeXskip=10
simulation_out_nodeYfirst=51
simulation_out_nodeYlast=451
simulation_out_nodeYskip=10
simulation_out_nodeZfirst=1
simulation_out_nodeZlast=1
simulation_out_nodeZskip=1
```

```
Sat Jan 24 06:38:21 PST 2004
#postproc_load ...
postprocess_activity=pgv_map
postprocess_results_host=gravity.usc.edu
postprocess_results_directory=/ng
postprocess_results_fileX=SSX3D222v
postprocess_results_fileY=SSY3D222v
postprocess_results_fileZ=SSZ3D222v
postprocess_results_files_exist=yes
```

Providing Data Management Capabilities

- Storage Resource Broker based Digital Library Collection now includes SCEC/PEER Scenario Ground Motion data collection, USC Green Tensors data collection (40TB+ Storage), TeraShake Simulations (40 TB+), and Puente Hills Simulation.

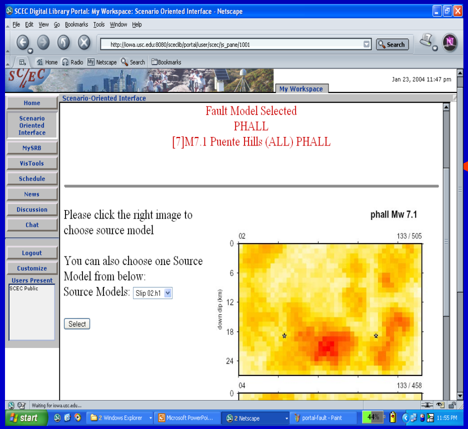
Select Receiver (Lat/Lon)



Select Scenario

Fault Model

Source Model



http://iowa.usc.edu:8080/sceclib/portal/user/scec/js_pane/1001

Jan 23, 2004 11:47 pm

Scenario-Oriented Interface

Fault Model Selected
PHALL
[7]M7.1 Puente Hills (ALL) PHALL

Please click the right image to choose source model

You can also choose one Source Model from below:
Source Models: Slip 02.h1

SCEC Public

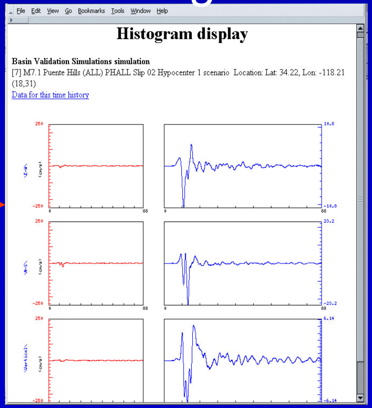
Waiting for iowa.usc.edu...

SCEC Community Library

Output

Time History

Seismograms



Histogram display

Basin Validation Simulations simulation

[7] M7.1 Puente Hills (ALL) PHALL Slip 02 Hypocenter 1 scenario Location: Lat: 34.22, Lon: -118.21 (18,31)

Data for this time history

More Information

Animations

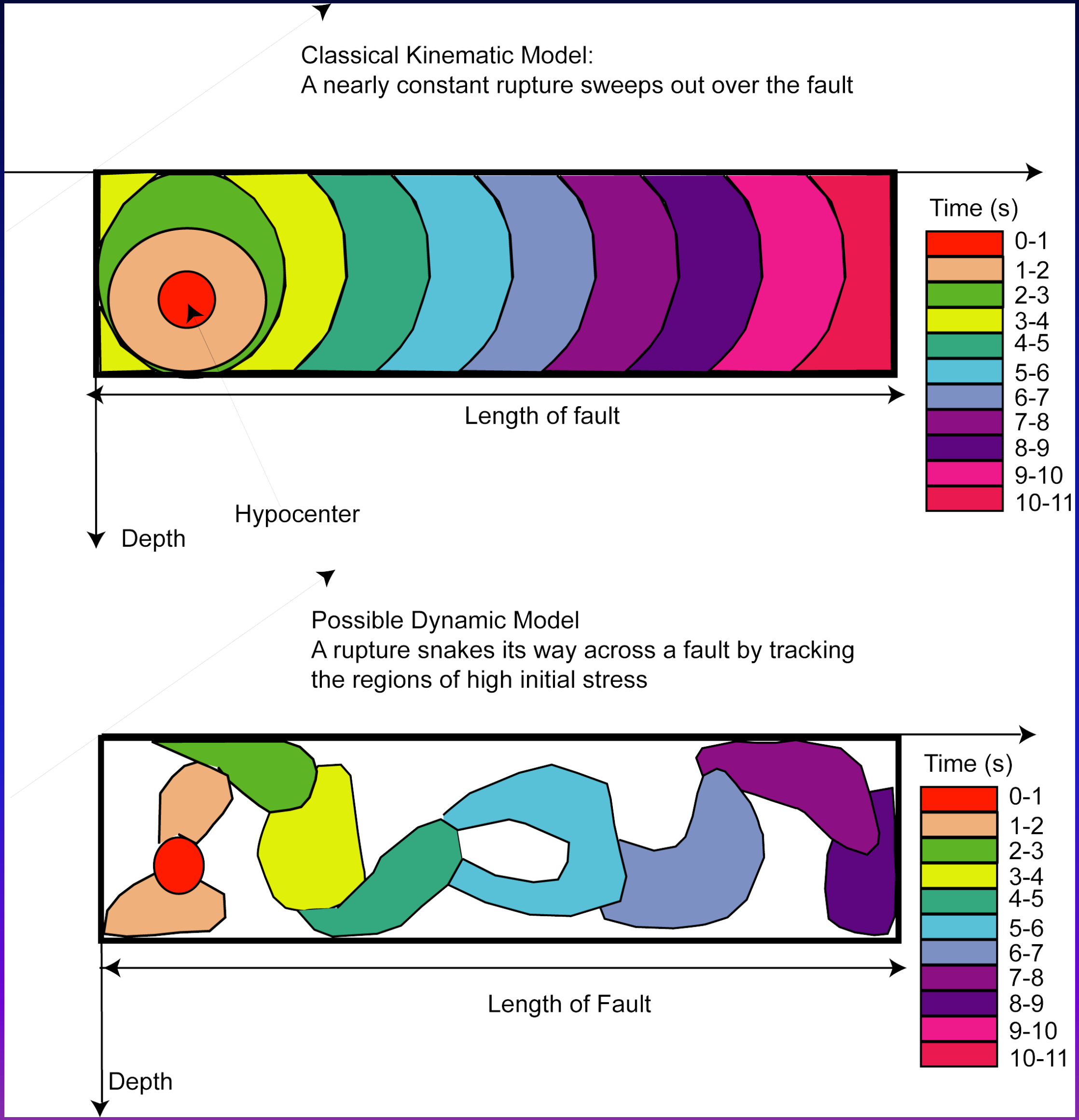
Access to Data

www.scec.org/cme

Please See Our Poster at this Meeting:

Synthetic Seismograms Access from the SCEC/CME

Cartoons that illustrate kinematic and dynamic ruptures



Classical Kinematic Model:
A nearly constant rupture sweeps out over the fault

Possible Dynamic Model
A rupture snakes its way across a fault by tracking the regions of high initial stress

Validation Exercises for Rupture Dynamic Codes

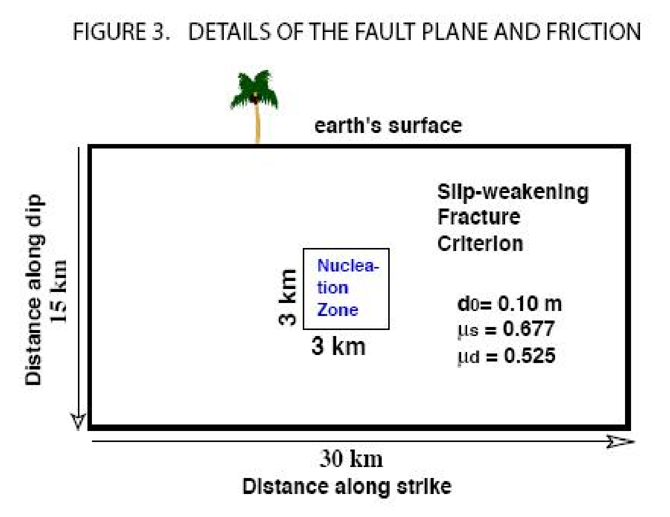
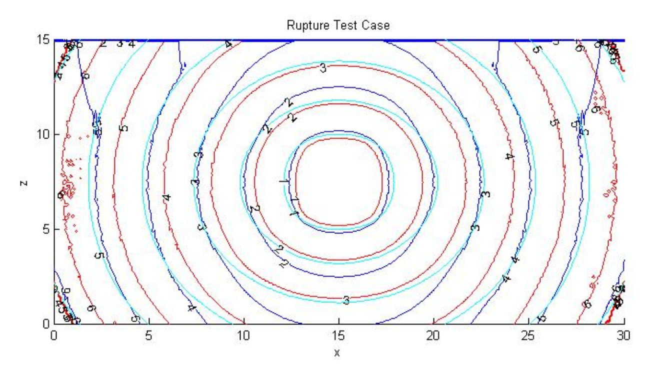


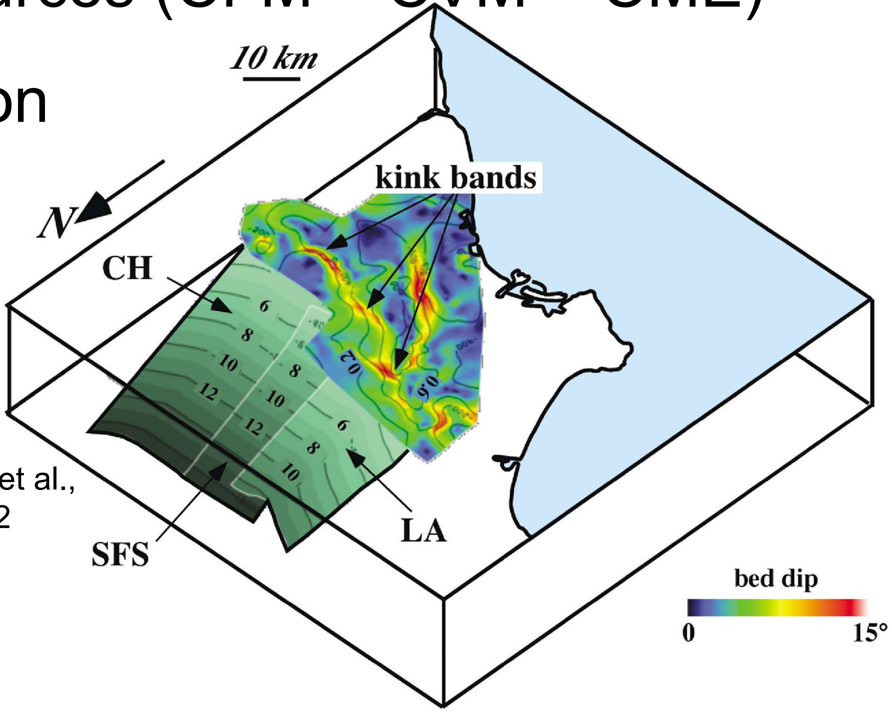
FIGURE 3. DETAILS OF THE FAULT PLANE AND FRICTION



Comparison of Dynamic Rupture Models
Rupture Test Case Contours

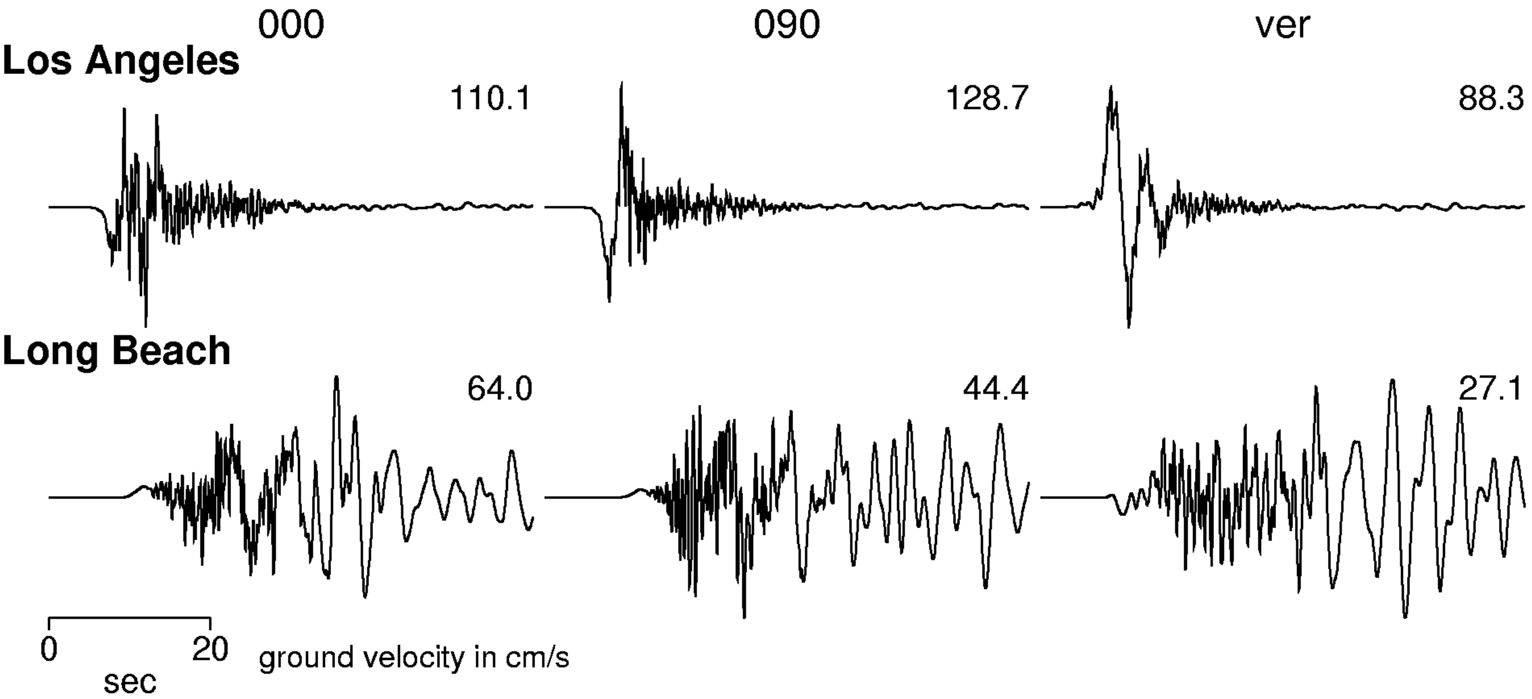
BROADBAND GROUND MOTION SIMULATION FOR THE PUENTE HILLS FAULT

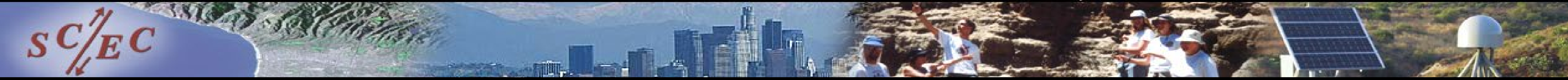
- Unprecedented in scope and scale (66,000 broadband time histories, 0 – 10 Hz)
- Utilizes many SCEC resources (CFM + CVM + CME)
- Ground motion visualization
- Ground motion maps



after Shaw et al., BSSA, 2002

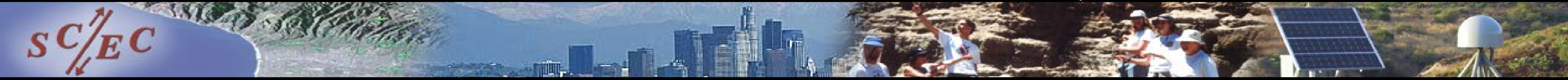
Puente Hills Mw 7.15: Broadband Ground Velocity





CyberShake Project

Using 3D Synthetic Seismic Waveforms In Seismic Hazard Analysis

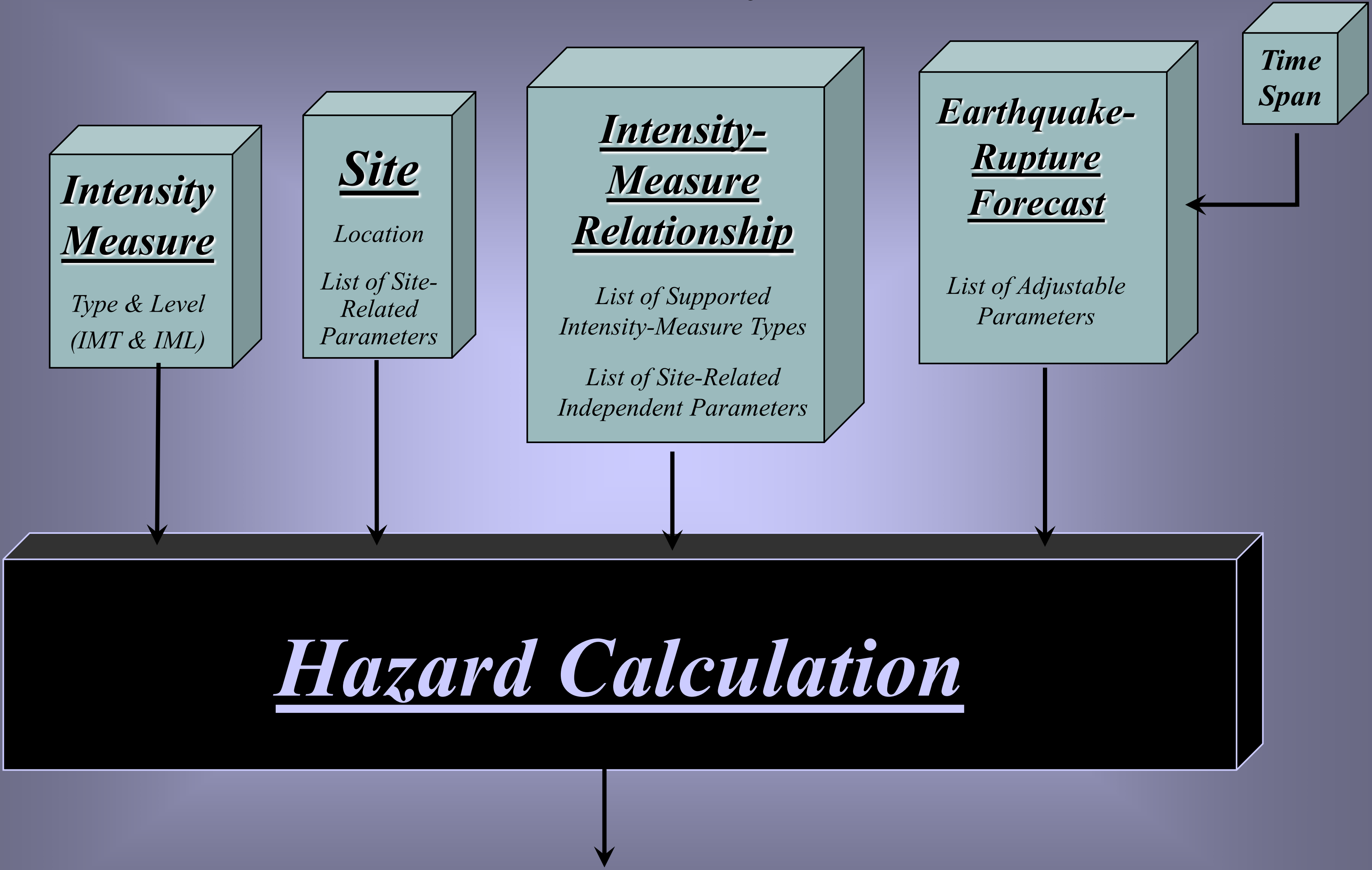


Goal of SHA:

The probability that some
“Intensity-Measure Type” (e.g. SpectralAcceleration)
will exceed a specified
“Intensity-Measure Level” (e.g. 0.5 g)

$$\left(Prob(IMT \geq IML) \right)$$

General Seismic Hazard Analysis Model:



Intensity Measure

Type & Level

(IMT & IML)

Site

Location

List of Site-Related Parameters

Intensity-Measure Relationship

List of Supported Intensity-Measure Types

List of Site-Related Independent Parameters

Earthquake-Rupture Forecast

List of Adjustable Parameters

Time Span

Hazard Calculation

Prob($IMT \geq IML$)

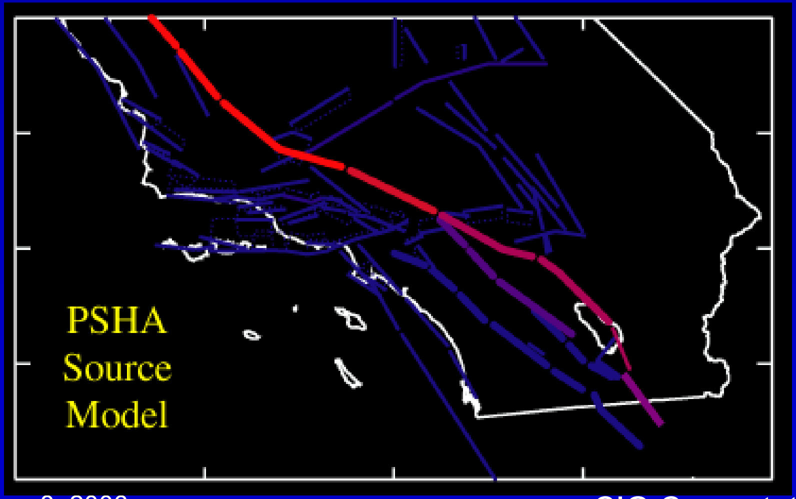
SHA has two model components:

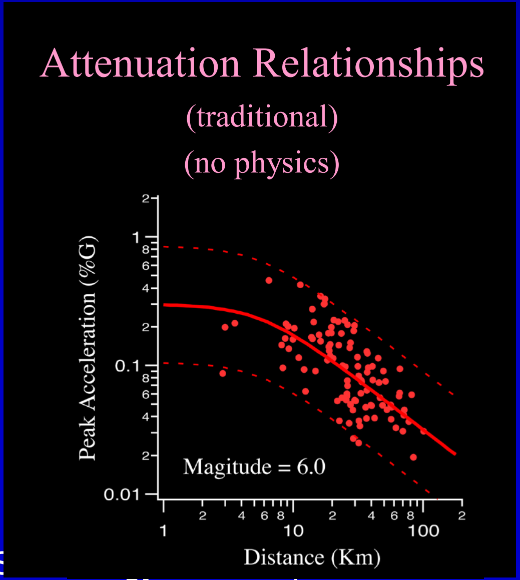
(1) Earthquake-Rupture Forecast (ERF)

Probability of all possible fault-rupture events (M≥~5) for region & time span

(2) Intensity-Measure Relationship (IMR)

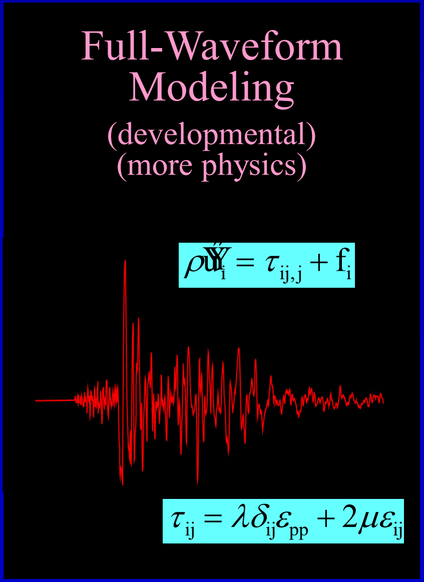
Gives Prob(IMT≥IML) for a given site and fault-rupture event




Attenuation Relationships

(traditional)

(no physics)


Full-Waveform Modeling

(developmental)

(more physics)

$$\rho \ddot{u}_i = \tau_{ij,j} + f_i$$

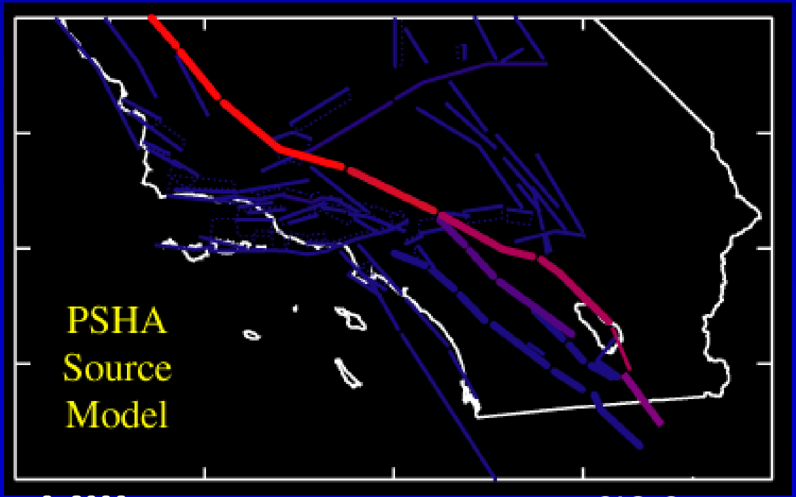
$$\tau_{ij} = \lambda \delta_{ij} \varepsilon_{pp} + 2\mu \varepsilon_{ij}$$

More physics & multiple models:

The model used in our National Hazard Maps assumes that each earthquake rupture is completely independent.

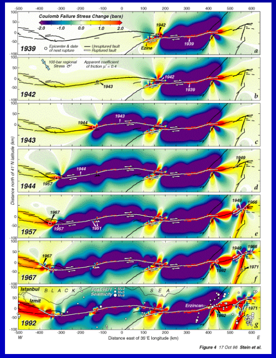
(1) Earthquake-Rupture Forecast (ERF)

Probability of all possible fault-rupture events (M≥~5) for region & time span



Others see time-dependent effects and interactions:

No consensus on how to build these types of models.



(Stein & Others)

Thus, the ***RELM*** working group is developing a variety.

IMR’s Can Use More Physics-based Approach

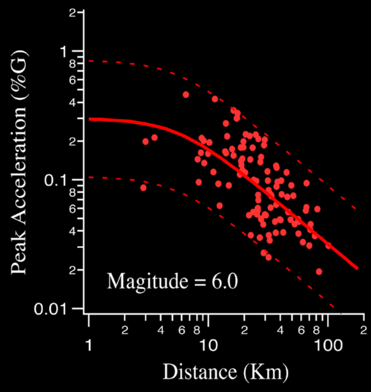
Intensity-Measure Relationship (IMR) Gives Prob(IMT≥IML) for a given site and fault-rupture event

Inherent limits with respect to accuracy (SCEC Phase III report).

Attenuation Relationships

(traditional)

(no physics)



Lack of physics can lead to non-physical results (e.g., a mean PGA of 14 g predicted for the Yucca Mt Repository).

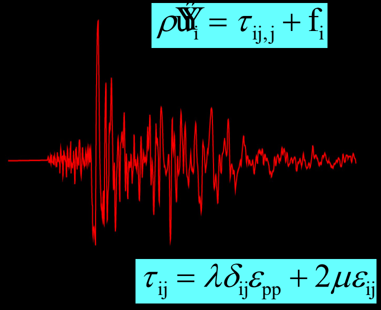
Potentially more accurate, but …

Computation limits with respect analyzing many scenarios, high frequencies, and uncertainties associated with the structural model and slip distribution.

Full-Waveform Modeling

(developmental)

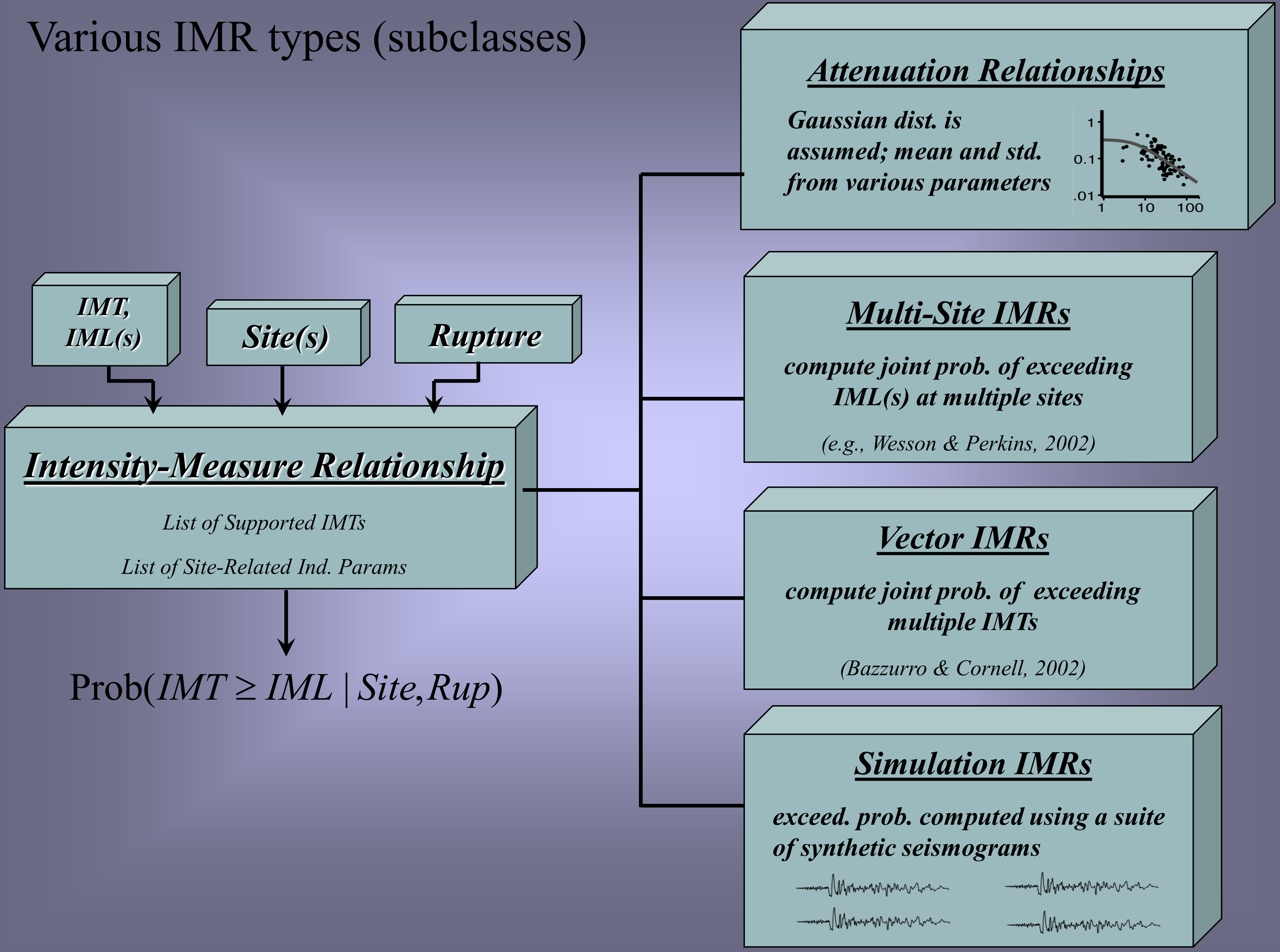
(more physics)



$\rho \ddot{u}_i = \tau_{ij,j} + f_i$

$\tau_{ij} = \lambda \delta_{ij} \varepsilon_{pp} + 2\mu \varepsilon_{ij}$

Various IMR types (subclasses)



IMT, IML(s)

Site(s)

Rupture

Intensity-Measure Relationship

List of Supported IMTs

List of Site-Related Ind. Params

$\mathrm{Prob}(IMT \geq IML \mid Site, Rup)$

Attenuation Relationships

Gaussian dist. is assumed; mean and std. from various parameters

Multi-Site IMRs

compute joint prob. of exceeding IML(s) at multiple sites

(e.g., Wesson & Perkins, 2002)

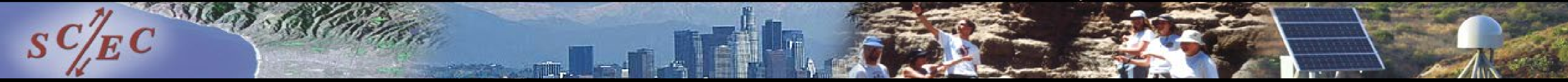
Vector IMRs

compute joint prob. of exceeding multiple IMTs

(Bazzurro & Cornell, 2002)

Simulation IMRs

exceed. prob. computed using a suite of synthetic seismograms



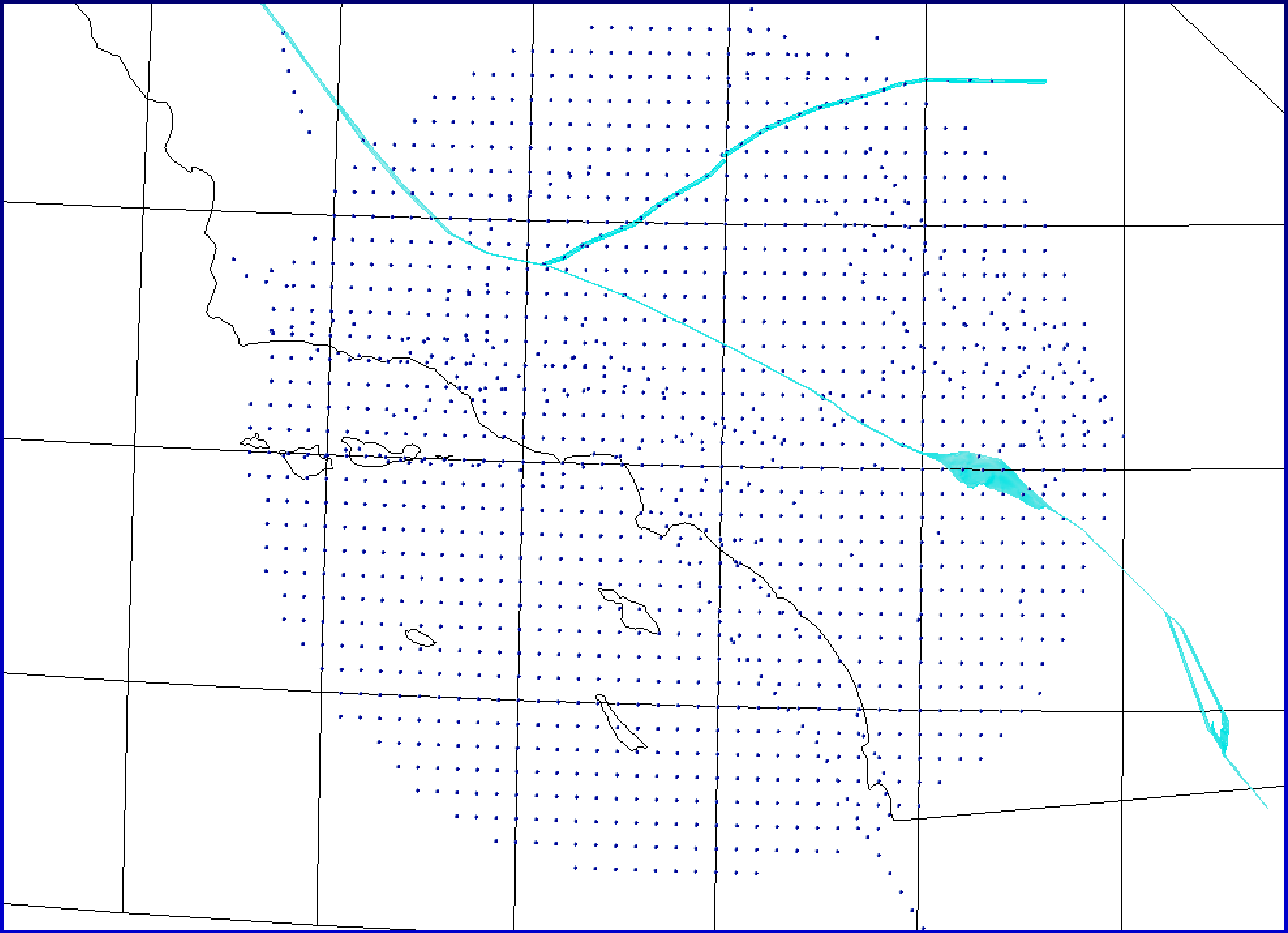
CyberShake Project Elements

- Use 3D waveform-based Intensity Measure Relationship (IMR) to calculate Hazard curves for sites in Los Angeles area.
- Generate 3D synthetics for required number of ruptures (40,000+ ruptures in ERF)
  - Low frequency (0.5 Hz) Intensity
- Use Reciprocity-base waveform approach
  - Allows many ruptures for a single site.
- Requires conversion from “static” Ruptures in ERF to “dynamic” ruptures used by AWM codes.

CyberShake Computational Elements

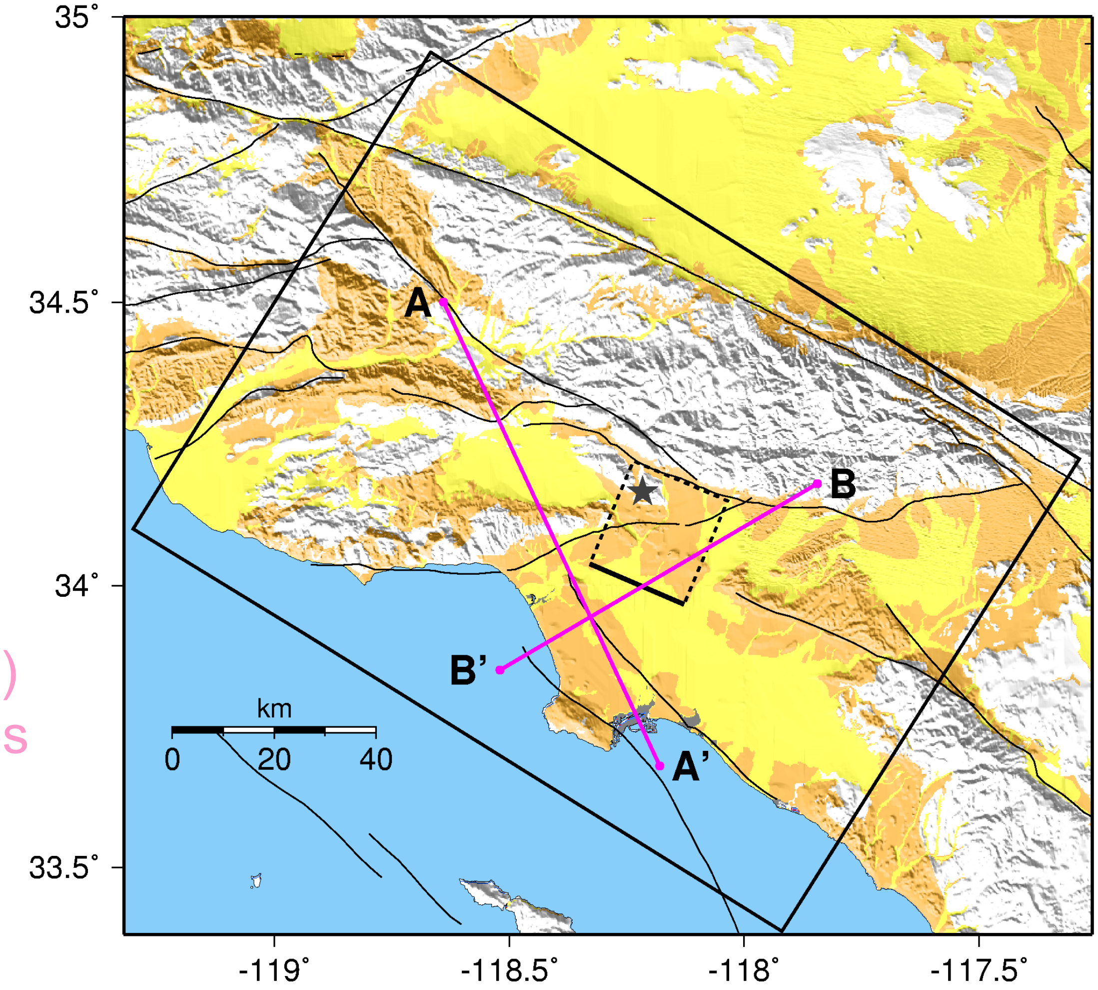
- Large (TeraShake Scale) forward calculations for each site.
- Requires calculation of 100,000+ seismogram for each site.
- SCEC/CME Grid-based scientific workflow system required to work at this scale.
  - Access to distributed computing resources
  - Large scale file management
  - High performance and high throughput computing.
- TeraGrid allocation awarded for effort
  - 145K SU (TG-BCS050001N)

Ruptures in ERF within 200KM of USC



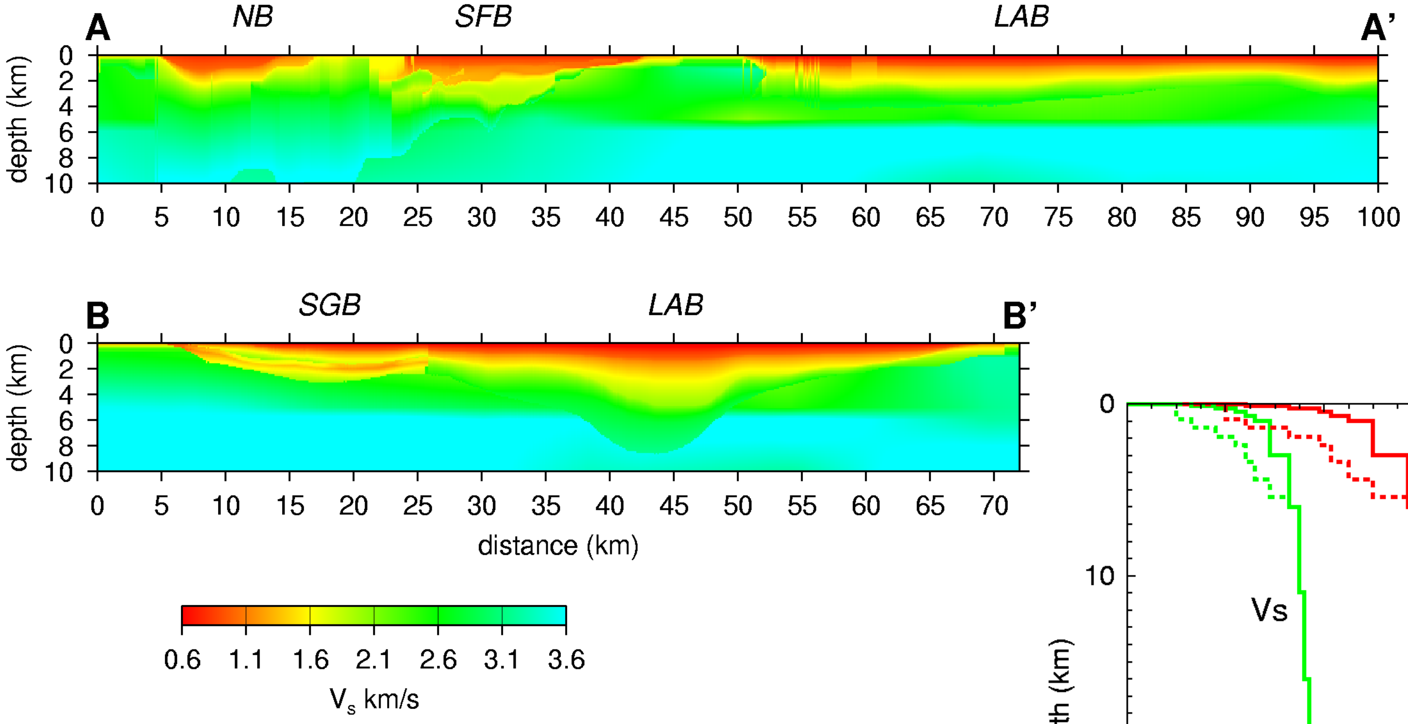
Model Region

- 150 km X 110 km X 45 km
- 380 X 10^6 node FD grid (h=125 m)
- Broadband (0-10 Hz) output at 66,000 sites

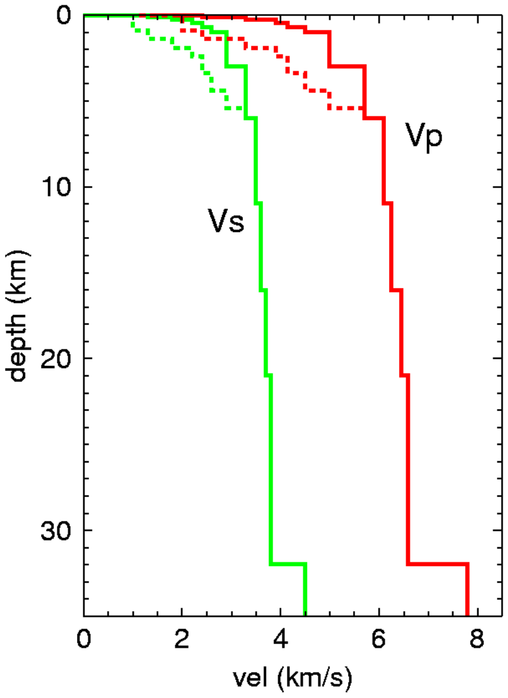


Complex 3D Basin Geology (deterministic)

SCEC V2.2b



Hybrid 1D Rock and 1D Basin Profiles (stochastic)



Deterministic Methodology (f < 1 Hz)

- **Kinematic representation of heterogeneous rupture on a finite fault**
    - slip amplitude
    - slip direction (rake)
    - rupture velocity from scaling relation
    - generic slip function and rise time

- **Visco-elastic wave propagation using full waveform Green's functions calculated for 3D velocity structure**

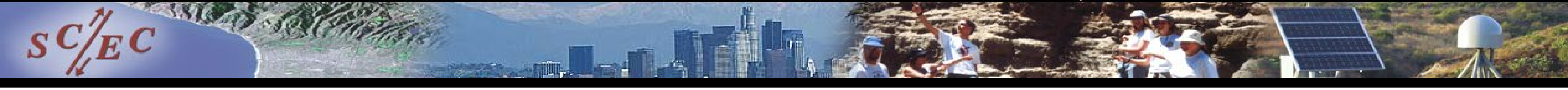
- **Site response based on V_s^{30} using Borcherdt's (1994) short- and mid-period amplification factors**

Stochastic Methodology (f > 1 Hz)

- **Limited kinematic representation of heterogeneous rupture on a finite fault (extension of Boore, 1983)**
  - slip amplitude (stress parameter = 50)
  - rupture velocity from scaling relation
  - empirical rupture duration
  - conic-average radiation pattern
  - stochastic phase

- **Simplified Green's functions for 1D velocity structure**
  - separate GFs for direct and downgoing rays
  - amplitude decays as inverse of ray path
  - gross impedance effects based on quarter wavelength theory Boore and Joyner (1997)

- **Site response based on V_s^{30} using Borcherdt's (1994) short- and mid-period amplification factors**



Simulation Parameters

- **Low Frequency (f < 1 Hz)**
  - 3D FD model using 400 million grid nodes (h = 125 m)
  - 8 hours run-time on 120 CPUs of HPCC Linux Cluster at USC
  - 3 component time histories saved at 66,000 surface locations (2.2 Gb)

- **High Frequency (f > 1 Hz)**
  - 24 hours run-time using single Linux PC
  - 3 component time histories computed at 66,000 surface locations

- **Post-Processing**
  - 24 hours data transfer USC to Pasadena
  - 24 hours to process and sum HF and LF into Broadband response on single Linux PC
  - Broadband (0 – 10 Hz) 3 component time histories at 66,000 locations