Southern California Earthquake Center

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Annual Report for 2009

USGS Cooperative Agreement 07HQAG0008

I. Introduction

The Southern California Earthquake Center (SCEC) is a regionally focused organization with a tripartite mission to

- gather new information about earthquakes in Southern California,
- integrate this information into a comprehensive and predictive understanding of earthquake phenomena, and
- communicate this understanding to end-users and the general public in order to increase earthquake awareness and reduce earthquake risk.

SCEC was founded in 1991 as a Science and Technology Center (STC) of the National Science Foundation (NSF), receiving primary funding from NSF's Earth Science Division and the United States Geological Survey (USGS). SCEC graduated from the STC Program after a full 11-year run (SCEC1). It was reauthorized as a free-standing center on February 1, 2002 to January 31, 2007 (SCEC2) with base funding from NSF and USGS and again authorized for another five year award period beginning February 1, 2007 (SCEC3).

This report highlights the Center's research activities during the third year (2009) of SCEC3. The report is organized into the following sections:

II. Planning, Organization, and Management of the Center

SCEC is an institution-based center, governed by a Board of Directors who represent its members. The SCEC membership now comprises 16 core institutions and >40 participating institutions.

A. Board of Directors

Under the SCEC3 by-laws, each core institution appoints one board member, and two at-large members are elected by the Board from the participating institutions. The 18 members of the Board are listed in Table II.1. New board members this year are Tom Brocher for USGS/Menlo Park, Ken Hudnut for USGS/Pasadena, and Jill McCarthy, for USGS/Golden.

Table II.1. SCEC Board of Directors

Institutional and At-Large Representatives

Thomas H Jordan* (Chair)	University of Southern California
Lisa Grant* (At-Large, Vice-Chair)	University of California, Irvine
Ralph Archuleta*	University of California, Santa Barbara
Peter Bird	University of California, Los Angeles
David Bowman (At-Large)	California State-Fullerton
Tom Brocher	USGS-Menlo Park
Emily Brodsky	University of California, Santa Cruz
James N. Brune	University of Nevada, Reno
Steven M. Day	San Diego State University
James Dieterich	University of California, Riverside
Yuri Fialko	University of California, San Diego
Thomas A. Herring	Massachusetts Institute of Technology
Ken Hudnut	USGS-Pasadena
Nadia Lapusta	California Institute of Technology
Jill McCarthy*	USGS-Golden
James Rice*	Harvard University
Paul Segall	Stanford University
Bruce Shaw	Columbia University

Ex-Officio Members

Greg Beroza (Deputy Director), John McRaney* (Executive Secretary), Mark Benthien (Associate Director, CEO), Phil Maechling (IT Architect)

* Executive Committee members

Ex officio members include the SCEC Deputy Director, Greg Beroza; the Associate Director for Administration, John McRaney, who also serves as Executive Secretary to the Board; the Associate Director for Communication, Education and Outreach, Mark Benthien, and the SCEC IT Architect, Phil Maechling.

B. External Advisory Council

SCEC's Advisory Council (AC) is an external group charged with developing an overview of SCEC operations and giving advice to the Director and the Board. Mary Lou Zoback of RMS Associates assumed the chair of the AC in 2008. The Advisory Council's report, along with a list of member, is reproduced in Section VI. Steve Mahin replaced Jack Moehle on the AC this year.

C. Organization of Research

A central organization within SCEC is the Science Planning Committee (PC), which is chaired by the Deputy Director and has the responsibility for formulating the Center's science plan, conducting proposal reviews, and recommending projects to the Board for SCEC funding

The PC membership includes the chairs of the major SCEC working groups. There are three types of working groups—disciplinary committees, focus groups, and special project groups. The Center is fortunate that some of its most energetic and accomplished colleagues participate as group leaders (Table II.2).

The Center sustains disciplinary science through standing committees in *seismology*, *tectonic geodesy*, and *earthquake geology*. These committees are responsible for planning and coordinating disciplinary activities relevant to the SCEC science plan, and they make recommendations to the Science Planning Committee regarding the support of disciplinary infrastructure. Interdisciplinary research is organized into seven science focus areas: *unified structural representation*, *fault and rupture mechanics*, *crustal deformation modeling*, *lithospheric architecture and dynamics*, *earthquake forecasting and predictability, ground motion prediction*, and *seismic hazard and risk analysis*. The focus groups are the crucibles for the interdisciplinary synthesis that lies at the core of SCEC's mission.

Table II.2. Leadership of the SCEC Working Groups

Disciplinary Committees	
Seismology:	Egill Hauksson (chair)* Elizabeth Cochran (co-chair)
Tectonic Geodesy:	Jessica Murray (chair)* Rowena Lohman (co-chair)
Earthquake Geology:	Mike Oskin (chair)* James Dolan (co-chair)
Focus Groups	
Unified Structural Representation:	John Shaw (leader)* Kim Olsen (co-leader)
Fault and Rupture Mechanics:	Judi Chester (leader)* Ruth Harris (co-leader)
Crustal Deformation Modeling:	Liz Hearn (leader)* Kaj Johnson (co-leader)
Lithospheric Architecture and Dynamics:	Paul Davis (leader)* Thorsten Becker (co-leader)
Earthquake Forecasting and Predictability:	Terry Tullis (leader)* Jeanne Hardebeck (co-leader)
Ground Motion Prediction:	Brad Aagaard (leader)* Steve Day (co-leader)
Seismic Hazard and Risk Analysis:	Paul Somerville (leader)* Nico Luco (co-leader)
Special Project Groups	
Southern San Andreas Fault Evaluation:	Tom Rockwell (chair)* Kate Scharer (co-chair)
Working Group on California Earthquake Probabilities:	Ned Field (chair)*
Collaboratory for the Study of Earthquake Predictability:	Tom Jordan (chair)* Danijel Schorlemmer (co-chair)
Extreme Ground Motion:	Tom Hanks (chair)*
Petascale Cyberfacility for Physics-Based Seismic Hazard Analysis:	Phil Maechling (chair)*

There are several new members of the Planning Committee this year. Elizabeth Cochran is now co-chair of Seismology, replacing Jamie Steidl; Kim Olsen has replaced Jeroen Tromp as co-chair of USR; Kaj Johnson has replaced Tom Parsons as co-chair of CDM; Thorsten Becker has replaced Gene Humphreys as co-chair of LAD; Jeanne Hardebeck has replaced Bernard Minster as co-chair of EFP; Brad Aagaard is now chair of GMP, with Rob Graves moving to co-chair, replacing Steve Day; and Tom Rockwell is now chair of SoSAFE, replacing Ken Hudnut, with Kate Scharer as co-chair. In addition to the disciplinary committees and focus groups, SCEC manages several special research projects, including the Southern San Andreas Fault Evaluation Project, the Working Group on California Earthquake Probabilities, the Collaboratory for the Study of Earthquake Predictability, Extreme Ground Motion, and the Petascale Cyberfacility for Physics-Based Seismic Hazard Analysis (SCEC/ITR) Project. Each of these groups is represented on the Science Planning Committee by its chair.

The long-term goals and short-term objectives laid out in the SCEC Strategic Plan provided the basis for the SCEC Program Announcements, which are issued annually in October. This proposal process is the primary mechanism through which SCEC recruits scientists to participate in its research collaborations. The process of structuring the SCEC program for 2009 began with the working-group discussions at the annual meeting in September 2008. An RFP was issued in October 2008, and 182 proposals (including collaborations) requesting a total of $6.95M were submitted in November 2008.

All proposals were independently reviewed by the Director and Deputy Director. Each proposal was also independently reviewed by the chairs and/or co-chairs of three relevant focus groups or disciplinary committees. (Reviewers were required to recuse themselves when they had a conflict of interest.) The Planning Committee met on January 22-23, 2009 and spent two days discussing every proposal. The objective was to formulate a coherent, budget-balanced science program consistent with SCEC's basic mission, short-term objectives, long-term goals, and institutional composition. Proposals were evaluated according to the following criteria:

a. Scientific merit of the proposed research.
b. Competence and performance of the investigators, especially in regard to past SCEC-sponsored research.
c. Priority of the proposed project for short-term SCEC objectives.
d. Promise of the proposed project for contributing to long-term SCEC goals.
e. Commitment of the P.I. and institution to the SCEC mission.
f. Value of the proposed research relative to its cost.
g. The need to achieve a balanced budget while maintaining a reasonable level of scientific continuity given very limited overall center funding.

The recommendations of the PC were reviewed by the SCEC Board of Directors at a meeting on February 2-3, 2009. The Board voted unanimously to accept the PC's recommendations, pending a final review of the program by the Center Director, which was completed in late February. A list of funded projects was submitted to NSF and the USGS.

SCEC is coordinating its research program with the USGS through a Joint Planning Committee (JPC). The USGS members of the JPC attend the proposal review meeting of the SCEC Planning Committee as non-voting participants and contribute to the discussion of proposals.

D. Communication, Education, and Outreach

SCEC is committed to applying the basic research in earthquake science to the practical problems of reducing earthquake losses. To accomplish this aspect of its mission, SCEC maintains a vigorous Communication, Education, and Outreach (CEO) Program that receives 10% of its base funding plus other funds from special projects, such as the Electronic Encyclopedia of Earthquakes. CEO activities are managed by the Associate Director for CEO, Mark Benthien. The programmatic elements include structured activities in education and public outreach and two new structures: an *Implementation Interface*, designed to foster two-way communication and knowledge transfer between between SCEC scientists and partners from other communities—in particular, earthquake engineering, risk analysis, and emergency management, and *a Diversity Task Force*, responsible for furthering the goal of gender and ethnic diversity in earthquake science. A report on the third-year CEO activities is given in Section IV.

III. Research Accomplishments

This section summarizes the main research accomplishments and research-related activities during 2008-2009. While the presentation is organized sequentially by disciplinary committees, focus groups, and special project working groups, it is important to note that most SCEC activities are crosscutting and could be presented under multiple focus groups.

A. Disciplinary Activities

The following reports summarize recent progress in the three main infrastructural activities and the discipline-oriented research, *Seismology, Geodesy,* and *Geology.*

1. Seismology

Four projects were funded in the Seismology Infrastructure focus group in 2008-09. These were the Southern California Earthquake Data Center, the Borehole Seismometer Network, the Portable Broadband Instrument Center, and a Caltech/UCSD collaboration assembling earthquake catalogs and measuring earthquake properties and structure. In addition, several innovative projects were funded as part of the seismology research effort.

a. Southern California Earthquake Data Center (SCEDC)

Major 2008-09 Accomplishments:

1. Continued our key data-acquisition and archiving functions by maintaining and updating the primary online, near real-time searchable archive of seismological data for southern California. Added 88,246 station-days of continuous data and parametric and waveform data for 13,291 local events and 274 teleseismic earthquakes.
2. The SCEDC has upgraded both its database servers in both hardware and database version and they are now used fully in production. One is a database cluster composing of 3 Dell nodes. The other is an IBM server that was awarded to the SCEDC through an IBM-Caltech grant. This upgrade has allowed significant performance improvements to the users of catalog search applications and STP, especially in continuous waveform searches.
3. The SCEDC has replaced its single web server with two IBM x3650 web servers. This will allow greater redundancy and ability to handle higher loads that are expected with heightened public interest from a significant event.
4. In response to user recommendations at the SCEDC town-hall meeting, the SCEDC began continuous archiving of all EH and SH channels as of Jan 1, 2008. This is a significant increase spatial coverage of the continuous archive – from 328 stations in 2007 to 374 stations in 2008.
5. In an effort with the SCSN, timing on the entire SCSN catalog is now complete. Events from 1932 to present are now all available through STP or the catalog search pages on *www.data.scec.org*.
6. The SCEDC continues to make improvements Station Information System (SIS) with the Southern California Seismic Network (SCSN). Station fieldwork is entered by field technicians in SIS through a web interface, any changes to the station response

are then automatically distributed to the data center databases and a dataless SEED volume is produced. The response changes are also made available to SCSN Real Time processes. All updates made by a field technician in the SIS are now available to users of SCEDC within 24 hours. Some developments in 2008-09 include a user interface called ‘Channel Manager’ which allows users to edit station response data for single channel epochs as well as batch updates. This kept the SCSN metadata current when SCSN renamed the HL channels of 170 stations to HN in compliance with SEED channel naming convention.

7. The SCEDC hosted a mirror site to the SCEC Earthquake Response Content Management System (ERCMS) for the November 2008 ShakeOut. The SCEDC will continue to host this mirror site for SCEC.

8. The SCEDC expanded the ANSS XML straw man and developed a schema for distributing seismic station metadata. The SCEDC has been a leader in XML formats, having previously developed an event and parametric information schema for the distribution of catalog data. The SCEDC released version 1.0 of the StationXML schema for sharing station metadata. StationXML has been accepted by the CISN and opened to review from the ANSS. The SCEDC is a leader in XML development, having previously developed an event and parametric information schema for the distribution of catalog data. StationXML and our other schemas are available at *http://www.data.scec.org/xml/station/* and *http://www.data.scec.org/xml/*.

9. The SCEDC will continue to serve out fault data to the SCEC WGCEP group. Contribution to the SCEC Community.

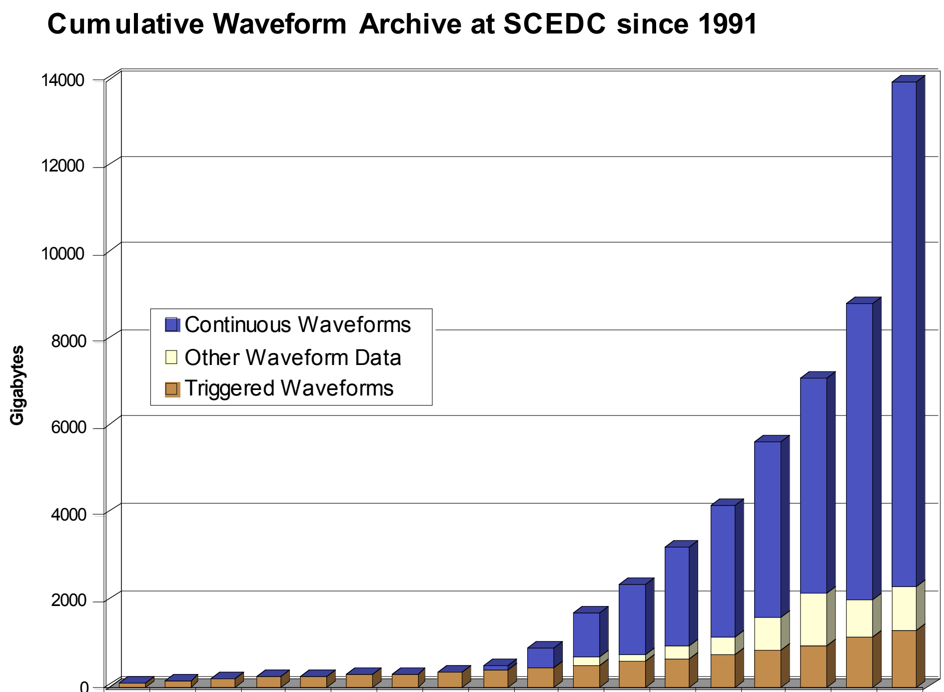
The Data Center is a central resource of SCEC and continues to be an integral part of the Center. In 2008-09, the SCEDC continued to contribute to the SCEC scientific community by providing online access to a stable and permanent archive of seismic waveforms and earthquake parametric data. The seismological data archive held at the SCEDC has contributed significantly to the publication of many scientific papers pertinent to the region, most of which have SCEC publication numbers. The Caltech/USGS catalog archived by the SCEDC is the most complete archive of seismic data for any region in the United States.

The SCEDC has allowed the data to be distributed to a much broader community of scientists, engineers, technologists, and educators than was previously feasible. The electronic distribution of data allows researchers in the worldwide scientific community to analyze the seismic data collected and archived in southern California and contribute their results to the SCEC effort.

The archive at the SCEDC currently has the following holdings:

- Caltech/USGS catalog of over 631,854 earthquakes spanning 1932-present.
- 12.92 terabytes of continuous and triggered waveforms (Figure 1).
- 15.2 million phase picks.
- 70.1 million triggered waveform segments.
- Nearly 8 years of continuous broadband recording of representing more than 470,880 station-day records, accumulating at ~50,000 station-days per year (for the current 166-station network).
- 30.4 million amplitudes available for electronic distribution.

- Triggered data for more than 9,475 significant teleseismic events.



Year	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Continuous Waveforms	0	0	0	0	0	0	0	0	102	485	1004	1596	2274	3013	4008	4969	6850	1163
Other Waveform Data											168	188	272	412	792	1186	854	1035
Triggered Waveforms	76.8	157	185	231	261	286	311	337	392	438	512	579	660	746	839	974	1141	1281

Figure 1. The SCEDC waveform archive.

b. 2008-09 SCEC Borehole Instrumentation Program Activity

One of the main accomplishments of the SCEC borehole instrumentation program has been the high degree of collaboration and cost sharing between multiple agencies and institutions that operate networks and collect and archive seismic data. The goal of the SCEC borehole instrumentation program, from its inception in SCEC 1, has been to facilitate the deployment of borehole observation stations in southern California (Figure 2).

The philosophy behind the SCEC borehole instrumentation program was that all data should be integrated with the existing network infrastructure for real-time transmission, processing, and archival. This provides all researchers with equal access to the data as soon as it's made available from the network operators. In addition, the borehole data is being used by the network for earthquake locations. In 2008-09 multiple researchers have started using the borehole data in southern California to look for evidence of non-volcanic tremor signals. Access to this data through the SCEDC made this possible.

Southern California Borehole Instrumentation

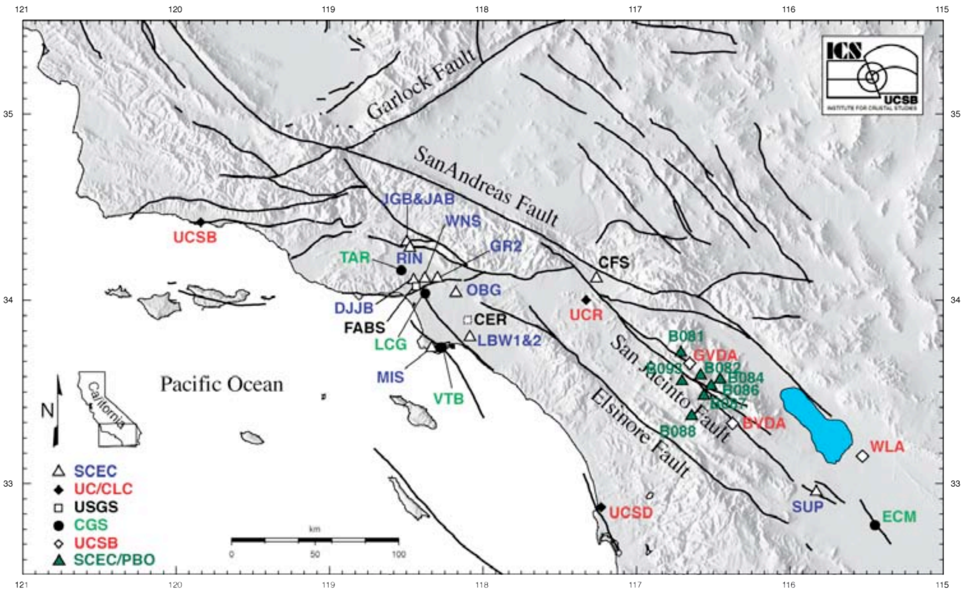


Figure 2. The Borehole instrumentation network in the Southern California region.

Other accomplishments for 2008-09 include:

1. SCEC collaboration with NEES program
   - Software development using the Matlab toolbox interface to the Antelope real-time data processing at UCSB.
   - Routine processing of borehole data to provide signal to noise quality factors on event-by-event basis.
   - Calculation of spectra and routine spectral source parameter estimation using Matlab curve fitting toolbox.
   - Development of web-based data dissemination tool for providing event based data in multiple formats from the SCEC borehole stations.
2. Collaborative upgrade of the communication link on Superstition Mountain (SUP) site.
   - WiLan 11 Mbps radios at the superstition mountain site were replaced with Trango 45 Mbps radios to support the increased data communications from this SCEC borehole station that also servers as a repeater station. This repeater serves as a communication link to many stations in the PBO network, and the NEES facility in the Imperial Valley.
3. General maintenance of the SCEC borehole instrumentation infrastructure.
   - Replacement of datalogger at the WNS site. The GPS engine had failed on the existing datalogger causing the data to be incorrectly time stamped. Swapping out the datalogger (using a working replacement provided by CISN) fixed the timing issue.
   - Repair and critter abatement at the LBW site. Data quality began to degrade at this station and the culprit was rodent infestation. Cables for power, GPS, and

sensors had to be repaired or replaced. Improvements to overall security of the site and protection for the cables were made.

- Restoration of the communications at the JAB site. Data telemetry was restored when the failed UPS was removed, and power returned to the WiLan radio.
- General quality control of all the existing borehole stations using the NEES@UCSB software data processing systems to pull data from the real-time systems at Caltech and UNAVCO to provide assistance with troubleshooting problem stations.

c. 2008-09 SCEC Portable Broadband Instrument Center Activities

2008-09 ShakeOut: Integration of PBIC and IRIS real-time stations to CISN. The data from the PBIC stations can be integrated directly into the network processing at Caltech/USGS in Pasadena. In 2008-09, as part of the ShakeOut exercise, the SCEC real-time equipment was deployed along with equipment delivered from IRIS PASSCAL. A total of 12 stations were deployed, with a single station located in Indio right along the SoSAF and an array of 11 stations deployed in a fault-crossing configuration an the SoSAF at Whitewater Canyon (Figures 3-5).

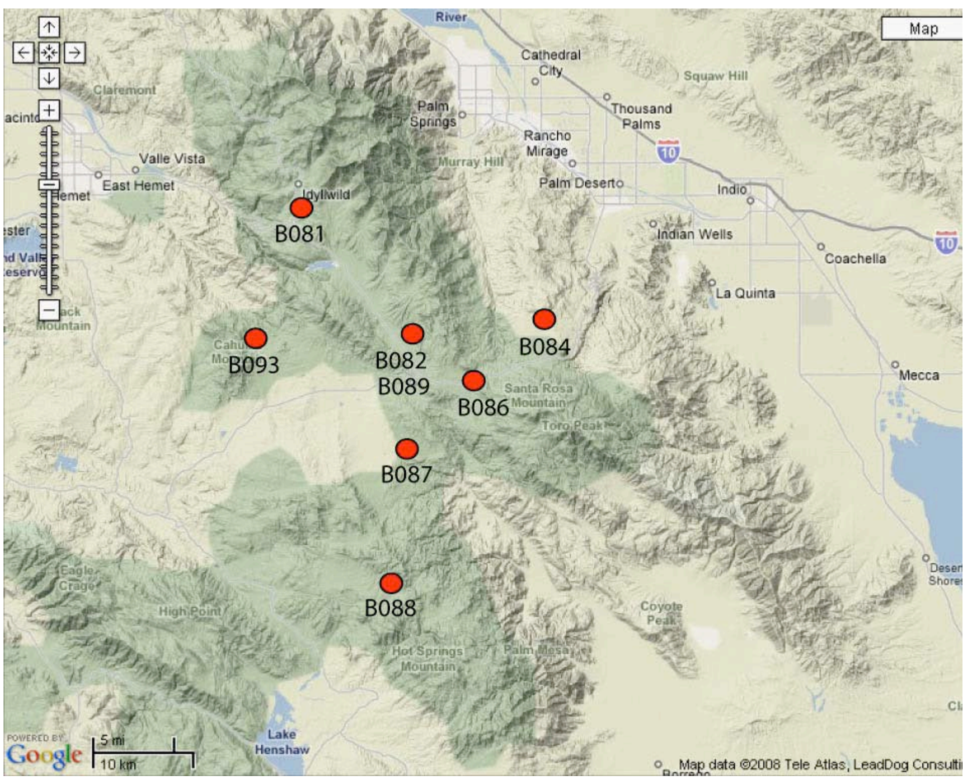


Figure 3. Joint SCEC/PBIC and IRIS/PASSCAL RAMP deployment for the 2008 ShakeOut exercise. Station IND1 located in Indio and WWC0 the center station of the fault-crossing array at Whitewater Canyon shown on Google Earth along with 1-week of seismicity.

This deployment is testing the ability to quickly integrate newly deployed portable stations into the routing data processing at the regional network level. Normally new stations come on line over the course weeks to sometimes months, as the station is prepared both in the field and at the network level with the collection of metadata into the station information system and the network systems configuration. Given a significant earthquake, the speed at which we can integrate new stations is important, and pushing the integration of new stations down to 24 hours is a significant challenge. The ShakeOut exercise using the SCEC and IRIS RAMP equipment tested the capabilities at the network level in southern California and this exercise will improve our ability to respond quickly in the next significant event.

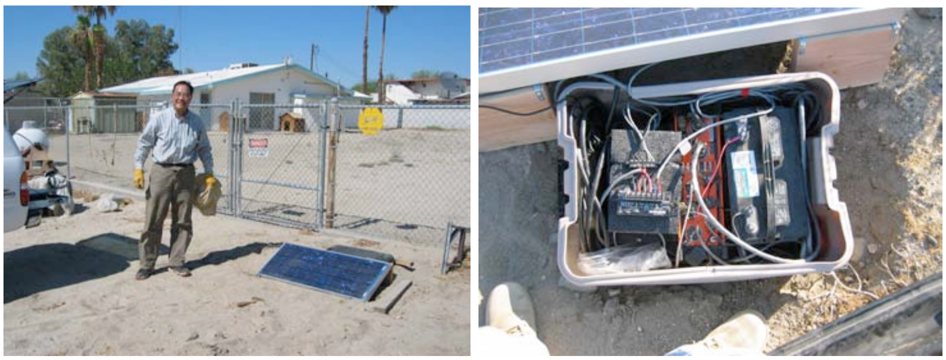


Figure 4. Joint SCEC/PASSCAL ShakeOut deployment in 2008. Installation of the SCEC PBIC real-time equipment at the [Left] Indio site with SCEC researcher Yong-gang Li shown for scale, and WWC0 center station [Right] at Whitewater Canyon.

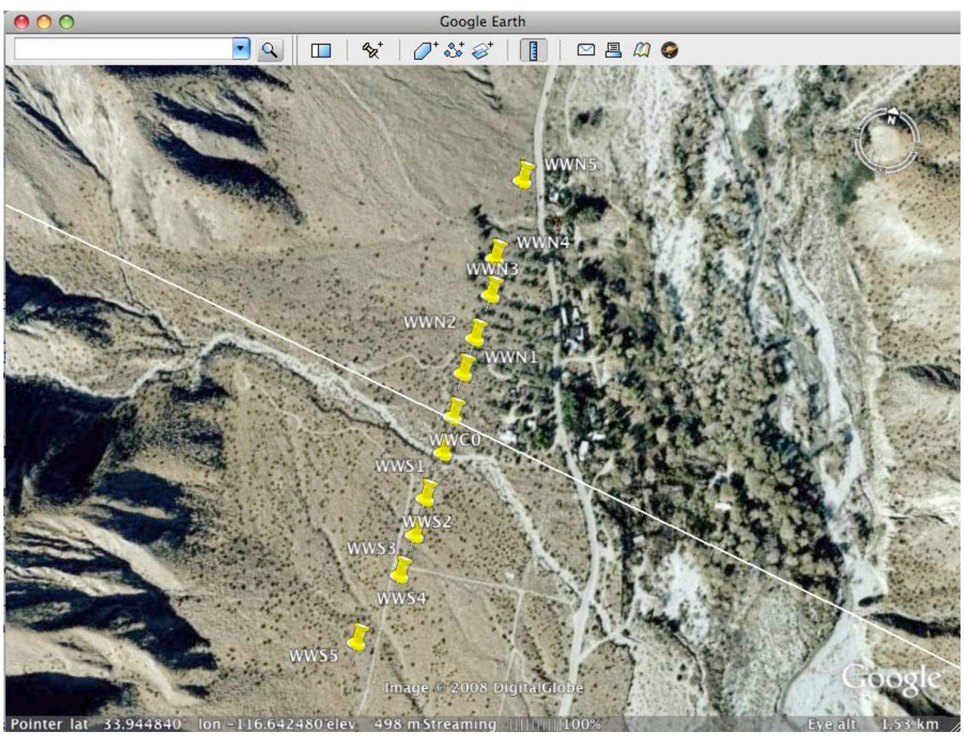


Figure 5. ShakeOut 2008 Whitewater Canyon fault-crossing array with the SoSAF approximate location shown as a white line running perpendicular to the array.

d. Superstition Hills Fault Project Support

One of the important aspects of the PBIC is the involvement of undergraduate students in field deployments, and post processing of the data as it comes back from the field. This year continued this involvement with two geology and one geophysics undergraduate majors participating in these activities through the Superstition Hills Fault monitoring project. This experiment ended in 2008, with the students being involved with the decommissioning of the stations and the data processing and archival procedures.

This experiment was the testing ground for the two new PBIC stations that have real-time capabilities. The deployment of these real-time stations in this rather remote location and harsh environment was a great success for the PBIC. Data was transmitted in real-time to the Caltech/USGS regional network monitoring, and was used help improve the location of earthquakes in this seismically active region. The use of 6-channel real-time stations also provides the three-component strong-motion channels for use in shake map production in the event a significant earthquake strikes the region and the weak-motion channels go off scale. The use of this modern equipment provided the project PI with instant access to the data with no post processing, and is now already available to the entire research community via the usual data dissemination tools from the SCEC data center!

Database and Web page updates. The newest PBIC equipment has been added to the PBIC online inventory database and is now tracked there as it comes into and goes out from the lab space at UCSB. The main website page as well as the "locals only" student assistant pages are being updated on a regular basis now. The latter being pages that the students use to document and provide tutorials on PBIC maintenance tasks, and data processing procedures.

Satellite Phone testing. The PBIC equipment now includes a Satellite phone (purchased with matching funds from UCSB) for communications after a significant event, when cell towers may be unavailable and wireless networks are over capacity. The UCSB phone was tested as part of the ShakeOut response planning, and the number is now listed on the SCEC response wiki.

e. Application of Waveform Cross-Correlation and Other Methods to Refine Southern California Earthquake Data

Earthquake focal mechanisms are a key constraint on fault orientations and the state of stress in the crust. However, moment tensor solutions based on synthetic seismograms can be computed only for earthquakes of M ~ 3.5 or greater because of signal-to-noise limitations. Thus focal mechanisms for the vast majority of earthquakes recorded in southern California are computed from high-frequency P phase data. Traditional methods, such as the FPFIT program [Reasenberg and Oppenheimer, 1985], use P polarity information alone. Results of Jeanne Hardebeck [Hardebeck and Shearer, 2002, 2003] have shown that focal mechanisms computed from P polarities typically have large uncertainties due to gaps in the focal sphere coverage; however, improved results are possible, even from small numbers of stations, when S/P amplitude information is also used. Adding S/P ratios needs to be done carefully because S/P amplitude ratios can vary significantly, both at local and regional distances [e.g. Kennett, 1993]. Julian and Fougler [1996] developed a method to use amplitude ratios as inequality constraints, thus making it possible to use ratios as additional polarity observations. Using a different approach, Tan and Helmberger [2007] have shown that short-period P amplitudes can be used to determine focal mechanisms, and are particularly effective when empirical amplitude correction terms are computed for individual stations.

Shearer and Hauksson have done a preliminary comparison of three methods for determining focal mechanisms: 1) Tan and Helmberger [2007] using both first motion polarities and P-wave amplitudes (Ying Tan kindly provided their results); 2) Hardebeck and Shearer [2002] polarity only; and 3) Hardebeck and Shearer [2002] polarity and S/P amplitude ratios. Figure 6 compares the three methods (TH07, HS_pol, and HS_amp) for the 2003 Big Bear sequence. Generally, there is reasonable agreement among the methods. The biggest discrepancies are TH07 events such as 13936380, 13936812, and 13939520, which deviate from the prevailing strike-slip trend.

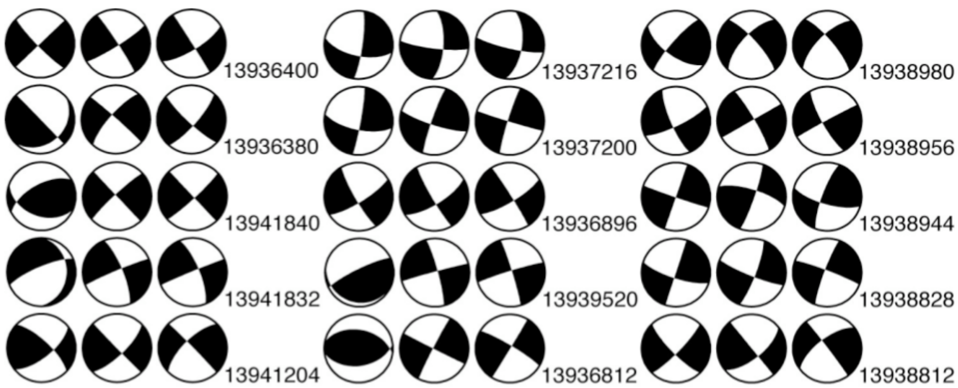


Figure 6. *P* velocity perturbations in the new 3-D crustal velocity model (Lin et al., 2007). The black contour lines enclose the well-resolved parts of the model. The best resolution is between about 3 and 10 km depth where ray coverage is best.

Ground Motion Prediction Using the Ambient Seismic Field. Under this grant Beroza et al. have developed the capability to use the ambient seismic field, sometimes referred to as ambient noise, to predict ground motion in earthquakes. Despite the complex and apparent random nature of the ambient field, it has a weak coherence that can be extracted even in the presence of multiple scattering. In particular, the correlation of diffuse wavefields recorded at two receivers can be used to extract the impulse response (i.e., the Green's function) for an impulsive excitation at one receiver, as recorded at the other. Figure 7 from Ma et al. [2008] compared all three components of the ambient-noise Green's functions at station FMP with theoretical, finite-element Green's functions calculated by applying a smooth vertical force with Gaussian time dependence at station ADO for SCEC CVM 4.0 and CVM-H5.2 community velocity models. The fit is limited primarily by our imperfect and incomplete knowledge of crustal structure.

They have used the ambient field to document basin amplification for seismic stations in the Los Angeles basin. We use 31 days of non-overlapping 2-hour segments recorded during January 2007 and calculate the impulse response of the unaltered seismograms between all three components of velocity. We stack using coherence weighting to reduce the effect of incoherent data on the results, and use the closest station to the coast to deconvolve, since it is closest to the predominant microseism source. Prieto and Beroza [2008] compared the response to a horizontal impulse, using station BBR as a virtual earthquake source, at seismic stations across metropolitan Los Angeles with seismograms of the February 10, 2001 (Mw 4.63) Big Bear earthquake, which is within 4 km horizontally and 10 km vertically of station BBR. The horizontal impulse is applied in the fault normal direction, following the earthquake mechanism given by Graves [2008], who independently modeled ground motions.

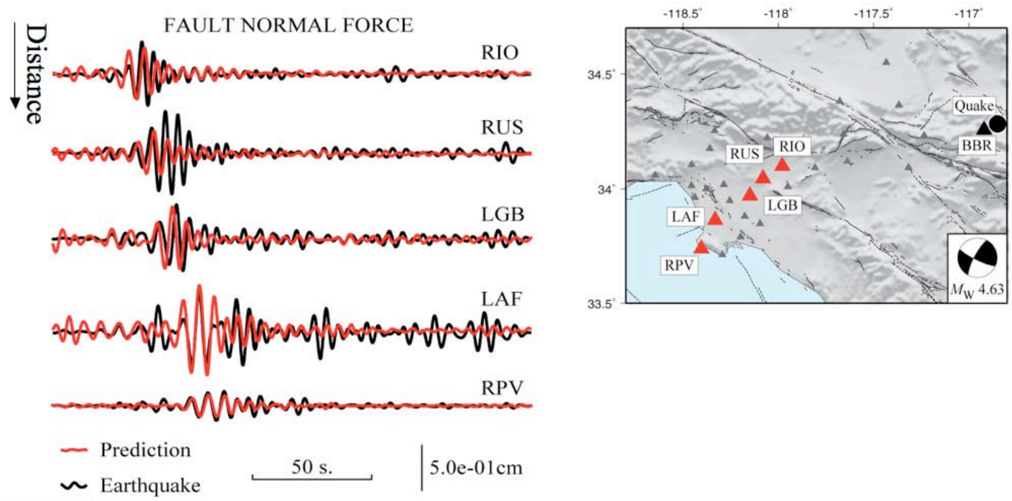


Figure 7. Ambient-noise Green's functions (red) at 4-10s period for 5 stations in the Los Angeles basin and seismic station BBR, compared to ground motions from the 2001 Big Bear earthquake (black), located near station BBR. Both the duration and relative amplitudes of ground motions across the Los Angeles Basin are recovered from ambient-noise observations.

Taken together, these techniques form the kernel of an important new capability for SCEC. Ambient-noise Green's functions can be used both for direct ground motion prediction, and to improve and test velocity models.

f. Seismic Documentation of Fault Cores and Damage Zones on the San Andreas Fault from Fault-Zone Guided Waves

In their previous study at Parkfield, San Andreas and the Calico fault in Eastern Mojave Desert, Li et al. used the fault-zone trapped waves (FZTWs) generated by explosions and microearthquakes and recorded at the dense linear seismic arrays to characterize the near-fault crustal properties, including the fault-zone rock damage magnitude and extent, and healing process from measurements of seismic velocity changes caused by the mainshock. The damage magnitude and extent on the SAF inferred by FZTWs [Li et al., 2004, 2006] have been confirmed by the SAFOD mainhole drilling and logs. The progression of coseismic damage and postseismic healing observed at the Parkfield SAF is consistent with those observed at rupture zones of the Landers and Hector Mine earthquakes [Li et al., 2006, 2007]. These results indicate that the greater damage was inflicted and thus greater healing is observed in regions with larger slip in the mainshock.

Li et al continued their efforts to determine the on- and off-fault damage at the San Andreas fault, Parkfield and the Calico fault using fault-zone guided waves. They used the FZTWs data recorded at the seismograph installed in the SAFOD mainhole at ~3 km depth where the borehole passed the SAF. The data include three-component waveforms from ~350 aftershocks of the 2004 M6 Parkfield earthquake. Many of aftershocks occurred at depths of 5 to 10 km so that the data allow us to constrain damage on the deep portion of the fault zone with higher resolution than those recorded at the surface array. They studied the heterogeneities in geometry and material property of fault zones to further understand the origin and mechanisms of fault damage and healing and their implications for stress heterogeneity and seismic hazard over the earthquake cycle. They also studied the contribution of on-fault damage to the total earthquake energy budget and the relationship between the damage magnitude and the absolute local stress level and stress drop.

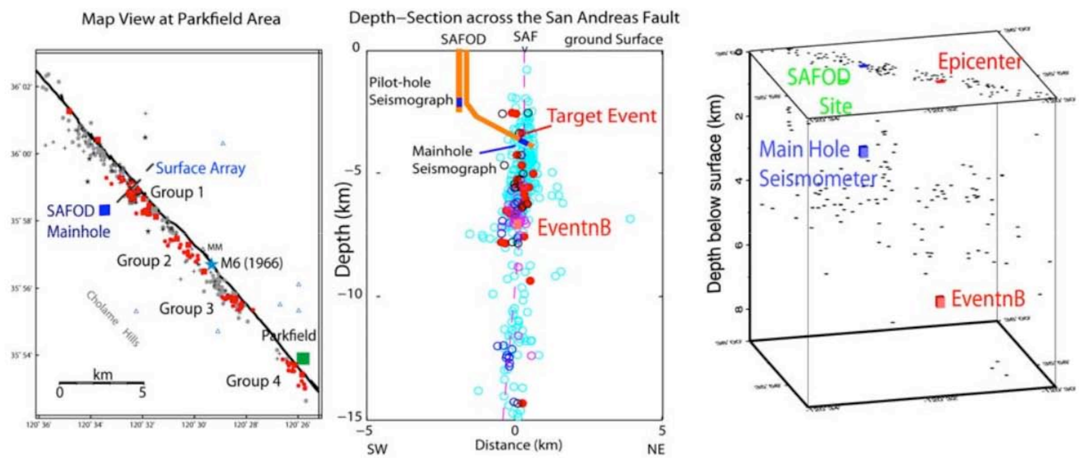


Figure 8. Left: Map view shows locations of ~350 aftershocks (circles) of the 2004 M6 Parkfield earthquake recorded at SAFOD borehole seismographs during December of 2004 and afterwards. Red circle denotes aftershocks in 4 groups at different epicentral distances to SAFOD site. The fault-zone trapped waves generated by these aftershocks are used in this study. The data recorded at the surface array (solid line across the fault) deployed in 2003 have been used in Appendix I. Middle: The vertical section across the SAF fault strike show locations of ~350 aftershocks (circles) recorded at SAFOD main-hole and pilot-hole seismographs. The fault-zone trapped waves generated by aftershocks in 4 groups denoted by red, black, pink and blue, respectively, are prominent in the SAFOD main-hole seismograms but not clear in the pilot-hole seismograms. Right: The 3-D view of locations of aftershocks (black dots) of the 2004 M6 Parkfield earthquake recorded at the SAFOD Main Hole seismograph (blue box). The red box denotes an example event which waveforms show the large secondary phases identified here as fault zone guided waves (see Fig. 2d in Appendix I). Waveforms recorded at the surface array for the target event and recorded at the SAFOD main-hole seismograph for Event B are shown in Fig. 2c of Appendix I.

In December 2004 a seismograph was installed in the SAFOD mainhole at ~3 km depth, where the highly fractured, low velocity zone of the SAF was found in the SAFOD drilling and well logs [Hickman et al., 2005]. A string of seismographs worked in the 1.2-km-deep pilot hole at the same time. The borehole seismographs recorded ~350 aftershocks of the 2004 M6 Parkfield earthquake. Locations of these aftershocks are shown in Figure 8. They have systematically examined the data recorded at the SAFOD borehole seismographs for the aftershocks in 4 groups with epicentral distances from the array: 1-2 km, 4-5 km, 8-10 km and 14-16 km, respectively (Figure 8).

g. Seismic and Geodetic Evidence For Extensive, Long-Lived Fault Damage Zones

During earthquakes slip is often localized on preexisting faults, but it is not well understood how the structure of crustal faults may contribute to slip localization and energetics. Accumulating evidence suggests that the crust along active faults suffers macroscopic strain and damage during large quakes [Fialko et al., 2002; Vidale and Li, 2003; Li et al., 1998; Ben-Zion et al., 2003].

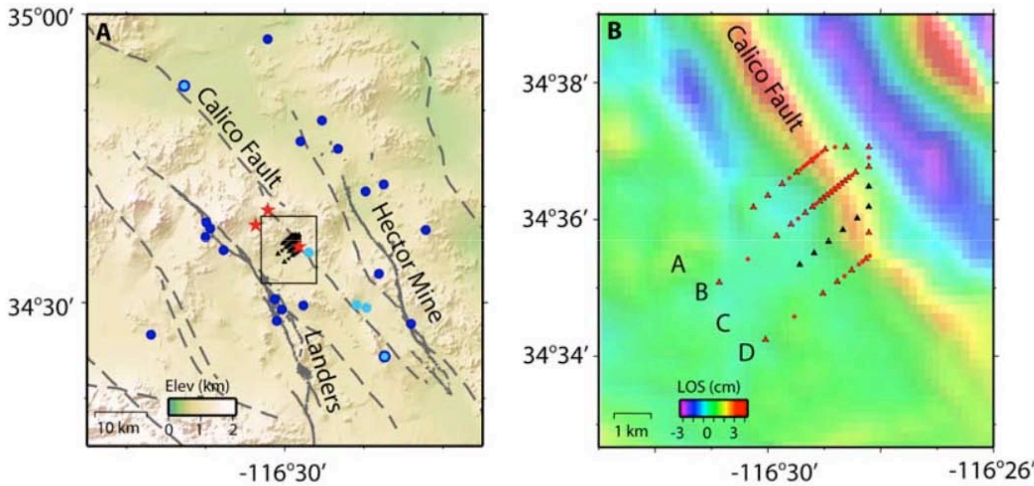


Figure 9. (A) Shaded relief map of Mojave region. Faults shown by dashed gray lines. Landers and Hector Mine ruptures are solid gray lines. Circles indicate local earthquakes used in the fault zone trapped wave and travel-time analyses, respectively. Light blue circles were used in both analyses. Red stars denote shots. Black triangles and circles show seismic stations. Gray square outlines the region in Figure 9B. (B) High-pass-filtered coseismic interferogram from the Hector Mine earthquake that spans the time period from 13 January 1999–20 October 1999 (after Fialko et al., [2002]). Colors denote changes in the line of sight (LOS) displacements. Black triangles and red circles are intermediate-period and short-period seismic stations.

Seismic and geodetic data from the Calico fault in the eastern California shear zone reveal a wide zone of reduced seismic velocities and effective elastic moduli (Figure 9). Using seismic travel times, trapped waves, and inSAR observations, Cochran et al. document seismic velocities reduced by 40 - 50% and shear moduli reduced by 65% compared to wallrock in a 1.5-km- wide zone along the Calico fault. Observed velocity reductions likely represent cumulative mechanical damage from past earthquake ruptures. No large earthquake has broken the Calico fault historically, implying that fault damage persists for hundreds or perhaps thousands of years. These findings indicate that faults can affect rock properties at substantial distances from primary fault slip surfaces, and throughout much of the seismogenic zone, a result with implications for the portion of energy expended during rupture to drive cracking and yielding of rock and development of fault systems.

h. Maintenance and Further Products for the Online-Database of Finite-Source Rupture Models

Since the launching of the Internet-accessible database of finite-source rupture models (*http://www.seismo.ethz.ch/srcmod*) summer 2007, Mai et al. have received very positive feedback on the quality and accessibility of the source-model data. With "data quality" we refer to the representation of the available rupture-model information in form of MATLAB-based data structures and in form of comprehensive ascii-files. In terms of "accessibility", individual rupture-model data can be easily reviewed online (and downloaded), or the entire database can be retrieved as an easy-to-use MATLAB-structure (which seems to be the preferred choice for most users). However, despite this initial positive feedback, we received a number of constructive suggestions for improving and expanding the database. Many of these suggestions were implemented in the SCEC funding period 2008-09.

i. Interaction and Predictability of Small Earthquakes at Parkfield

How stress perturbations influence earthquake recurrence is of fundamental importance to understanding of the earthquake cycle. The large population of repeating earthquakes on the San Andreas fault at Parkfield provides a unique opportunity to examine the response of the repeating events to the occurrence of moderate earthquakes.

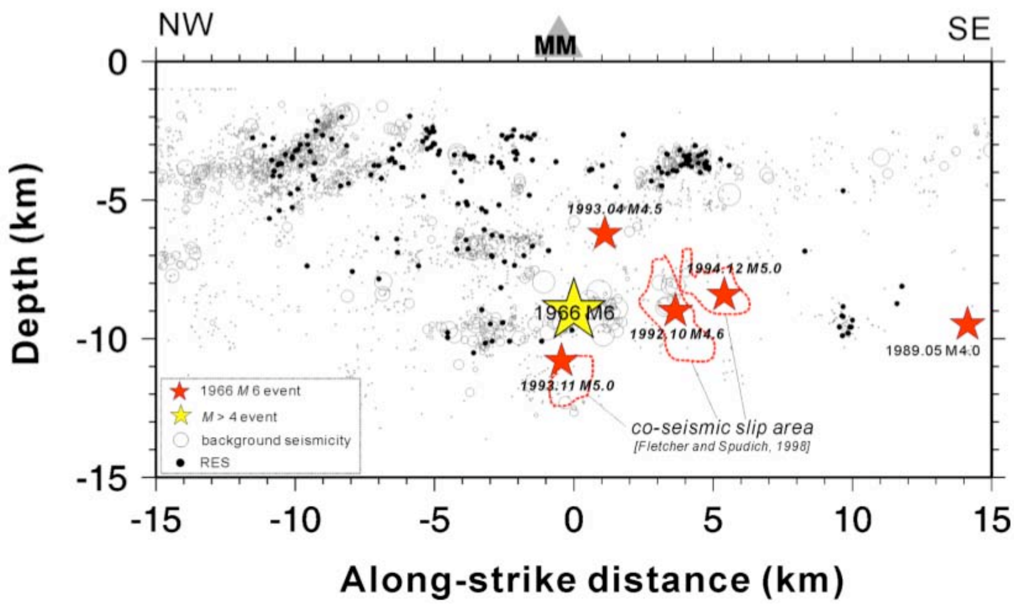


Figure 10. Along fault depth section showing 187 repeating earthquake sequences (1987-1998, black dots) and background seismicity. Catalog data are available at *http://www.ncedc.org/hrsn/hrsn.archive.html*). 1966 M 6 hypocenter is indicated by a yellow star. M 4-5 earthquakes that occurred in the period of 1987-1998 are denoted by red stars. Slip models of the M≥4.6 events that occurred in October 1992, November 1993, and December 1994 by Fletcher and Spudich [1998] are outlined by red dashed lines.

Using 187 M -0.4 ~ 1.7 repeating earthquake sequences from the High Resolution Seismic Network catalog, Burgmann et al. find that the time to recurrence of repeating events subsequent to nearby M 4-5 earthquakes is shortened, suggesting triggering by major events. The triggering effect is found to be most evident within a distance of ~5 km, corresponding to static coseismic stress changes of > 6 - 266 kPa, and decays with distance (Figure 10). They also find coherently reduced recurrence intervals from 1993 to 1998. This enduring recurrence acceleration over several years reflects accelerated fault slip and thus loading rates during the early 1990s.

j. The Source and Significance of High-Frequency Bursts Observed on Strong Motion Records from the Chi-Chi Taiwan and Parkfield California Earthquakes

High-pass filtering (>20 Hz) of acceleration records from the 1999 Chi-Chi Taiwan and 2004 Parkfield, California earthquakes reveal a series of bursts that occur only during strong shaking. Initially interpreted as originating from asperity failure on the Chelungpu fault, bursts observed during the Chi-Chi earthquake were subsequently determined to be a local effect within about 1 km of the seismic stations. Similar bursts were observed at UPSAR during the Parkfield earthquake and were constrained to originate less than 20 m from the instruments. Such small shallow events cannot result from the triggered release of stored elastic energy because rate-and-state friction rules out stick-slip instability on small, shallow patches. Sammis et al. infer that the bursts are not triggered, but are driven by simultaneous shear and tensile stresses near the surface during the strong motion. At 2 Hz, SV to P wave mode conversion at the free surface produces tensile stresses to depths of 70 m. Where standard triggering releases stored elastic energy and adds to the incident wavefield, this new driving mechanism takes energy out of the 2 Hz strong motion and reradiates it at high frequencies. It is thus an attenuation mechanism, which we estimate can contribute 3% to the net attenuation in the very shallow crust [Fischer et al., 2009].

k. Near real-time determination of earthquake sources for post-earthquake response

This past year Shaw et al. initiated a new project to develop an automated system for determining, immediately following an earthquake in southern California, what fault or faults likely generated the event. This effort employs the SCEC Community Fault Model (CFM) [Plesch et al., 2007] and CISN/SCSN real-time earthquake information. The system takes real-time earthquake information and calculates distances between the hypocenters and faults represented in the CFM. This data is used in combination with other criteria, such as the event magnitude and preliminary focal mechanism solution (including both event type and nodal plane orientations), to assign probabilities of association with various faults in the CFM. In the first year of this project, Shaw et al. have defined and implemented the approach for automatically calculating the proximity of earthquakes to triangulated surface representations of faults in the CFM, and are now in the process of refining an algorithm that will combine this information with other fault and earthquake attributes to assign probabilities of association (Figure 11). In the next phase of the project, we will set up a prototype system using a training dataset of southern California earthquakes.

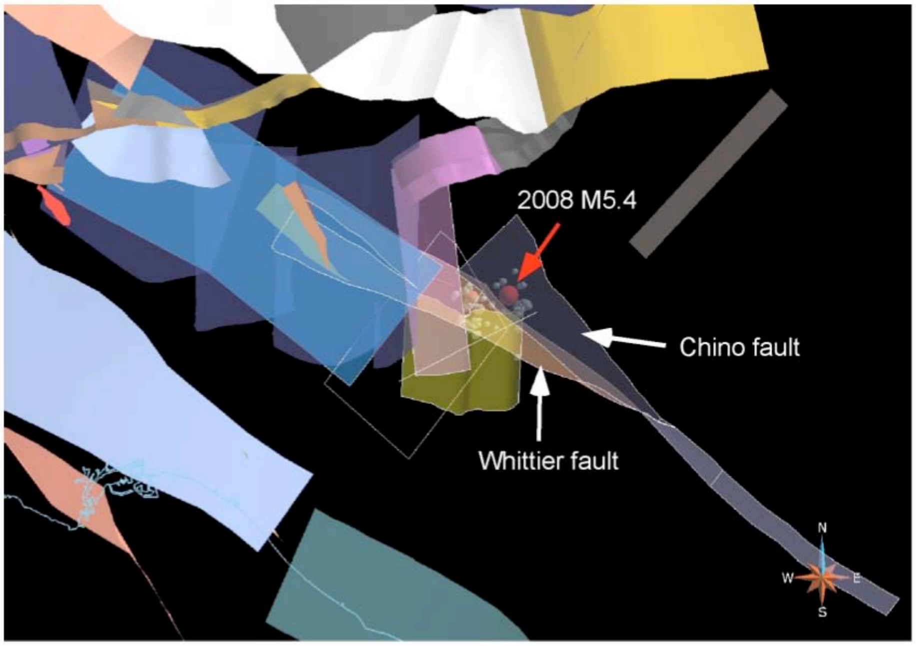


Figure 11. View of the CFM with the mainshock and aftershocks of the 2008 Chino Hills (M 5.4) earthquake. The earthquake occurred at a complex juncture of the Chino, Whittier, and several other faults, illustrating the complexity of defining the causative fault(s) for such events.

l. Modeling Short-Period Seismograms

Helmberger et al. report on a detailed test of a recently developed technique, CAPloc, in recovering source parameters from a few stations against results from a large broadband network in Southern California.

The method uses a library of 1D Green's functions, which are broken into segments and matched to waveform observations with adjustable timing shifts. These shifts can be established by calibration against a distribution of well-located earthquakes and assembled in tomographic images for predicting various phase-delays. Synthetics generated from 2D cross-sections through these models indicates that 1D synthetic waveforms are sufficient in modeling but simply shifted in time for most hard- rock sites. This simplification allows the source inversion for both mechanism and location to easily obtain by grid search (Figure 12). We test one-station mechanisms for 160 events against the array for both PAS and GSC, which have data since 1960. While individual solutions work well for mechanism (about 80%), joint solutions using these two stations produce more robust results. Inverting for both mechanism and location also works well except for complex paths crossing deep basins and along mountain ridges [*Tan et al*., 2009].

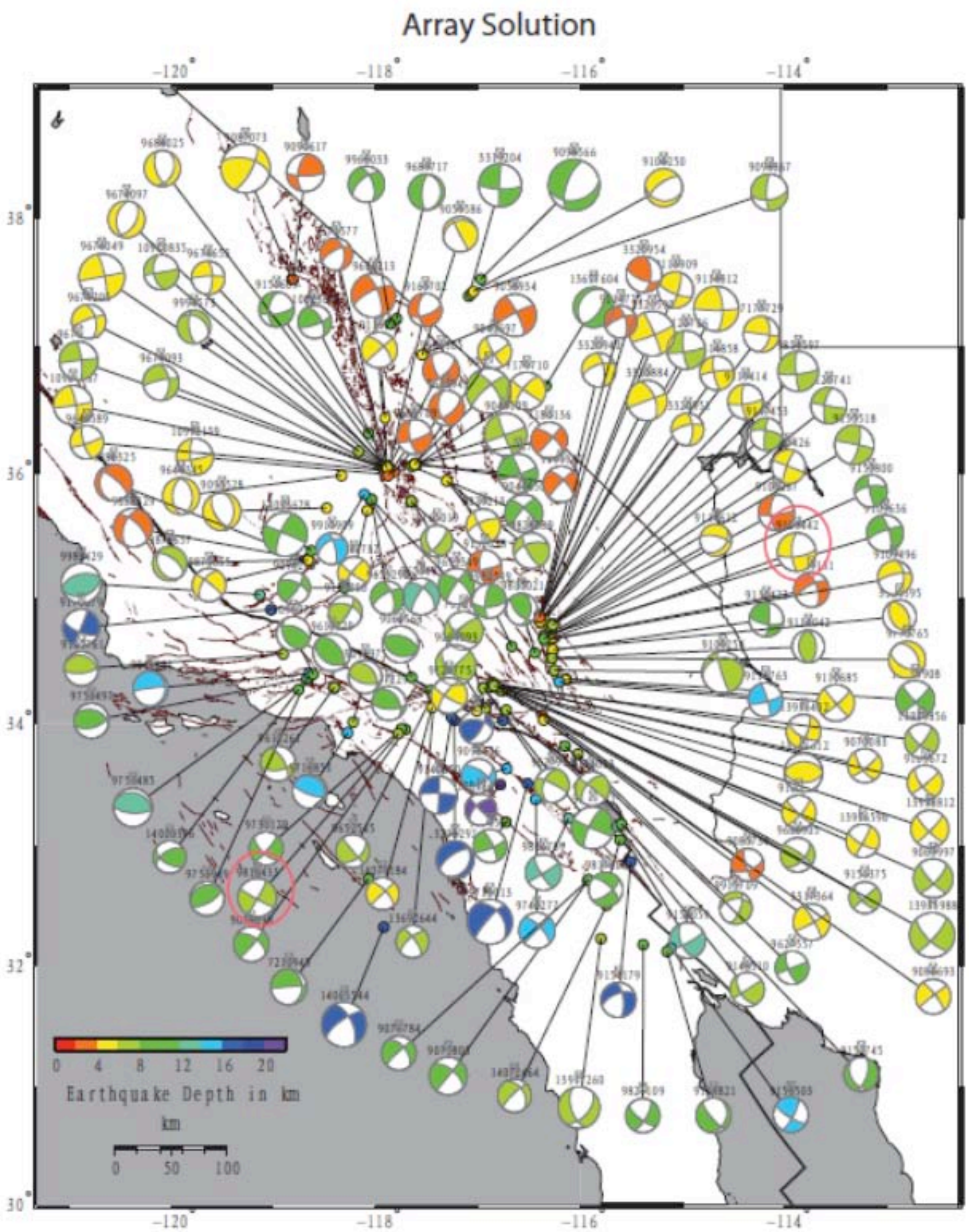


Figure 12. Source parameters of 160 Southern California events estimated by the CAP method with source parameters are shown. Source depths are indicated by color, ranging from 3 to 20 km.

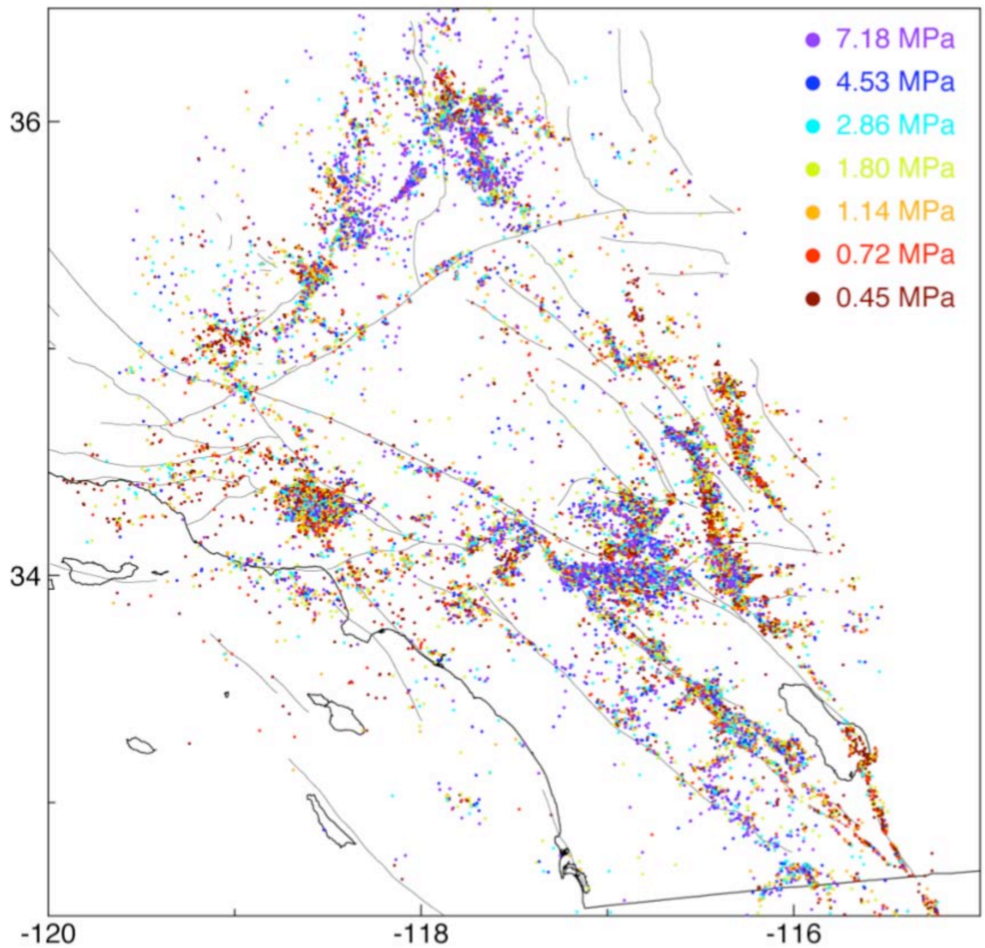


Figure 13. Estimated Brune-type stress drops for over 65,000 southern California earthquakes from 1989 to 2001. Results are colored in equal increments of log Δσ.

m. Analysis of Coda Waves in Southern California for Earthquake Source Properties

In earlier SCEC work, Shearer et al. computed and saved *P*, *S*, and noise spectra from over 2 million seismograms from 1984 to 2003 using a multitaper method applied to a 1.28 s signal window and a pre-arrival noise window. Next, they stacked the *P* spectra to isolate source, receiver, and propagation path contributions to the spectra (Figure 13). The advantage of the method is that it identifies and removes anomalies that are specific to certain sources or receivers. This is an important step because individual spectra tend to be noisy and irregular in shape and difficult to fit robustly with theoretical models. However, by stacking thousands of spectra it is possible to obtain much more consistent results [Shearer et al., 2006].

Shearer et al also analyzed Mogi doughnut behavior preceding small earthquakes in southern California. Earthquakes cluster strongly in time and space, but it is not yet clear how much of this clustering can be explained as triggering from previous events (such as occurs for aftershock sequences following large earthquakes) and how much the clustering may reflect underlying physical processes (such as apparently drive many earthquake swarms, e.g., Hainzl, [2004], Vidale and Shearer, [2006]). Seismologists have long studied the seismicity preceding big earthquakes to see if any distinctive precursory patterns could be identified. In some cases, a period of low earthquake activity or quiescence is observed for years in the vicinity of the eventual rupture zone of large earthquakes, surrounded by a region of continuing or increasing activity [Kanamori, 1981]. This seismicity pattern has been given the name "Mogi doughnut" (e.g., Mogi [1969]), with the doughnut hole representing the low seismicity rate around the impending hypocenter. However, analyses of large earthquake catalogs to evaluate the reliability of quiescence in predicting earthquakes have yielded mixed results [Habermann, 1988; Reasenberg and Matthews, 1988]. At shorter time scales of days to hours, some earthquakes are preceded by foreshock sequences near their hypocenters, but no distinctive properties in these sequences have yet been identified that would distinguish them from the many observations of earthquake clusters that do not lead to large earthquakes.

Figure 14. (Left) students working to conceal the location of seismometer and solar panels using tumbleweeds. (Right) A sizeable hole dug for one of the sensors deployed along the array.

n. Seismology Rapid Response Test During the SoSAFE Shakeout

With the funding provided by SCEC, Cochran, Steidl, Li, and others tested the procedure for requesting instruments for a RAMP array, deploying seismometers with both on-site and telemetry data collection and integrating the data into the Southern California part of the project we also coordinated the deseismic RAMP equipment from two sources, a undergraduates to deploy seismometers (Figure 14).

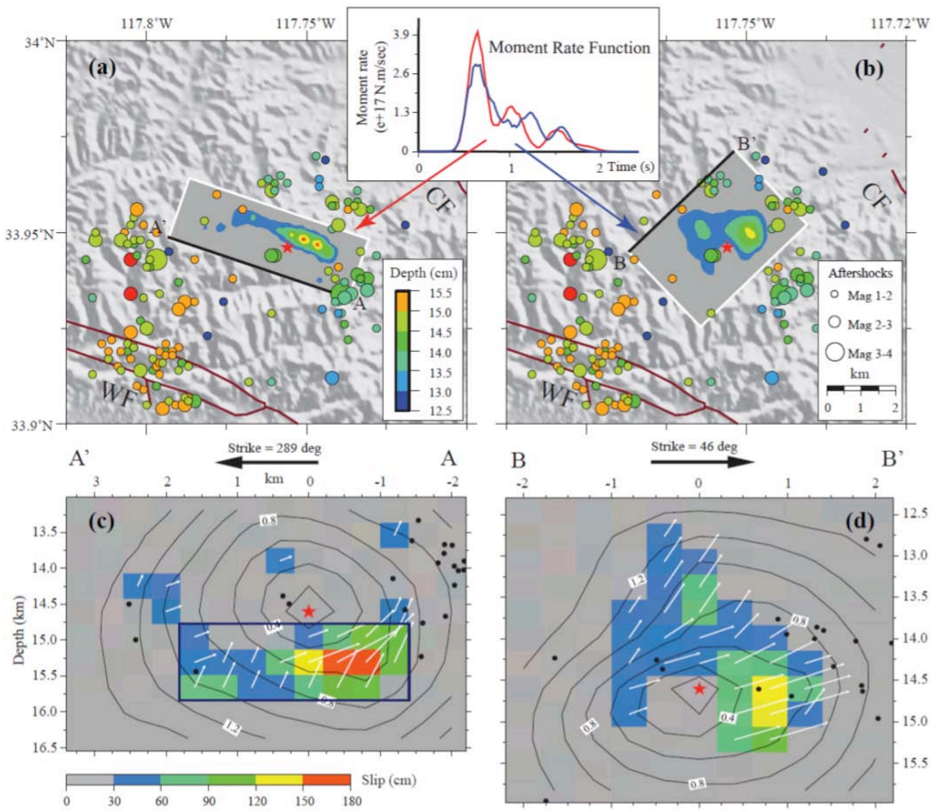


Figure 15. Comparison of inverted finite fault models based on two nodal planes (Table 1). (a) Surface projection of the Model I (white box) superimposed on the shaded relief. The red star indicates the epicenter of the mainshock. Black line A-A' indicates the top edge of the fault plane. Circles represent relocated aftershocks [Hauksson et al., 2008] during the first month, with filled color denoting their hypocenter depth, and the radius indicating their magnitudes. WF-Whittier Fault; CF-Chino Fault. (b) Same as (a) but for Model II (c) Vertical cross-section of slip distribution of Model I. The black arrow indicates the fault strike and the red star denotes the hypocenter location. For each subfault, the color shows its dislocation amplitude and the arrow indicates the motion direction of the hanging wall relative to the footwall. The high slip region was outlined by a blue box. Black contours show the rupture initiation time in an interval of 0.2 s. Black dots denote the selected aftershocks located within 1 km of the fault plane (d) Similar to (c) but for Model II. Inserted figure compares the moment rate functions of Model I (red line) and Model II (blue line).

o. Finite fault parameterization of intermediate and large earthquakes in Southern California

The quick finite-fault algorithm, which is currently used to monitor the global large earthquakes, is being modified by Ji et al. to routinely study finite fault parameters of the mediate and large earthquakes in Southern California using the CISN real-time dataset. Since this technique has already been demonstrated for the study of large earthquakes, during 2008-09 our research focused on the feasible data process and inverse schedules for the study of the moderate earthquakes. To study the moderate earthquake, we need use the higher frequency seismic waveforms, which is very sensitive to the 3D earth structure. *Tan and Helmberger* [2007] pointed out that the high frequency P waveforms (0.5-2Hz) recorded at LA basin could be modeled using 1D Green's functions after adding path-dependent time shifts and multiplying amplitude amplification factors (AAFs). They defined the AAFs as the amplitude ratios between records of a calibration event and the corresponding 1D synthetics, and found that the AAFs are relatively stable and mechanism independent [*Tan and Helmberger*, 2007]. However, a good calibration event may not always be available. So we have attempted to define them using state-of- art 3D SCEC-CVM models**.** The 2008 Chino Hills earthquake was used as the test event [Shao et al., 2009] (Figure 15).

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2. Tectonic Geodesy

In 2008-09, geodetic activities within SCEC focused on a range of activities that were highlighted in the RFP, including the acquisition of new GPS and strainmeter data, modeling of fault slip rates, and the use of multiple data types to estimate interseismic velocity fields. Areas in the RFP that received less attention include the use of high-rate GPS data, and the assessment of use of combined data sets in interpretation of tectonic or non-tectonic signals. continued as chair and co-chair of Tectonic Geodesy.

a. Transient detection and investigation of underlying processes and implications

In the summer of 2008, the leaders of the Tectonic Geodesy working group (Jessica Murray-Moraleda and Rowena Lohman) held a 2-day workshop on transient detection, which recommended a blind test exercise using synthetic data to identify promising detection approaches. This spring Phase I of the blind test transient detection exercise was completed and Phase II, with ~ 11 participating groups, is currently underway. There will be a 2-day workshop immediately before the 2009 SCEC meeting to summarize the results and discuss the timeline for tests using real data.

b. Modeling of geodetic data for slip rates, strain rates, and stress evolution

Efforts to invert geodetic data this year fell into two main categories – placing constraints on fault slip rates (and exploring the implications of geologic/geodetic rate discrepancies), and estimates of the spatial distribution of stress or strain rates across Southern California (linked to earthquake productivity and seismic hazard). Fault slip rate studies were generally divided into block models and field studies.

Johnson found that block models using an elastic layer overlying viscoelastic asthenosphere (uniform or layered), can result in differences in inferred slip rate of the order that are observed between geodetic and geologic estimates. He found that the predicted rates (Figure 16) are higher for models that include a layered viscoelastic space than for those with a uniform, high viscosity layer beneath the elastic crust. A test for the distribution of fault creep on the San Andreas reproduced the known creeping sections in the Salton trough and Parkfield. This year, Meade adapted his block models to include more realistic rectangular dislocations over most of Southern California (from CMM-R), with complicated triangulated geometries (500 elements) from CFM for the Puente Hills Thrust. In cases where the CMM-R representation included intersecting faults (which could not be included in the block model approach), they used the fault deemed most likely to have the fastest slip rate.

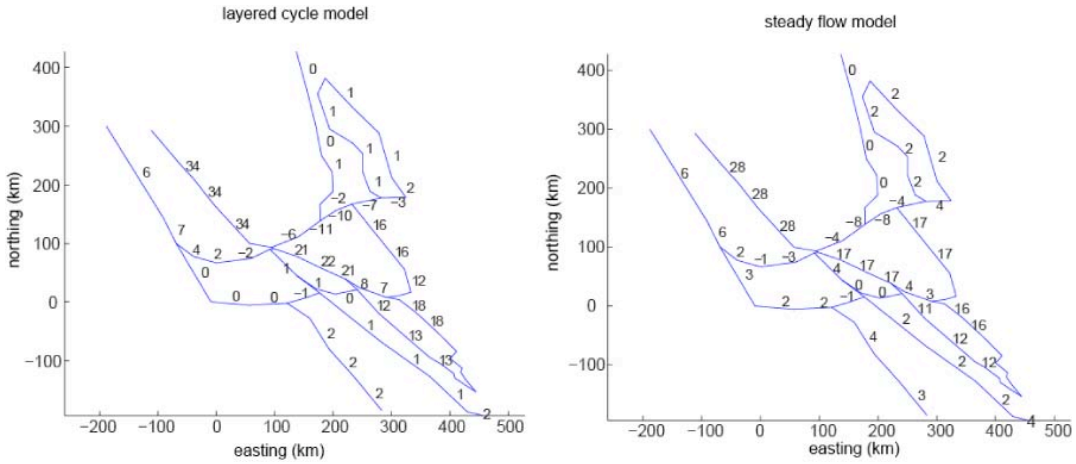

Figure 16. Slip rate estimates for a layered and homogeneous (steady flow) lower crust. Right-lateral rates are positive, left-lateral rates are negative.

Smith-Konter and Sandwell continued development of a model of the San Andreas Fault system that ingests historic and paleoseismic data and estimates the stress field due to coseismic, postseismic and interseismic loading. This year they explored uncertainties in their stress rate estimate due to variations in slip rates, locking depths, frictional coefficients, slip history, and mantle viscosity. Ward examined the use of geodetic data in seismic hazard estimation, either independently (stand-alone approach) to determine moment rate and earthquake rate from estimates of strain rate, or in combination with fault systems and earthquake simulators (combined approach). Part of the stand-alone approach involves the use of a virtual "scoop" of the Earth, with the base of the scoop tiled with slipping dislocations constrained by geodetic observations. This allows forward modeling of strain fields both at the surface and along arbitrary faults, and facilitates integration with earthquake simulator efforts (the ALLCAL simulator in this work).

c. Refine interseismic crustal motion maps - particularly vertical motion

Efforts in this category included attempts to merge SCIGN and Plate Boundary Observatory GPS products. Herring and King reported on three activities: Merging non-PBO data from SCIGN into the routine PBO processing, inclusion of the effects of the Landers and Hector Mine earthquakes into Southern California GPS time series, and their participation in the SCEC-sponsored transient signal detection activity. They find that sites in their merged data show similar weighted rms scatter, at least within the uncertainty due to differences in the length of processing for the different families of sites. The merged results are made available through the REASON project (reason.scign.org). Hreinsdottir and Bennett also include the processing of PBO and SCIGN data using an absolute phase-center model, with a focus on the vertical rate and data since 1994. They have completed processing of all of the PBO stations and have completed 70% of the SCIGN stations. They check for offsets at the times of equipment changes and earthquakes and perform first-order evaluations of time series quality.

Work on refining crustal motion maps included the use of both GPS and InSAR observations, with some discussion of whether the results were consistent with one another.

Fialko and collaborators continued work on improvements to InSAR time series analysis using their stacking algorithm. Their method focuses on the suppression of the contribution from individual noisy imagery to the secular rate, where “noisy” is defined as scenes that tend to result in interferograms with a large norm. They compare their results to independent time series methods along a profile across the southern San Andreas Fault and get good agreement. They focus on high-gradient profiles across the Blackwater fault in particular, using data from two overlapping tracks that have different viewing angles. The steep gradient would be interpreted as corresponding to a very shallow (3-5km) locking depth if the entire LOS signal came from horizontal motion. However, they find that a compliant zone 2-3km wide along the fault might be responding to coseismic strain from the Hector Mine and Landers earthquakes, resulting in vertical deformation that contributes to the LOS signal.

Funning, Jin, Houlie and Burgmann estimate the effects of tropospheric water vapor on SAR interferograms and GPS within the Los Angeles Basin. They explore three approaches to assess or mitigate the effects of atmospheric noise, using estimates from surface-based meteorological stations, families of SAR interferograms, and dense networks of GPS sites. They observed tropospheric delays that vary by up to 10 cm at individual GPS sites, with the magnitude of the total delay depending on thickness of the troposphere at each site. The use of collocated weather data suggests shifts of a similar magnitude. InSAR observations made using two sets of scenes each spanning 70 days, but that are separated by only 28 minutes, show that significant variability exists even over timescales where we would not expect to see surface deformation due to the extraction/injection of subsurface fluids, suggesting that atmospheric models must be generated at time intervals that are dense at the timescale of atmospheric phenomena.

Fay and Bennett focused on determining and modeling the vertical GPS velocity field, within a swath extending from south of the Sierra Nevada northeast to the Walker Lane Belt in Nevada. They are particularly interested in the constraints that are placed on buoyancy, rheology and lithospheric stress state. They constrain vertical velocity of 11 sites relative to the average of 5 sites in the Yucca Mountain region, and find rates of +/- 0.5 mm/year with 0.2-0.3 mm/yr precision. They explore several viscoelastic structures and model relaxation due to the 1872 Owens Valley and 1952 Kern County earthquakes, finding that lateral viscosity variations or a more complete catalog of earthquakes may be need to explain the observations.

d. Data collection

Efforts to collect new data or to improve existing catalogs are related to better estimates of interseismic motion, preparations for the next big earthquake and detection and interpretation of transient strain events. SCEC continued support of the strainmeters at Pinon Flat observatory (PFO), which consists of three laser strainmeters and two long-base tiltmeters. This year, the PI’s reported on comparisons between PFO strainmeters and other instruments in Southern California, including those at Durmid Hill and the EarthScope instrumentation (Figure 17). Comparisons between a Plate Boundary Observatory borehole strainmeter installed at PFO with the laser strainmeters show that the latter are more stable at periods longer than a week or two. Data accessibility has been improved significantly through the archiving of all data at the NCEDC, with older data available on request. Standard upgrades and maintenance were performed, including the reconstruction of the long-base tiltmeters, which were damaged by lightning.

McGill, Bennett and Spinler resurveyed 18 (including 3 new) sites in the San Bernardino Mountains – a key region near the junction of several major faults that is poorly-constrained by continuous geodetic sites, and important for understanding deformation in this tectonically complex area. All data are being archived through the SCEC data center by Duncan Agnew. The work was primarily completed by undergraduate students and SCEC interns. They also explored modeling of data from SCEC Crustal Motion Map 3 with slip rates for the San Bernardino and San Gorgonio pass sections of the San Andreas. New observations from their survey are plotted, but not included in the analysis pending assessment of reference frame issues.

Lipovsky, Funning & Miller attempted to resurvey 35 sites in the San Jacinto/Anza region, of which 21 were successfully resurveyed. Previous surveys of these sites range from 1990 to 2009. Rinex files from all the surveys are freely available on their website.

Sandwell and graduate student Brendan Crowell performed rapid static GPS surveys of the region south of the Salton Sea. The surveys included at least three occupations of ~50 densely spaced monuments associated with the Imperial fault and Brawley seismic zone, and the establishment of new, easily located, monument types along irrigation culverts in two locations. All data is being archived at SOPAC. The real-time accuracy had the side benefit of facilitating the identification of some monuments, which were often buried in regions that were resurfaced frequently by farming equipment or road crews.

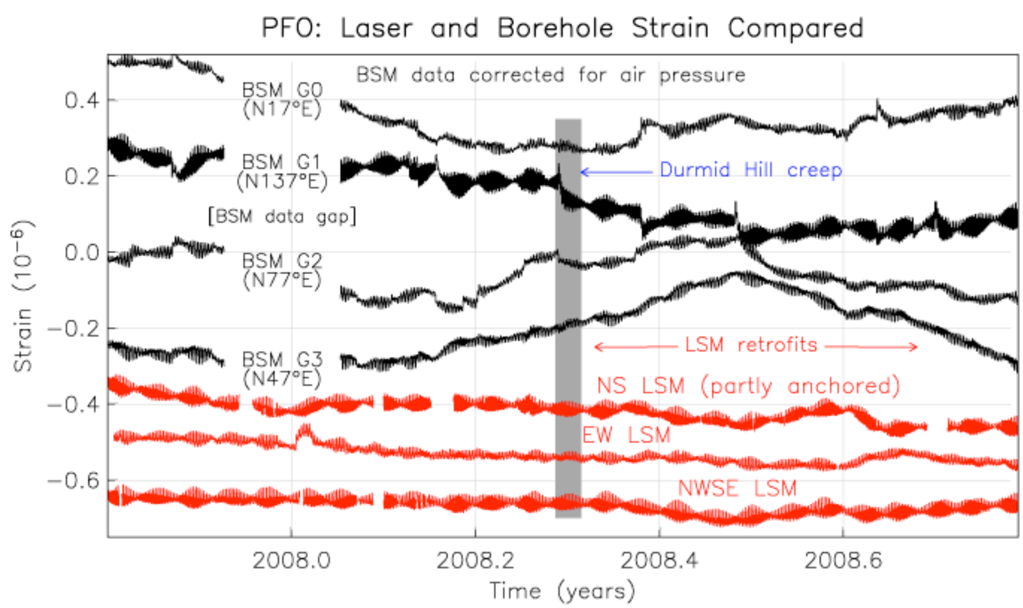

Figure 17. Comparison of most recent PBO borehole strainmeter data (black) and laser strainmeter data (red), both located at Pinon Flat. No signal is observed during the time period where localized aseismic deformation was observed at Durmid Hill.

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3. Earthquake Geology

The SCEC geology disciplinary group coordinates diverse field-based investigations of the Southern California natural laboratory. The majority of Geology research accomplishments in SCEC3 fall under two categories, (1) focused studies of the southern San Andreas and San Jacinto faults in coordination with the SoSAFE (Southern San Andreas Fault Evaluation) special project, and (2) studies of other portions of the southern California fault network toward better understanding fault system behavior. Geology also continues efforts to characterize outstanding seismic hazards to the urban region, and supports field observations related to various focus-group activities. In support to these efforts the Geology group coordinates geochronology infrastructure resources that are shared among various SCEC-sponsored projects.

a. Southern San Andreas Fault Evaluation (SoSAFE)

By focusing the efforts of the geology community, the SoSAFE special project has blossomed into the centerpiece of SCEC3 geology research. The primary objective of the SoSAFE is to develop a comprehensive 2000-yr event history for the main plate boundary structures (San Andreas and San Jacinto faults). As a result of this project several critical data gaps have been filled and exciting new developments have unfolded.

The foremost SoSAFE research target was to develop a paleoseismic site in the northern Big Bend of the San Andreas fault. Information here is desperately needed for correlation of event records from the Carrizo Plain to the central Transverse Ranges [Biasi and Weldon, 2009]. Land-access, drought conditions, and special project funding all aligned to enable new, deeper investigations at the Frasier Park site to begin filling this critical data gap [Scharer et al., 2007]. Work at this site is now externally supported by the NSF tectonics program. The other paleoseismic focus of the SoSAFE project has been in the Coachella Valley – the only portion of the San Andreas fault that has not ruptured historically [Philsobian et al., 2007] and is presumably overdue. The northern San Jacinto fault remains a target of interest for paleoseismology because of the potential trade-off of activity with the nearby San Andreas fault [Bennett et al., 2004; McGill et al., 2008; Le et al., 2008]. SoSAFE-supported efforts to locate a suitable site for investigation are ongoing [Onderdonk, 2008].

The other objective of the SoSAFE special project is to gather new slip-rate and slip-per event data. A highlight is the exciting result from Zielke and Arrowsmith [2008] that numerous, subtle 5m offsets are present along the Carrizo Plain section of the San Andreas fault. These offsets are about half the ~10 m slip attributed to the 1857 Fort Tejon earthquake by Sieh [1978]. This new result agrees well with new paleoseismic recurrence from the Bidart fan paleoseismic site [Akciz et al., 2009]. The net impact of these findings is that great earthquakes on the southern San Andreas fault are about twice as frequent as previously thought. Slip-rate studies within the Big Bend and south have focused on longer time-scales that integrate earthquake behavior. One of these sites, near Palmdale, promises to resolve a long-standing debate on the rate of slip (25 vs. 35 mm/yr) of the San Andreas through the Transverse Ranges (Sgriccia and Weldon, research in progress). Several studies address the long-term slip-rates and trade-off inactivity between the southernmost San Andreas fault and the San Jacinto fault. These include an intensive study of slip-rate and epistemic uncertainty of rate calculations from the Biskra Palms site on the San Andreas [Behr et al., 2008; Fletcher et al., 2007], thorough documentation of slip-rates showing a gradient in activity on the San Bernardino segment San Andreas north of San Gorgonio Pass [McGill et al., 2008], and a multi-site investigation of slip rates and their potential temporal variation on the southern San Jacinto fault [Le et al., 2008; Janecke, 2008]. Much of this slip-rate work is ongoing, but the preliminary results so far suggest that slip on the southernmost San Andreas system involves complex spatial and temporal trade-offs in activity. Results from SoSAFE funding are detailed in the "special projects" section of the annual report.

b. Fault System Behavior

The second major emphasis of the Geology group has been to characterize patterns in fault system behavior that could significantly affect earthquake hazards. This effort specifically addresses earthquake clustering and its potential relationship to temporal variation in fault loading rates. The eastern California shear zone and the conjugate Garlock fault offer the most compelling examples of clustered earthquake behavior and its potential relation to anomalously elevated fault loading [Peltzer et al., 2001; Dawson et al., 2003; Oskin and Iriondo, 2004; Dolan et al., 2007; Oskin et al., 2008; McGill et al., 2009]. As a test of the clustering hypothesis SCEC3 sponsored a paleoseismic study of one of the dextral faults of the shear zone: the Calico fault. Because this fault slips at a rate ~2x its neighbors [Oskin et al., 2007, 2008], it was expected that its earthquake record would show clusters of events during periods of regional earthquake activity documented by Rockwell et al. [2000]. This expectation was confirmed by Ganev et al. (in preparation) who found a cluster of two earthquakes ~5-6 ka (Figure 18), during the penultimate regional cluster documented by Rockwell et al. [2000].

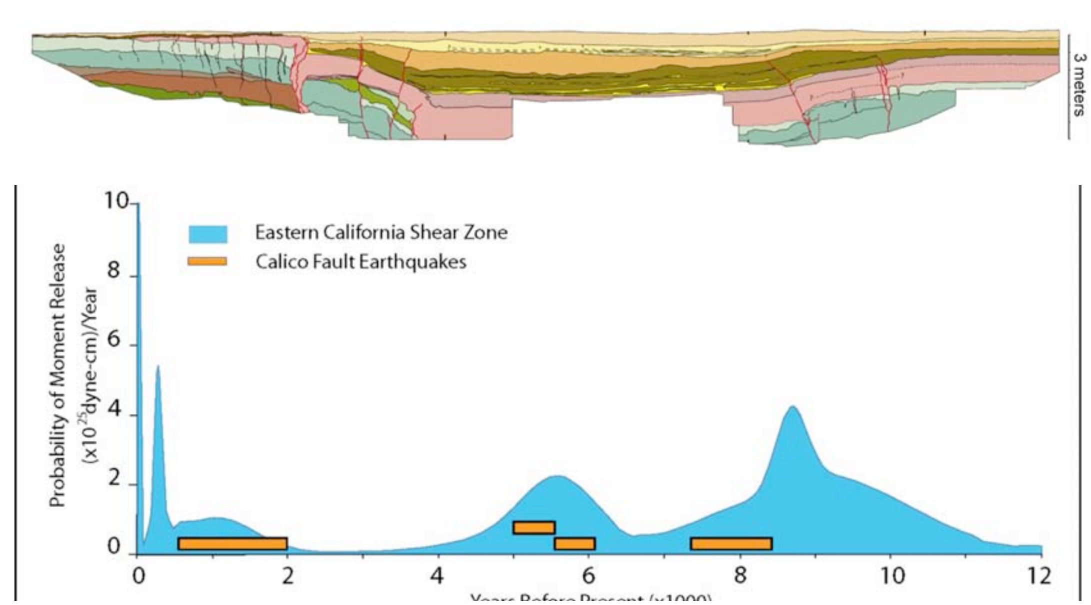

Figure 18. (A) Log of exposure of the Calico fault near Newberry Springs, California. Thickening of units and cross-cutting relationships indicate four event horizons in this exposure. (B) Plot of event ages from the Calico fault against aggregate event probability for the Eastern California Shear Zone from Rockwell et al. [2000]. Calico fault earthquakes fall within regional cluster time periods. Two events are found to lie within the penultimate cluster at 5-6 ka, consistent with the hypothesis that multi-event clusters on the Calico fault contribute to its faster longer-term slip rate than other shear-zone faults. Data from Plamen Ganev, James Dolan, and Mike Oskin.

The multi-site slip-rate study of the San Jacinto fault by Le et al. [in review; 2008] tackles the problem of what processes may drive variations in fault slip-rate over time. By exploiting the multi-stranded nature of the southern San Jacinto fault, she shows that slip-rates may have coherently varied across this system. Because these strands are separated by >5 km throughout the seismogenic zone, their coherent behavior is likely driven by changes in strain rate on a shared ductile shear zone at depth. Work is currently underway to confirm the ages of offset features from multiple techniques in order to rule out systematic errors. Another approach to study of fault system behavior is to examine the repeatability of earthquake ruptures at a site. The Imperial fault is a rare well-documented example that ruptured twice in historic time. In their SCEC3 study, Meltzner and Rockwell [2008] showed that these historic events were anomalously low slip. Their detailed 3-D paleoseismic investigations indicate that larger earthquake slips are more common on the Imperial fault. The significant (factor of ~2) variability in slip per event at this site undermines the characteristic earthquake/slip patch model that is often assumed in the course of seismic hazard estimation.

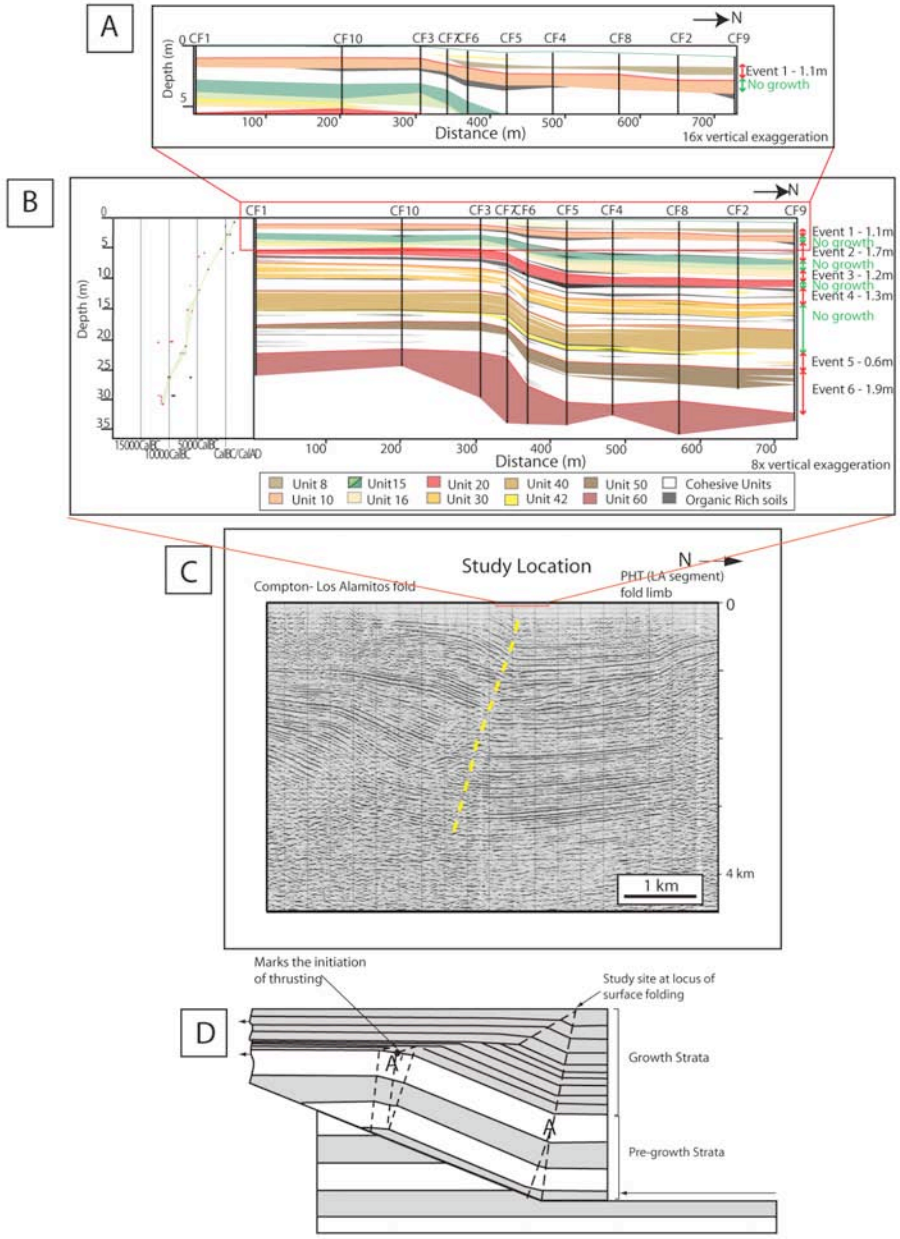

Figure 19. (A) Borehole results from the Stanford Avenue transect. Cross section of major stratigraphic units (16x vertical exaggeration) showing details of the most recent uplift event (Event 1). Vertical lines are boreholes. Green horizontal line is the ground surface. (B) Cross section of major stratigraphic units (8x vertical exaggeration). Colors denote sedimentary units. Thin red lines mark tops of major sand and gravel units. Double-headed red arrows along the side of the figure show stratigraphic range of sedimentary thickening across the transect, with uplift in each event shown in red to the right of each arrow. Double-headed green arrows show intervals of no sedimentary growth. Red box indicates location of cross-section in A. (C) Seismic reflection data across the Los Angeles central trough showing folding associated with Compton Thrust and Puente Hills Thrust. (D) Kinematic model for folding of the hanging wall of the Compton Thrust as it is buried by basin deposits. Data from Lorraine Leon and James Dolan.

c. Blind Thrust Faults

Though Geology's emphasis has shifted away from hazard estimation to process-based studies, SCEC3 continues to sponsor research of major blind-thrust earthquake sources in the urban region. Documentation of activity of blind thrust systems beneath central Los Angeles continues with borehole studies of the Compton thrust, once declared inactive [Mueller, 1997]. More recent data collection clearly shows evidence of activity from thickening of strata across fold hingelines [Dooling et al., 2008]. Work is also in progress to recover a high-precision record of coseismic folding and earthquake timing from a trench investigation of folding above the Puente Hills thrust (Figure 19). Another SCEC3 study targets the Ventura anticline, one of the fastest-moving shortening structures in California. Here work is in progress by T. Rockwell to date emergent beach terraces that record at least four several-meter-high coseismic uplift events in the late Holocene. The magnitude of coseismic uplift on both the central Los Angeles and Ventura folds both suggest that large (M ~7) blind-thrust earthquakes are likely.

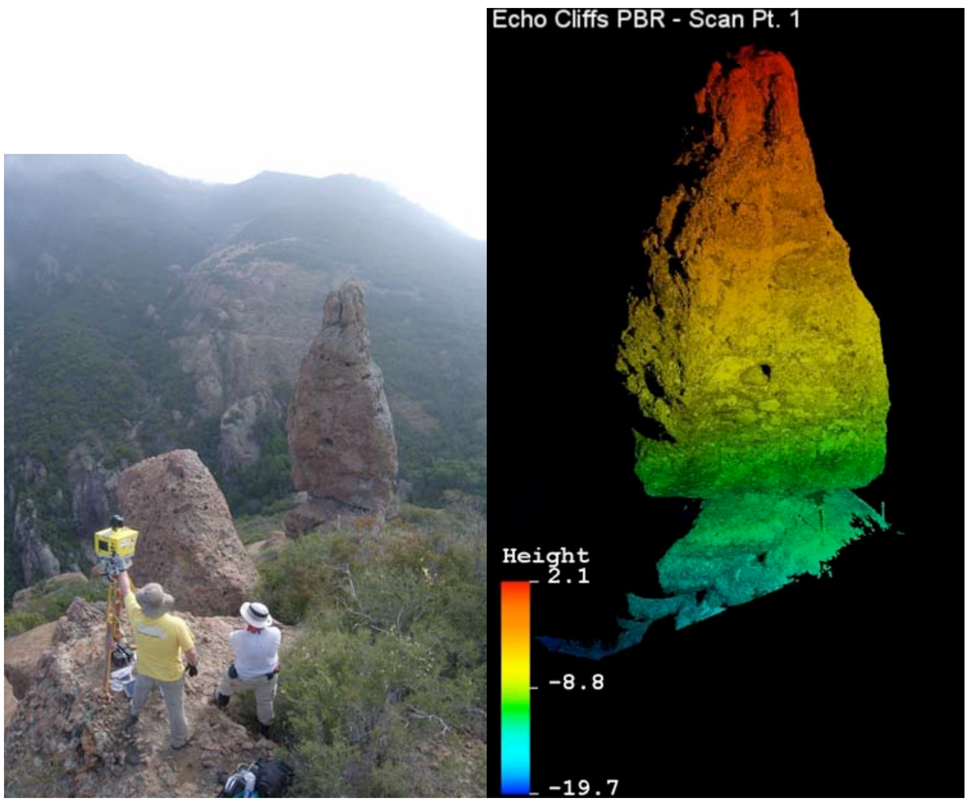

Figure 20. (A) Photograph of precariously balanced rock (PBR) 'Echo Cliffs' and survey team using ground-based LIDAR to image rock geometry (David Haddad, Arizona State University and David Phillips, UNAVCO). (B) LIDAR scan produced in part A, color coded by height above the base of the PBR. This data will be used to more precisely quantify the stability of the PBR during earthquake shaking. Photo and LIDAR image from Ken Hudnut.

d. Shared Geochronology Infrastructure

The shared geochronology infrastructure program represents an important innovation that has greatly enhanced the quality of SCEC3 Geology results. In short, more dates lead to better constraints on earthquake time series and slip rates. By pooling resources under established partnerships (expanded under SCEC3), SCEC efficiently allocates resources and exposes the research community to new techniques/collaborations. SCEC Geology was able to quickly re-allocate geochronology among the various San Andreas trenching studies as needs arose. The collaborations developed under the geochronology program also led to new innovations, such developing applications of surface-exposure dating to precarious rocks (Figure 20) that are important for constraining extreme ground motions [Rood et al., 2008] and an intensive effort to date the Lake Cahuilla shorelines [Verdugo and Rockwell, 2008] to develop a system-level record of earthquake activity from the high slip-rate faults that traverse the Salton Trough.

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B. Focus Group Activities

Within the new SCEC structure, the focus groups are responsible for coordinating interdisciplinary activities in six major areas of research: *unified structural representation*, *fault and rupture mechanic, crustal deformation modeling*, *lithospheric architecture and dynamics, earthquake forecasting and predictability, ground motion prediction*, and *seismic hazard and risk analysis*. The following reports summarize the year's activities in each of these areas.

1. Unified Structural Representation

The Unified Structural Representation (USR) Focus Area develops digital models of crust and upper mantle structure in southern California for use in a wide range of SCEC science, including strong ground motion prediction, earthquake hazards assessment, and fault systems analysis. These efforts include the development of Community Velocity Models (CVM & CVM-H) and Community Fault Models (CFM & CFM-R), which together comprise the USR. The Focus Area also supports the evaluation and improvement of these models. For the CVM/CVM-H, this often involves the comparisons of recorded seismograms with synthetic waveforms generated by numerical ground motions simulations.

This pat year's efforts have been focused on:

1. Improving the Community Velocity Model (CVM-H v. 5.7), by development of independent Vp and Vs models, and the inclusion of updated regional basin models, tomographic models, teleseismic surface wave models, and a bedrock geotechnical layer;
2. Evaluating the CVM and CVM-H models by comparisons of the recorded seismograms with synthetics, including those for the 2008 Mw5.4 Chino Hills earthquake;
3. The development of new, 3D adjoint tomographic models based on CVM-H that offer significant improvements to the crustal wave speed structure;
4. Developing a statewide Community Fault Model, through partnerships with the U.S. and California Geological Surveys, and improving fault representations in the CFM using new relocated earthquake catalogs.

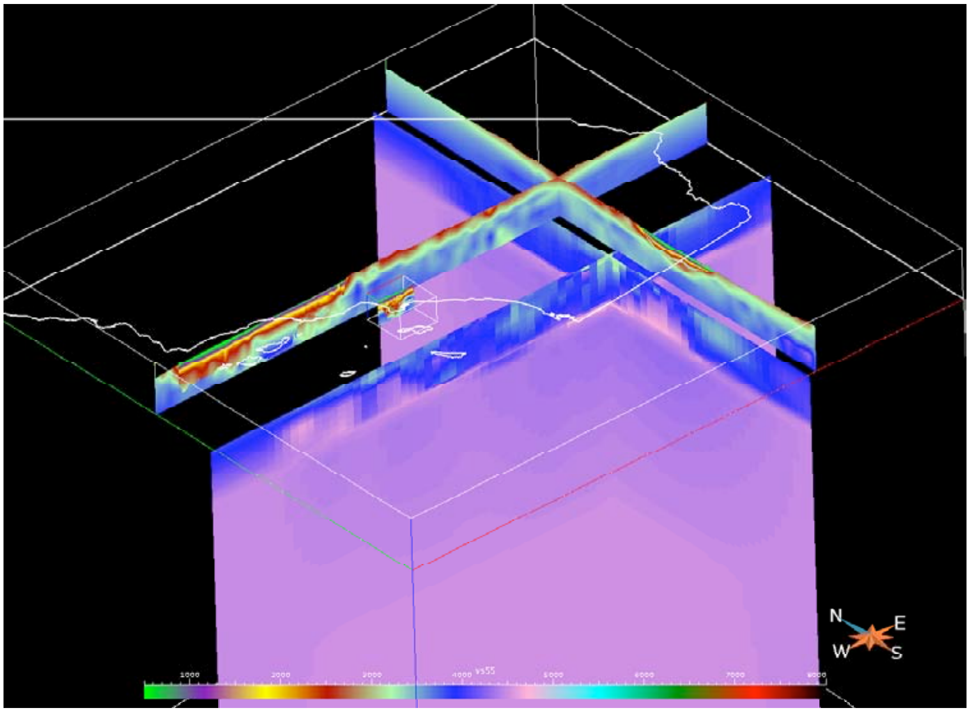

Figure 21. Perspective view of CVM-H 5.5, which includes basin structures embedded in a tomographic model that extends to 35 km depth, which is underlain by a teleseismic surface wave model that extends to a depth of 300km. Vs is shown.

a. Community Velocity Models (CVM, CVM-H)

This past year's efforts involved a series of improvements to the community velocity model (CVM-H) [Plesch et al., 2008; Süss and Shaw, 2003], to better facilitate its use in strong ground motion prediction and seismic hazards assessments. The community velocity models consist of basin descriptions, including structural representations of basin shapes and sediment velocity parameterizations, embedded in regional tomographic models. Enhancements to the community velocity model were implemented in new model versions (CVM-H 5.5, 5.7) released at the 2008 annual meeting and in January 2009, respectively (Figure 21). Model improvements included:

1. New Vp, Vs, and density parameterizations within the Santa Maria basin and Salton Trough;
2. Incorporation of updated Vp and Vs tomographic models (Hauksson, 2000) that extend to a depth of 35 km. These new models were developed by Egill Hauksson at Caltech using the sedimentary basin structures included in the current CVM-H;
3. Addition of a new upper mantle teleseismic and surface wave model that extends to a depth of 300 km. This new model was developed by Toshiro Tanimoto at UCSB using Hauksson's tomographic model as a starting point;
4. Implementation of a new bedrock geotechnical layer (GTL) based on the depth-velocity relations of *Boore and Joyner* [1997]. In this implementation, we used the empirical velocity gradient to scale upwards from the base of the GTL (top of basement), resulting in gradual vertical velocity gradients and lateral variations in velocities at the surface.

In addition, we made a series of enhancements to the structure of the CVM-H and the code that delivers the model. Most significantly, the CVM-H now consists of separate Vp and Vs models, whereas previous model versions consisted of only Vp with Vs and density specified by fixed relations with Vp. We chose to develop separate Vp and Vs models to more faithfully represent data that independently constrain these properties and the nature of the upper mantle models. In addition, we updated the C-code that delivers the CVM-H. These code enhancements were designed to enhance the precision of the model output, and facilitate better the construction of computational meshes and grids used for numerical wave propagation simulations.

b. Evaluating the Community Velocity Models (CVM, CVM-H)

Efforts within SCEC have been initiated to develop an algorithm to systematically examine the goodness-of-fit (GOF) between two sets of broadband ground motion time series (Mayhew and Olsen, 2009). The method includes a set of user-weighted metrics such as peak ground motions, response spectrum, the Fourier spectrum, cross correlation, energy release measures, and inelastic elastic displacement ratios. The GOF algorithm was initially used to evaluate the accuracy of the CVM-H and CVM-S, using synthetics and observed data for the 2008, Mw 5.4 Chino Hills, CA, earthquake. The two CVMs generate similar (and high) levels of goodness-of-fit for this event (see Figure 22). However, at selected sites, one of the CVMs tends to generate a slightly better fit to data than the other; i.e., CVM-S is better at STS and KIK, and CVM-H is better at CHN and LFP. Such comparisons, which have engineering significance, will be improved upon using additional stations, events and bandwidths in the future.

It is also interesting to note that the two CVMs generate some of the best fit to data in a banded area circling the epicenter counter-clockwise from the southeast to the northwest. This result is important, as this area of good fit includes the critical wave-guide corridor (San Bernardino-Chino-San Gabriel basin, CVM-S slightly better than CVM-H), where simulations of large northwestward earthquake rupture scenarios of the southern San Andreas fault (M7.7 TeraShake; M7.8 ShakeOut) produced unexpectedly large ground motions. The favorable long-period fits for Chino Hills include the Whittier Narrows area (e.g., station RUS), where the largest wave-guide amplification was found in the TeraShake and ShakeOut scenarios, as well as the Los Angeles basin. Other areas, such as the southern Los Angeles area (Orange County - Irvine) produce less favorable long-period GOF values and may suggest that improvement of the crustal structure in the SCEC CVM-S (V4.0) is needed here.

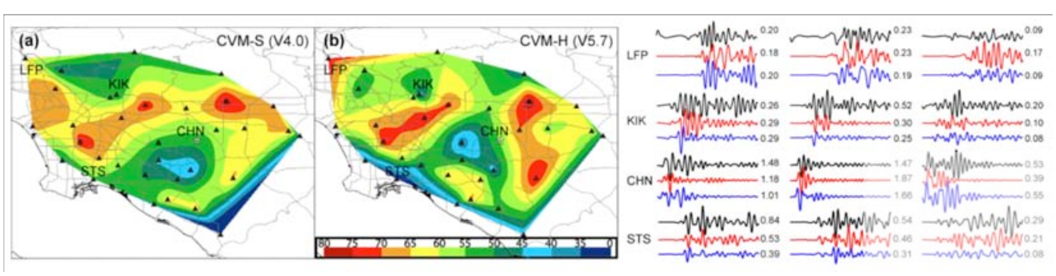

Figure 22. Maps of goodness-of-fit (perfect fit=100) at 0.1-0.5 Hz for synthetics relative to data from the 2008 Mw 5.4 Chino Hills, CA, earthquake. Simulations use (a) CVM-S4.0 and (b) CVM-H5.7. Seismogram comparisons show the E, N, and Z components of the recorded data (black traces), CVM-S synthetics (red traces), and CVM-H synthetics (blue traces) for selected stations, normalized by peak ground velocities (number labels, cm/s).

Additional comparisons of CVM-H and CVM-S were carried out by Robert Graves (unpublished reports, June 2009). As compared to CVM-S, a simulation of long-period (<0.5 Hz) ground motion for the ShakeOut V1.1.0 scenario (Figure 23) in CVM-H generated long-period ground motions (a) generally stronger in the near-field (b) significantly weaker in the LA basin, particularly along the Whittier-Narrows channel, (c) stronger in the Fillmore/Santa Clarita area, (d) stronger in the NW model area, and (e) stronger in the offshore area west of San Diego and Ventura/Santa Barbara. Another difference in ground motion patterns for the two models is a very strong and localized 'bright spot' at the intersection of the Garlock and San Andreas faults (PGV>800 cm/s). These differences in ground motions are clearly related to differences in the two CVMs. Future works should analyze the causes of these differences, and use observational data (e.g., as demonstrated in Figure 22) to estimate the accuracy of the two CVMs in the areas generating large differences in scenario ground motions.

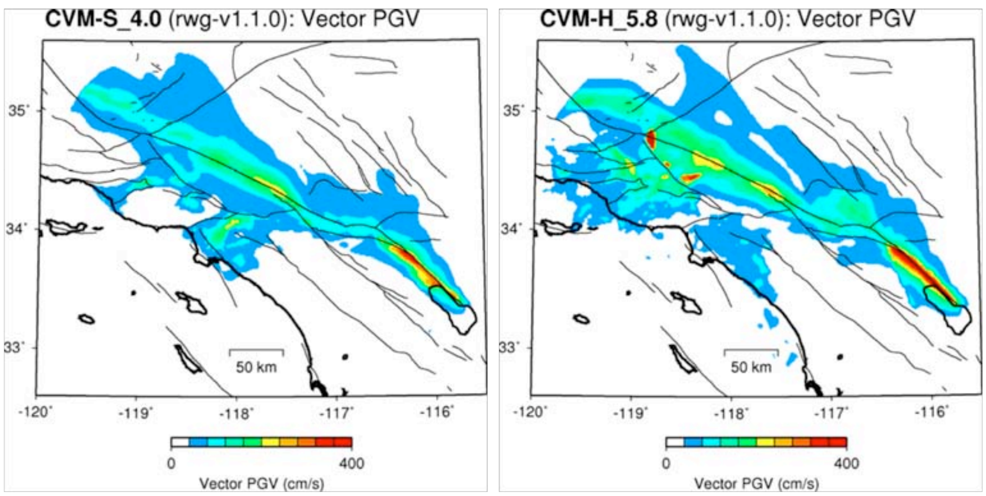

Figure 23. Maps of PGVs for a simulation of the ShakeOut V1.1.0 scenario in (left) CVM-S and (right) CVM-H.

c. Developing the Next Generation CVM

The USR Focus Area also supports the development and implementation of promising new approaches for improving 3D structural representations in future iterations of the community models. Previous efforts have focused on the development of new 3D waveform tomography models of southern California using scattering integral [Chen et al., 2007] and adjoint tomographic [Tromp et al., 2006] methods. Chen et al. [2007] employed this approach to develop the first fully 3D waveform inversion model of the Los Angeles basin, using the SCEC CVM 3.0 [Magistrale et al., 2001] as a starting model. This past year, efforts have focused on developing a 3D waveform tomographic model of southern California using adjoint methods and spectral element (SEM) wave propagation simulations [Tape et al., 2009] (Figure 24).

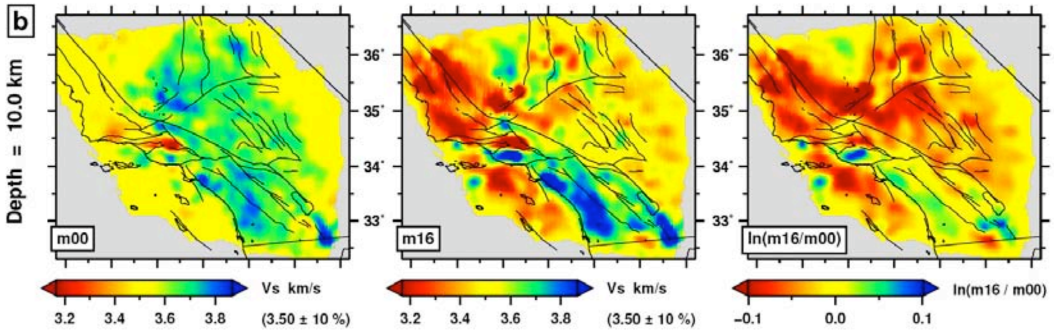

Figure 24. Horizontal sections of Vs adjoint tomographic model: Left, starting model (CVM-H); Center, adjoint model after 16 iterations; Right, model differences (after Tape et al., 2008; 2009).

The new model used an early version of the CVM-H as a starting point, and involved 16 iterations seeking to minimize the differences between simulated and recorded seismograms. This process involved 6800 wavefield simulations and nearly 1 million CPU hours, and yielded a revised crustal model with strong lateral velocity heterogeneity that illuminates a number of major tectonic features. The new model incorporates local changes in wave speeds of up to 30% relative to the background travel-time tomography models in the CVM-H, and clearly highlights key basin structures that were not represented in the original model, such as the San Joaquin basin. The primary goal for the USR Focus Area in 2009 will be to implement this revised velocity parameterization directly into a new version of the CVM-H. This will involve embedding the latest basin structures in the new adjoint tomography model, which will overlie the Moho surface and the underlying teleseismic/surface wave model. Subsequent testing of the model will establish the improvements it offers in simulating strong ground motions for southern California earthquakes.

d. Community Fault Model (CFM)

In partnership with the U.S. and California Geological Surveys, the USR Focus Area has continued efforts to develop a statewide fault model, consisting of the CFM in southern California [Plesch et al., 2007] and new representations of faults in northern California. This process included a SCEC-sponsored workshop in 2008, to review a preliminary statewide model and plan a course for its improvements. Following careful review of each of the preliminary fault representations, the working group agreed that geologic models of the greater San Francisco Bay area, developed largely by the U.S.G.S. (Menlo Park), should serve as the basis for representation in that area of northern California in a statewide CFM (e.g., Brocher et al. [2005]). Moreover, priorities were established for making improvements to fault representations in other areas of the state. These updates are currently being implemented by the working group with the goal of releasing an initial statewide CFM at the 2009 annual meeting. Ultimately, this new model will help improve our assessment of seismic hazards in California, and contribute directly to fault systems modeling activities within SCEC. In a related effort, the CFM in southern California is being systematically re-evaluated using new re-located earthquake catalogs developed by SCEC [Hauksson and Shearer, 2005; Shearer et al., 2005]. These new catalogs provide significantly improved resolution of many faults, and are being used to refine interpolated fault patches for many of the representations in the CFM [Nicholson et al., 2008]. These updates will also be incorporated in a new release of the CFM.

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2. Fault and Rupture Mechanics

The primary mission of the Fault and Rupture Mechanics focus group is to develop physics-based models of the nucleation, propagation, and arrest of dynamic earthquake rupture. We specifically target research that addresses this mission through field, laboratory, and modeling efforts directed at characterizing and understanding the influence of material properties, geometric irregularities, and heterogeneities in stress and strain over multiple length and time scales, and that contributes to our understanding of earthquakes in the Southern California fault system.

FARM studies aim to:

- Determine the properties of fault cores and damage zones and their variability with depth and along strike, including the width and particle composition of actively shearing zones, extent, origin and significance, of on- and off-fault damage, and poroelastic properties.
- Determine the relative contribution of on- and off-fault damage to the total earthquake energy budget, and the absolute levels of local and average stress.
- Investigate the relative importance of different dynamic weakening and fault healing mechanisms, and the slip and/or time scales over which these mechanisms operate.
- Characterize the probability and possible signatures of preferred earthquake rupture direction.
- Develop realistic descriptions of heterogeneity in fault geometry, properties, stresses, and strains, and tractable ways to incorporate heterogeneity in numerical models.
- Understand the influence of small-scale processes on larger-scale fault dynamics.
- Evaluate the relative importance of fault structure, material properties, and prior seismic and aseismic slip to earthquake dynamics, in particular, to rupture initiation, propagation, and arrest, and the resulting ground motions.

FARM encompasses a broad range of basic research aimed at illuminating physical processes of faulting and earthquake rupture mechanics. In 2008-09 research accomplishments included new findings by investigators working on earthquake and faulting problems in field, laboratory and computational settings. Over the past year important progress was made by FARM scientists on a number of fronts, much of this took place through a series of workshops. These workshops are a showcase of our collaborative efforts.

a. Dynamic Fault Parameters

On March 11, 2008, the SCEC-sponsored "Workshop on Dynamic Fault Parameters: What Do We Know, and Where Do We Go?" was held in Pomona, California. The workshop was lead-convened by David Oglesby. 43 people participated. Now that there are extensive computational capabilities for numerically simulating dynamic rupture, the theme of this workshop was how to decide which parameters are appropriate to use in the simulations, so as to best predict earthquake rupture physics and ground motions. Results from the March workshop included a compilation of what is known and guidance about what needs to be done next. Among the consensus views, is that confining pressure is approximately lithostatic to hydrostatic, and that the San Andreas fault likely corresponds to a "strong crust, weak fault" model. For friction, it appears that many mechanisms may lead to slow sliding at high slip rates, and that thermal effects may be particularly important. The bulk of slip appears to occur predominantly in the middle of the seismogenic zone; however, it was emphasize that kinematic seismic inversions determine the velocity of an apparent rupture front that is radiating seismic energy, but this does not necessarily correspond to the rupture velocity in spontaneous rupture models; The resolution of kinematic inversions may be event and data specific; Off-fault damage is an energy sink and it reduces rupture velocity.

An important outcome of the March workshop was a compiled list of future needs. From the observational perspective these included good near-source data, in situ temporally-strategic observations at depth across active faults, and a better understanding of shallow crustal rheology. From the modeling perspective, these included a recommendation that fault friction simulations explore mechanisms other than slip-weakening, including standard rate/state behavior at slow slip speeds and additional weakening mechanisms at fast slip speeds, such as those that involve thermal and chemical effects. The final recommendation, as with the other SCEC workshops this year, was that this is just a beginning and that the conversation should continue.

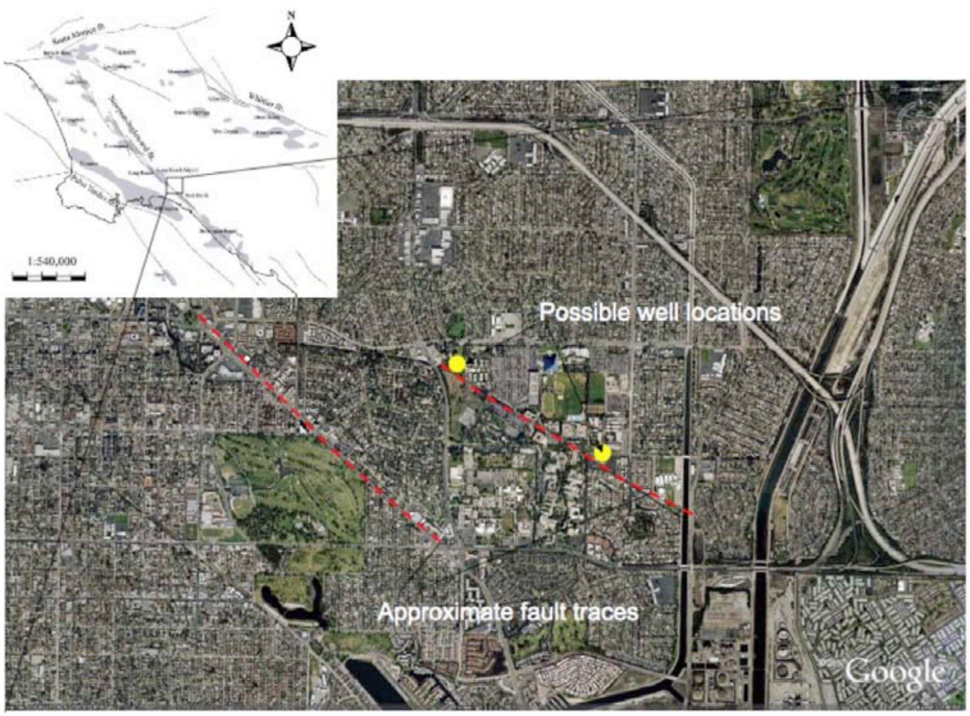

Figure 25. Possible locations of a well for drilling deep into the Newport Inglewood fault. Dashed lines are approximate locations of the Newport-Inglewood fault zone.

b. Newport-Inglewood Fault Zone Drilling

On May 9, 2008 more than 19 scientists participated in a SCEC workshop co-convened with California State University Long Beach and Signal Hill Petroleum. The topic was the Newport-Inglewood Fault Zone Corehole Project. The Newport-Inglewood fault zone produced the damaging 1933 Long Beach earthquake, and it currently cuts through one of the most densely populated areas in southern California, including major societal infrastructure. Critical questions remain about the structure of this fault zone, especially at depth, where most of the seismic energy is released in earthquakes.

The workshop, led on the SCEC front by Ralph Archuleta, presented information about an opportunity (Figure 25) to examine the Newport-Inglewood fault zone fault at depth, especially near the northern end of the 1933 rupture. Signal Hill Petroleum (SHP) is planning a 3D seismic survey, with analysis to be completed in a year. SHP then plans to drill a 3 km hole that would penetrate the fault zone at one or two depths, and collect intact core of the fault zone and its surrounding environment. In addition, there is an opportunity to collect ground motion data by instrumenting the drill hole after the drilling and coring are completed. This will allow for studies of how amplification occurs as seismic waves emerge from bedrock into softer sediments. The SCEC coordinator for this project is Ralph Archuleta.

c. Structure and Formation of Fault Zones

From June 11-12, 2008, approximately 35 scientists participated in the SCEC sponsored workshop 'The Structure and Formation of Fault Zones and their Role in Earthquake Mechanics'. Charlie Sammis was the lead organizer. Invited presenters covered topics including field, laboratory, and computational simulations of fault zones. Themes involved off-fault damage, fault geometry, and the evolution of fault zones. Particular emphases in the discussion sessions included whether or not fault zones record information about recent earthquakes, including size, rupture velocity and direction, and, if fault zone structure affects the dynamics of individual earthquake ruptures.

d. 3D Dynamic Rupture Modeling

The November 17, 2008 '2008 SCEC 3D Rupture Dynamic Code Workshop' led by Ruth Harris included approximately 34 participants, and was convened by SCEC on the Cal Poly Pomona campus. The theme of this meeting had close ties with the SCEC/USGS/DOE Extreme Ground Motions project, and one goal of the ExGM-related part of the project has been to test that other codes can reproduce results presented by Andrews, Hanks, and Whitney [2007] for elastic simulations of dynamic rupture and ground motions at Yucca Mountain. For the first time in the code-comparison exercise, the benchmark assignments tested 2D, in addition to the usual 3D simulations, and this was the first time that the benchmarks moved from vertical strike-slip faulting to simulated rupture on dipping faults (Figure 26). At this meeting the participants also viewed comparisons of results for rate-state friction benchmarks on a vertical strike-slip fault in a wholespace and in a halfspace (to date most rate-state modelers work with vertical rather than dipping faults).

During part of the dynamic rupture code meeting the participants learned about new results from spontaneous rupture simulations that include off-fault yielding, and participated in related discussions about whether or not critical benchmarks in the future, especially those related to Yucca Mountain, should include off-fault non-elastic yielding. Information about the benchmarks (Figure 26) and participants in the SCEC code comparison exercise can be found at the SCEC Code website *http://scecdata.usc.edu/cvws/.* General information about this SCEC collaboration can also be found *Harris et al*. [2009].

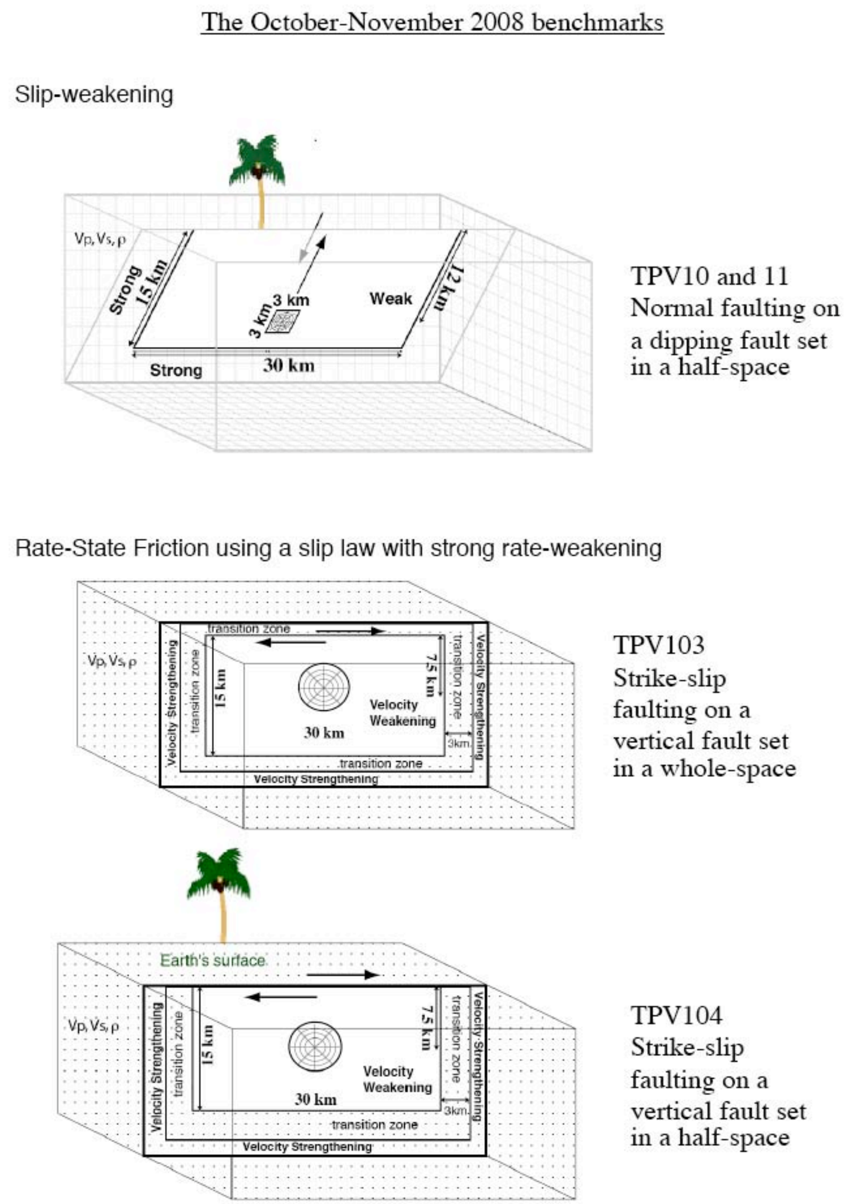

Figure 26. The benchmarks discussed at the November workshop involved slip-weakening on a dipping fault and rate-state friction on a vertical strike-slip fault.

e. Rapid Response Drilling

From November 17-19, 2008, 44 scientists participated in a three-day SCEC co-sponsored workshop on 'Rapid Response Drilling, Past, Present, and Future', in Tokyo, Japan. Other co-sponsors included the International Continental Scientific Drilling Program, UC Santa Cruz, and the University of Kyoto. The talks presented examples of previous work on drilling after large earthquakes, and general information about fault zone drilling in general. Discussion during the meeting presented tradeoffs between rapid drilling and the option of satisfying a diverse range of scientific goals.

Among the topics of discussion were collecting temperature measurements to assess the friction during a large earthquake, obtaining direct stress measurements to assess the magnitudes of stresses on faults, and procuring observations about fault healing mechanisms (Figure 27). A major challenge presented for all of these proposals is that previous drilling studies have found it difficult to find the most recent or most active slip surface. It was recommended that this challenge be confronted with a multi-disciplinary approach involving real-time gas monitoring, core analysis and borehole logs, and continuous coring with high recovery near the suspected slip zones. The SCEC coordinator for this project is Emily Brodsky.

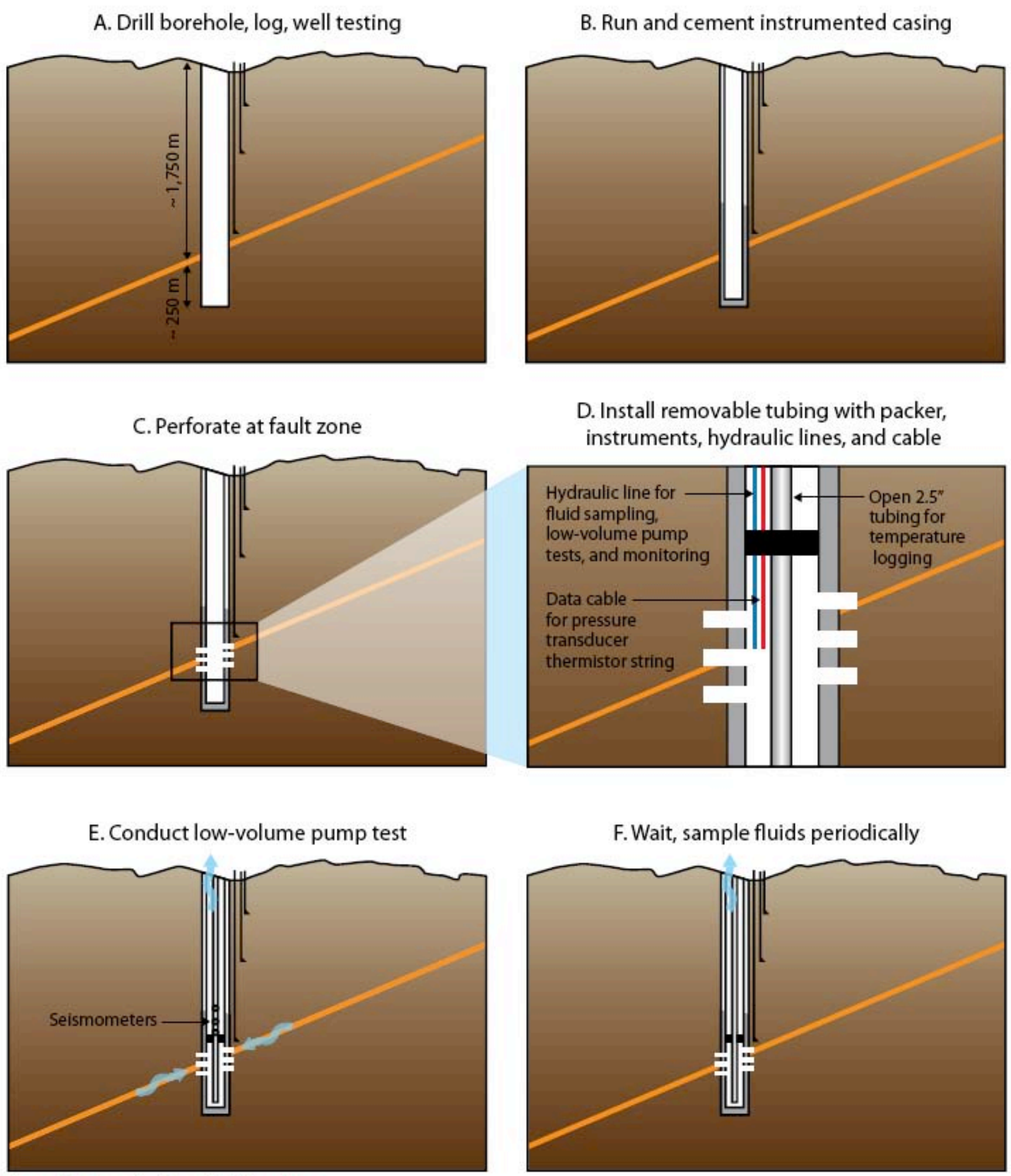

Figure 27. Schematic of a rapid drilling plan.

f. Effects of Rheology/Complex Fault Geometry

In addition to the 2008 workshops, much was learned by SCEC PI's about the effects of fault geometry and rheology on dynamic rupture, ground motions, and sequences of earthquakes. These were mainly elastic studies, but it was also recognized that off-fault behavior that is not elastic likely occurs, for example Dmowska and colleagues numerically showed the effects on ground motions of fault branching, in conjunction with off-fault yielding (Figure 28). Observations and measurements by Dor and colleagues (Figure 29) examined particle contents for off-fault materials, and a number of other FARMers observed, simulated and inferred the interactions between dynamic rupture on a fault and the medium surrounding the fault, providing a more comprehensive picture of fault zone behavior than has occurred in previous years.

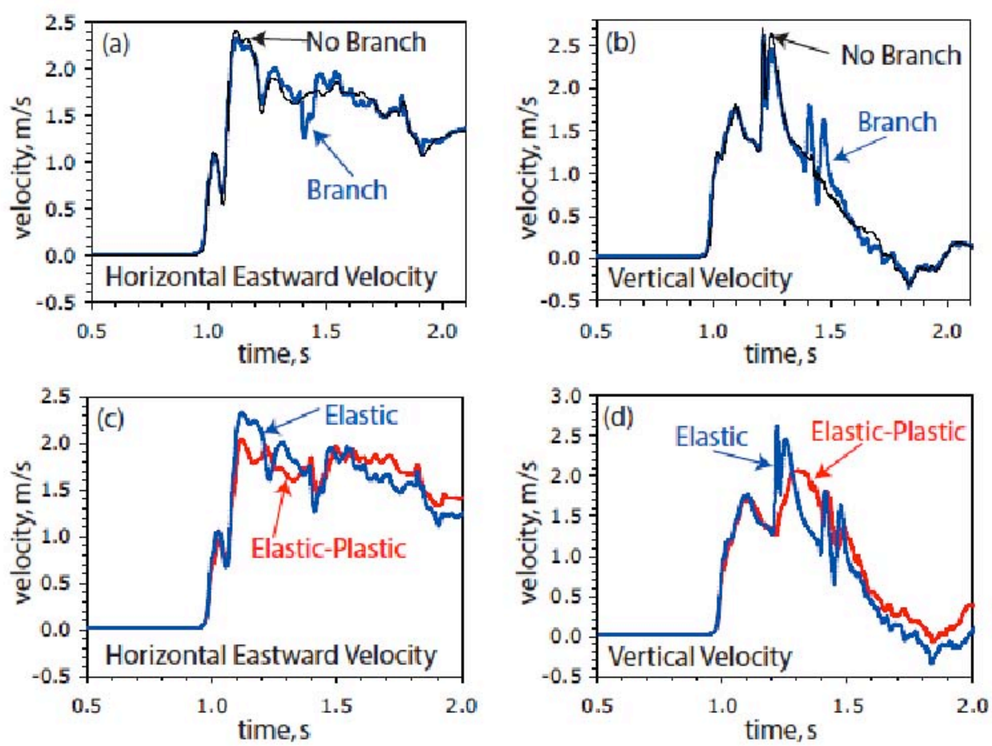

Figure 28. Effects of branch activation (a-b) and elastic-plastic off-fault material response (c-d) on vertical and horizontal ground velocities at the proposed repository site (1 km east of Solitario Canyon Fault, 200 m below the free surface) during supershear rupture of the SCF. Fault geometries that do and do not have a branch in the fault geometry of a dipping normal fault produce different ground motions. There is also a difference in the ground motions if off-fault yielding is included (red curves).

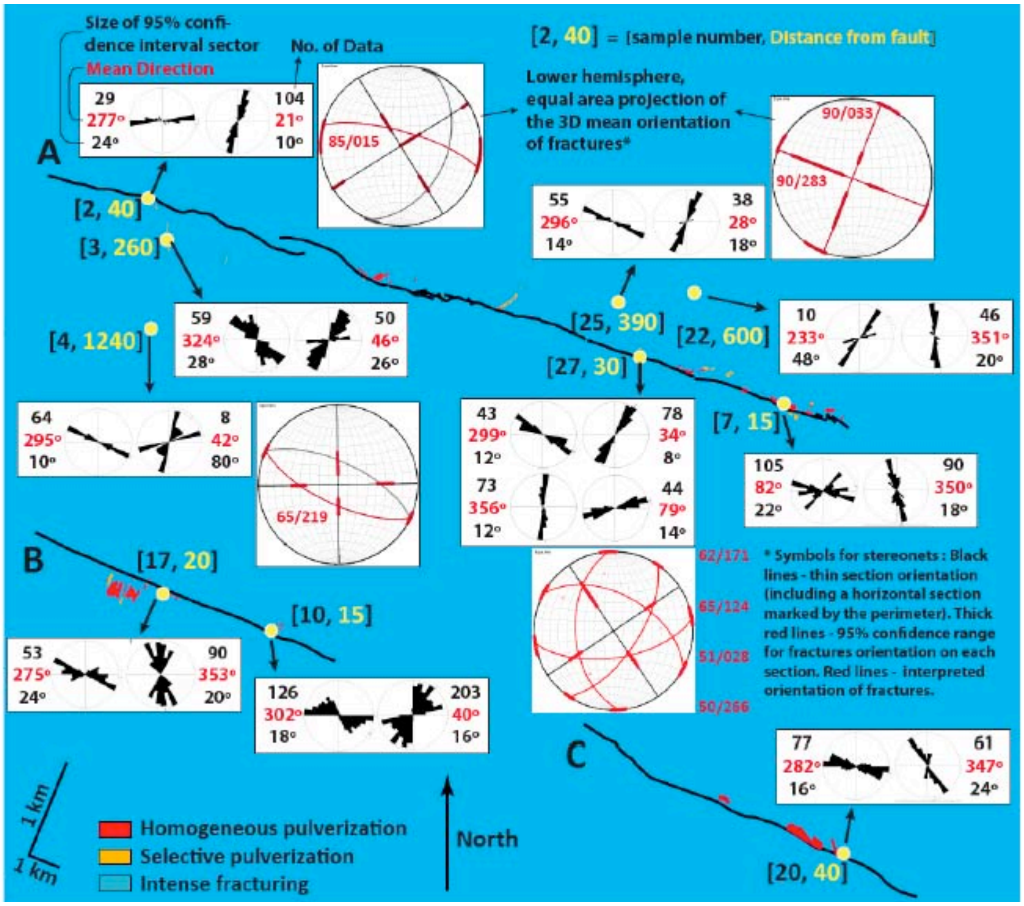

Figure 29. Analysis of data from pulverized rock samples collected along 3 different sections (A,B,C) of the San Andreas fault.

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3. Crustal Deformation Modeling

The SCEC Crustal Deformation Modeling (CDM) group conducts research on deformation associated with fault systems over time scales ranging from minutes to thousands of years, using mathematical models. The ultimate goal of our research is to understand spatial and temporal variations of stresses and stressing rates in the southern California crust, so this information can be incorporated into physics-based probabilistic seismic hazard assessment.

In the 2008 RFP, we emphasized numerical deformation models based on SCEC USR data products (the community seismic velocity model CVM-H; and the community fault models, CFM and/or CFM-R). We also sought studies assessing the level of detail required to adequately model stress evolution in the southern California crust, given available constraints. Progress on CFM-based models is accelerating, and we have begun to identify processes that may safely be excluded from system-wide stress transfer models.

a. Incorporating the SCEC CFM and CVM-H into Fault System Models

This past year, Charles Williams developed a model of southern California lithosphere incorporating 55 faults from the SCEC CFM and elastic properties computed from seismic velocity and density data in the SCEC CVM-H. This model incorporates viscoelastic earthquake cycles for all 55 faults, and is "spun up" to a state wherein modeled velocities have become insensitive to the initial stress conditions. Spinning up the model requires modeling many earthquake cycles for the fault with the longest recurrence interval (tens of thousands of years). Preliminary results illustrate the extensive influence of viscoelastic mantle and lower crust relaxation on the surface velocity field. Models with Newtonian or Kelvin-Voigt viscoelastic mantle and lower crust yield results that differ dramatically from each other and from elastic models. Suites of models are being run with plausible viscoelastic rheologies to assess which are consistent with the GPS velocity field: given slip rates, recurrence intervals, and penultimate event timing for the most important (high slip rate) faults. Currently, these fault parameters are based on UCERF 2. Implementation of power-law rheology and afterslip (not funded by SCEC) and new southern California models incorporating these rheologies are planned.

Kaj Johnson is doing something similar, using a combined boundary element + semi-analytical approach he has used to model active fault systems in several parts of the world. His preliminary models are based on the SCEC CFM, and incorporate both afterslip (at constant stress) and viscoelastic relaxation. He models various viscosity structures, including one based on his models of postseismic deformation in the Mojave region, thus taking the first step toward requiring a single lithosphere model to explain deformation over a variety of time scales. Like Williams' models, Johnson's models show that viscoelastic mantle relaxation contributes a significant, long-wavelength term to the interseismic GPS velocity field (Figure 30). This perturbation is sufficient to complicate efforts to invert GPS velocities for slip and locking rate with elastic models. However, it may be essentially stationary, except shortly after a large earthquake. Johnson has also inverted for interseismic creep rates (and level of uncertainty for these estimates) along the San Andreas Fault, taking into account simultaneous surface velocity contributions due to slip on all modeled southern California faults.

As Johnson and Williams continue to focus on a suite of realistic rheologies and lithosphere structures, we will soon have our answer to the question, do we really have to spin up all of our southern California stress transfer models to calculate stress accumulation on active faults over the next few decades? If a wide range of reasonable models gives somewhat stationary velocity contributions from viscoelastic relaxation of the mantle, for example, we may be able to just correct the GPS velocity field and carry on with elastic stress transfer modeling (e.g. Smith-Konter and Sandwell [2009]) for first-order solutions. For models incorporating stress-driven fault creep, viscoelastic relaxation, and other processes to address stress evolution between earthquakes, it may be sufficient to apply a traction-free boundary condition at the mantle asthenosphere. This could reduce computation time and increase the number of models we can run, leading to better estimates of poorly known fault parameters and stress transfer.

Brendan Meade (Harvard) has continued his work refining and improving kinematic block models of southern California. For the first time, his models of the region incorporate fault geometries from the SCEC CFM-R, and for the Puente Hills thrust fault, the CFM. Much of his work in 2008-09 has involved coming up with a reliable method to get the CFM into a format suitable for block modeling; this was a large enough task to merit a publication [*Meade and Loveless*, submitted, 2009]. The results of his modeling study (including slip rates for all CFM faults) will be described in a paper to be submitted this summer (2009).

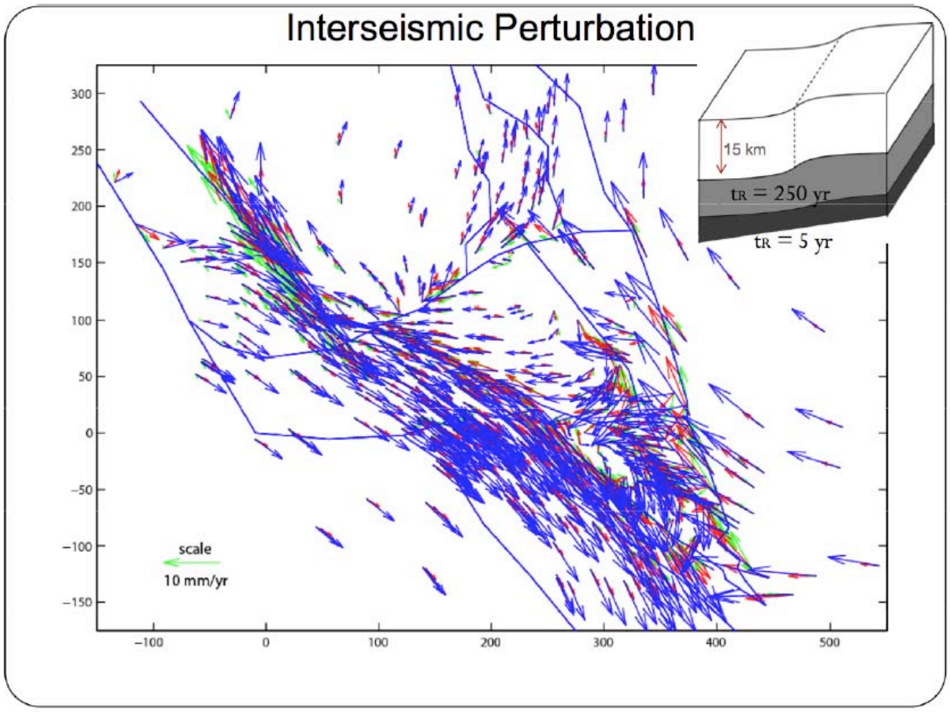

Figure 30. Interseismic velocity field perturbation relative to an elastic model, midway through an 1857-SAF earthquake cycle, due to viscoelastic relaxation (from Kaj Johnson). Indicated Maxwell times yield the velocity field perturbation shown with blue arrows. This model suggests significant viscoelastic contributions to the velocity field from relaxation of the mantle.

b. Models of Smaller, Geometrically Complex Regions

Brad Hager (MIT), his senior PhD student Jiangning Lu, Charles Williams, and Carl Gable (Los Alamos), have developed detailed elastic finite element meshes of the Ventura Basin region. Two sets of models, incorporating the CFM and CFM-R faults in this region, were developed, and heterogeneous elastic properties were assigned based on seismic velocities and densities from the CVM-H. The elastic models show that the CFM-R is not adequate for representing faults in this region, suggesting that the CFM (with its triangulated surfaces) should be used in models of areas with closely-spaced, geometrically complex faults. Hager's group also quantified the dramatic effect of elastic heterogeneity on deformation in the Ventura Basin. Modeled displacements differ from those predicted by a uniform elastic model by 30 to 100%.

Michele Cooke (U. Mass.) continues to investigate the kinematics of the San Gorgonio Pass and the LA Basin, using 3D elastic boundary element models. These models incorporate SCEC CFM fault geometries, constrained principally with uplift and fault slip rates. One goal of the San Gorgonio Pass work has been to actually refine SCEC CFM fault geometries at depth in this area, as well as estimating slip and stress accumulation rates [Dair and Cooke, 2009].

c. Other Crustal Deformation Modeling

Noah Fay (Arizona) and Thorsten Becker (USC) are using ABAQUS develop visco-plastic, dynamic FE models of the southern California lithosphere. Their models address fault loading and crustal stressing over the long term, without EQ cycles. They are not based on the SCEC CFM as they assume a simplified fault geometry and use plastic elements, rather than surfaces, to represent faults. Tractions from mantle convection models, buoyancy forces from estimates of gravitational potential energy variations, and velocity boundary conditions drive the deformation, and fault strength is varied to fit fault slip rates and GPS surface velocities. Figure 31 shows how variations in fault strength control patterns of surface velocities and crustal stresses. This modeling is distinct from most other CDM group efforts because it offers estimates of absolute stresses in the upper crust. Aside from the effort of Hearn and Fialko [2009], which addresses only the shallowest crust in a small region, this is unique.

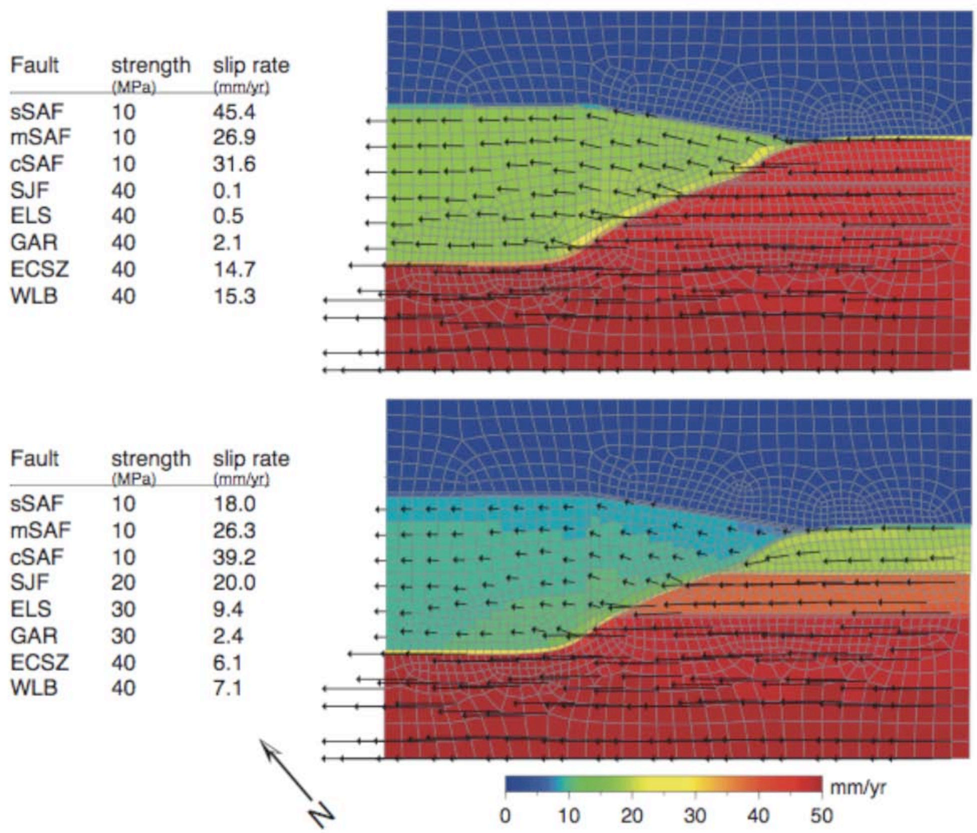

Figure 31. Results from Noah Fay and Thorsten Becker's lithosphere deformation models, showing how fault strength affects time-averaged surface velocities and slip rates. These models are not based on the SCEC CFM and do not explicitly include earthquakes, but they may provide valuable insights on the absolute strength of faults.

Another newly updated modeling study based on a simplified (non-CFM) representation of faults by Bridget Smith-Konter (U. Texas El Paso) addresses stress accumulation over a long history of paleoseismically-constrained SAFZ earthquakes [Smith-Konter and Sandwell, 2009]. Estimates of stress accumulation over past few thousand years are provided, as well as analyses of model sensitivity to uncertainties in fault slip rates and other parameters. Figure 32 shows how these stress accumulation rates, which are estimated with purely elastic models, differ from an estimate based on a model incorporating viscoelastic relaxation [Freed, 2007]. SCEC-supported viscoelastic earthquake cycle modeling (described above), together with improved surface velocity constraints near the SAF should address the extent to which viscoelastic relaxation of the lower crust and upper mantle affect stress accumulation estimates. Smith-Konter also points out that uncertainties in the length extent of large earthquakes (such as the 1857 SAF earthquake) could map to very large uncertainties in integrated stress accumulation along other SAF segments (because of differences in coseismic stress transfer).

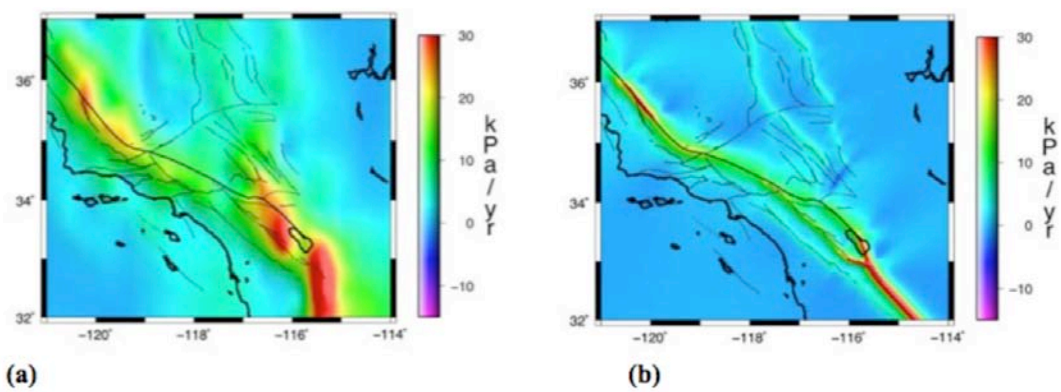

Figure 32. Stress accumulation rates for models with (left) and without (right) viscoelastic mantle relaxation (from Freed, 2007 and Bridget Smith-Konter, respectively; figure supplied by Bridget Smith-Konter). The model with viscoelastic relaxation at depth introduces a longer wavelength component to the stressing rate patterns. Better resolution of the GPS velocity field near faults, and more earthquake cycle modeling (with realistic rheologies and heterogeneities that are consistent with observed postseismic deformation) may help resolve which representation of stressing rates is closer to the truth.

d. Fault System and Damage Evolution

Modeling by Elizabeth Hearn's PhD student Yaron Finzi (UBC), in coordination with Yehuda Ben-Zion (USC), addresses whether damage evolution could significantly influence static stress transfer among southern California faults. Away from faults, modeled damage levels are low (except in the top few tens of meters): damage rapidly localizes to narrow zones, which appear to simplify geometrically as time progresses. Modeled fault damage zones are narrow at depth (in agreement with seismic and geologic observations) and may be treated as frictional surfaces. At depths of less than about 5 km and at extensional stepovers and bends, a highly softened damaged zone with essentially unchanging elastic properties is also present, and may locally affect stress transfer [Hearn and Fialko, 2009] and perhaps rupture propagation. These zones, also imaged with seismic methods, InSAR (e.g. Cochran et al., [2009]) and LIDAR [Wechsler et al., 2009], are up to 2 km wide at the surface along fault segments, and may be even wider at stepovers. These permanently softened zones achieve essentially steady dimensions and damage levels early in Finzi's simulations, and evolution of damage levels (and hence elastic properties) over earthquake-cycle time scales is minor. This work suggests that implementation of a brittle damage rheology in the upper crust is not needed for modeling static stress transfer among southern California faults.

e. NMCDEF Workshop

The CDM group continues to partner with the NSF and the Computational Infrastructure for Geodynamics (CIG) to sponsor the annual Numerical Modeling of Crustal Deformation and Faulting (NMCDEF) workshop at the Colorado School of Mines in Golden, Colorado. This well-attended workshop (now capped at 60 participants) includes tutorial sessions for meshing and finite-element modeling codes, as well as opportunities to provide feedback on CIG code development and participate in online benchmarking exercises. Presentations on topics such as experimental and theoretical constraints on lithosphere and fault zone rheologies have become more frequent in recent years. This meeting provides valuable hands-on training for graduate students and postdoctoral fellows, as well as a unique opportunity to solve modeling difficulties by brainstorming with like-minded researchers.

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4. Lithospheric Architecture and Dynamics

a. P/S Structure

Gene Humphreys' group has presented new P and S wave tomographic images based on finite frequency inversions (Figure 33). The travel times at a given station were corrected for crustal effects by ray tracing through the SCEC Harvard community velocity model (CVM and Thurber's crustal model, discussed below). The resulting images of mantle velocity variations exhibit high velocities under the southern Great Valley, and an east-west feature under the Transverse Ranges that extends to depths of 265 km. Both structures are attributed to dynamically important downwellings. Low velocities beneath the Salton Trough extend down to only ~180 km, and are especially pronounced in the S wave model.

Thurber developed a new crustal P and S crustal wavespeed model using the adaptive-mesh double-difference method, that incorporates data from the LARSE I and II profiles, as well as earthquake data. Significant differences are seen with the present version of the CVM in the upper 6 km. Methods of verification and updating of that model need to be developed (Figure 34).

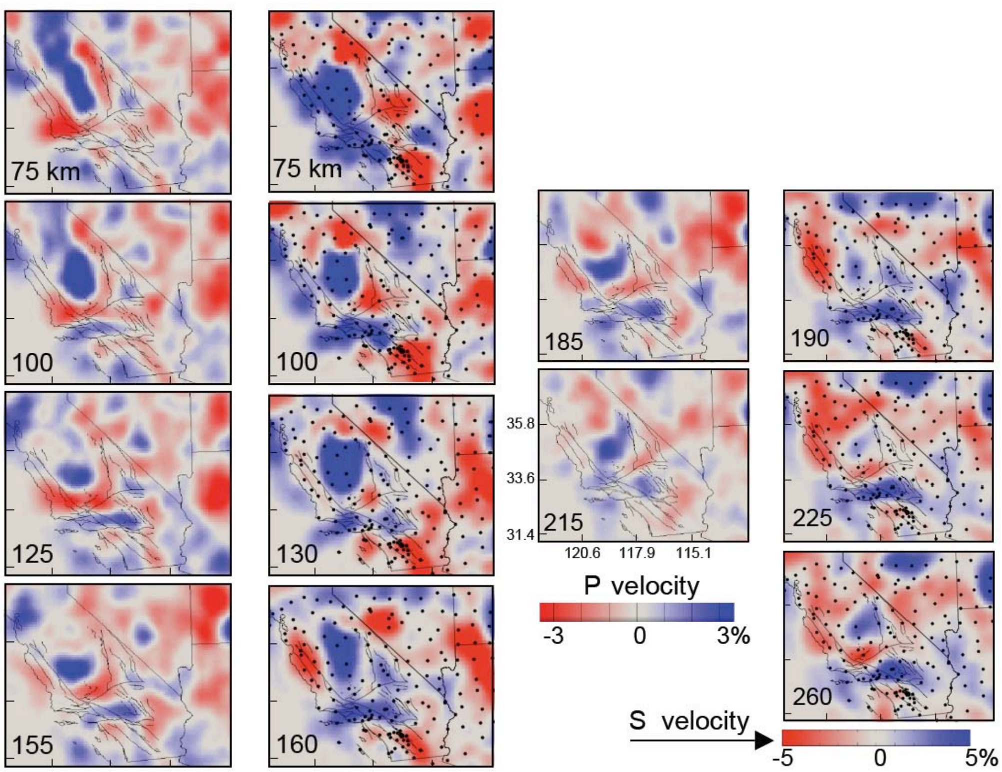

Figure 33. Finite frequency P and S velocity model cross sections at depth (km).

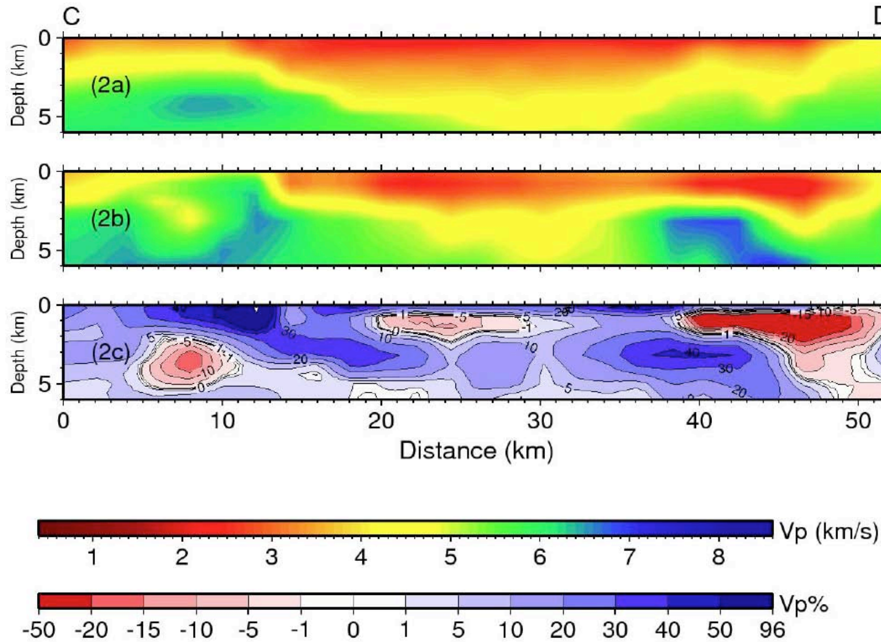

Figure 34. New crustal P-wave velocity model [Thurber, 2008] along the LARSE II line (though Malibu) based on double difference tomography and incorporating LARSE data. The three rows of panel shows (top) the starting CVM-H model, (middle) new model, and (bottom) the velocity perturbation of the new model relative to CVM-H. Significant differences from the CVM are apparent.

b. Anisotropy

The SKS splitting map has been updated and extended to include central and northern California stations (Figure 35). North of the Transverse Ranges splitting directions are parallel to the absolute plate motions of the Pacific and North American plates making a rapid transition near the San Andreas Fault (SAF), but south of the Big Bend they remain more parallel to the North American plate and do not make the transition to Pacific plate motion. Figure 36 shows southern California splitting values, corrected for splitting in the upper 100 km as determined by surface waves [Prindle et al., 2002], with absolute North American plate emotion vectors plotted on top. The degree of parallelism is so close that in many cases the underlying splitting vector is obscured. A tendency towards Pacific plate motion is seen in west-southern California, but for most stations west of the SAF including those in the Peninsular Ranges, nominally on the Pacific plate, the directions are parallel to the North American plate motion.

This puzzling behavior was recognized by Silver and Holt [2002] in which they proposed that a west directed flow in the mantle, possibly connected to the sinking Farallon plate, was needed to explain the difference. However the expected transition to Pacific plate motion west of the SAF does occur further north. Perhaps mantle flow related to the deeper structures found from tomography, if those structures are attached and moving with the North American plate could provide the explanation. Also Figure 36 shows that while directions are mostly parallel to NA plate motion values of splitting can be quite varied at nearby stations. Whether this is due to noisy data or associated with small scale motions in the mantle needs to be investigated.

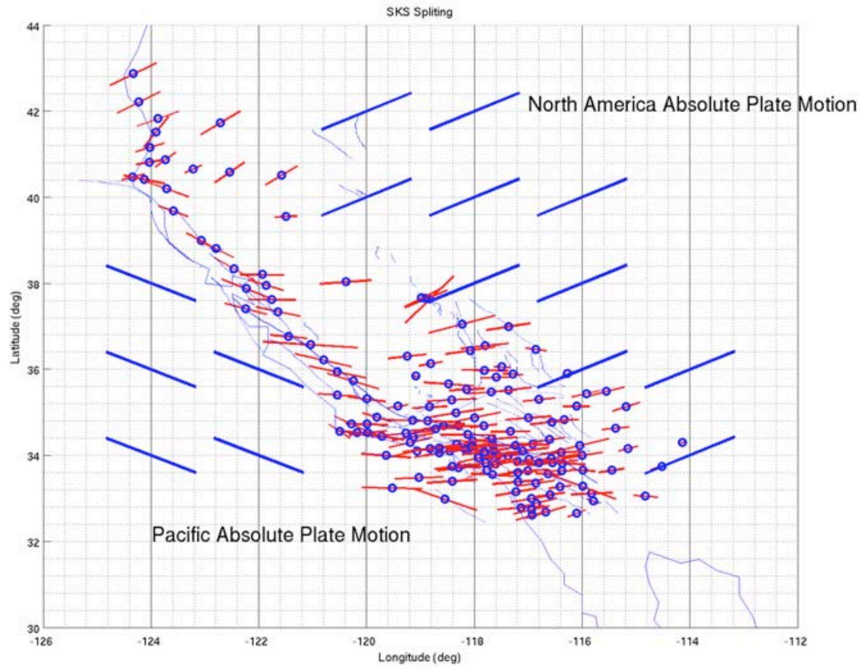

Figure 35. SKS splitting in southern California west of the San Andreas Faults splitting is more aligned with North American than Pacific plate motion. Perhaps movement of the deeper structures in the mantle shown in Figure 33 are affecting the asthenospheric flow as the North American plate moves WSW.

Zandt is examining receiver functions RF in order to obtain seismic properties of the lower crust including anisotropy. A large negative polarity contrast with depth is seen in the middle crust beneath the LARSE 1 line, that ran across the San Gabriel Mountains through Azusa, followed by a positive contrast associated with the Moho (Figure 37). Converted RF phases at the Moho have tangential energy. Both these observations are explained as due to the lower crust being composed of under-plated schist related to relative motion of the Farallon and North American plates (Figure 38).

Estimates of lower crustal anisotropy show that, while anisotropic, it is too small a region and too low an anisotropy to explain SKS splitting. Similarly various estimates (Surface waves, splitting from local earthquakes) of upper crustal anisotropy show that splitting is of order 0.1 s again not a significant part of the splitting signal.

In summary anisotropy in southern California can be separated into at least 4 layers (1) the upper crust with about 0.1 sec splitting with fast axis north-south, possibly associated with cracks and structures related to N_S compressive stresses, (2) lower crust with a similar splitting value oriented NE associated with underplaying of schists such as Catalina etc., at the time of subduction, (3) Mantle lithosphere with variable fast directions, but a coherent pattern in the Big Bend region aligned with structures caused by the transpression and (4) deeper asthenospheric values that amount to 1.5 s splitting and for most of the State are aligned with absolute plate motion, but in southern California is at a large angle to Pacific plate motion, for reasons we do not completely understand. A version of the CVM could be developed that includes anisotropy.

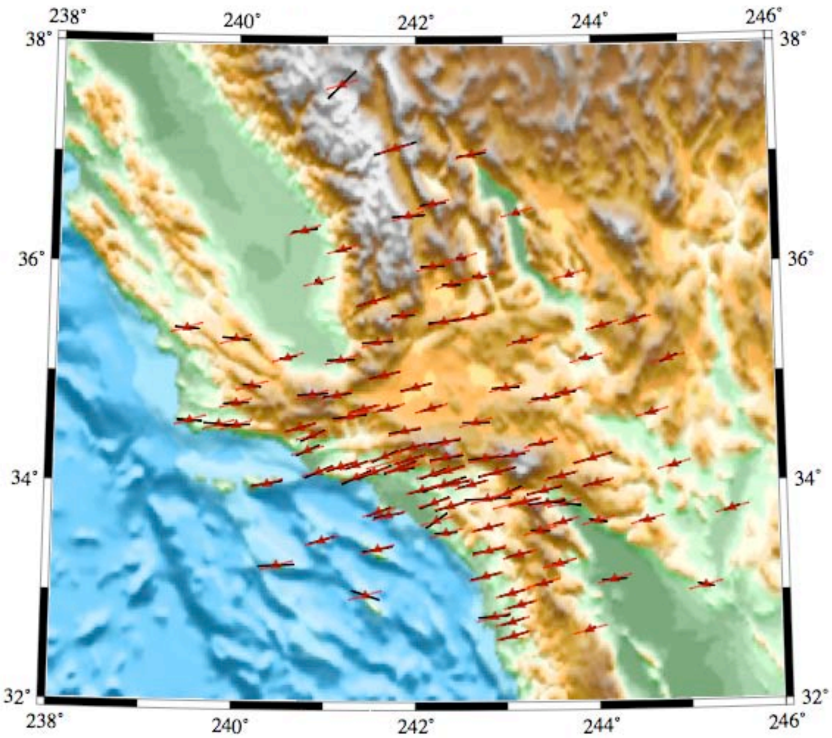

Figure 36. SKS splitting and Apparent plate motion. Black lines give SKS splitting directions. Red lines are North American absolute plate motion relative to the stationary mantle hot-spot reference frame. The disagreement with Pacific plate motion (NW) west of the SAF, suggests that asthenospheric flow does not follow plate motion in Southern California, but may in northern and central California (Figure 35).

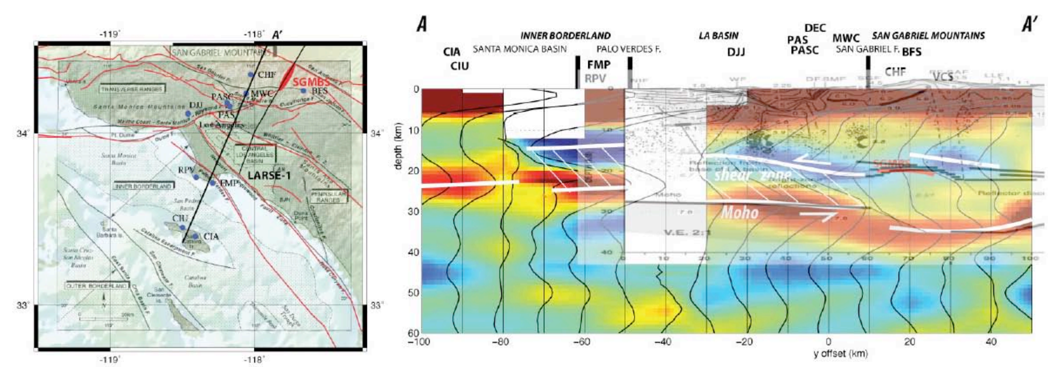

Figure 37. Moho variation (red) lies beneath an anisotropic low velocity layer (blue) in the lower.

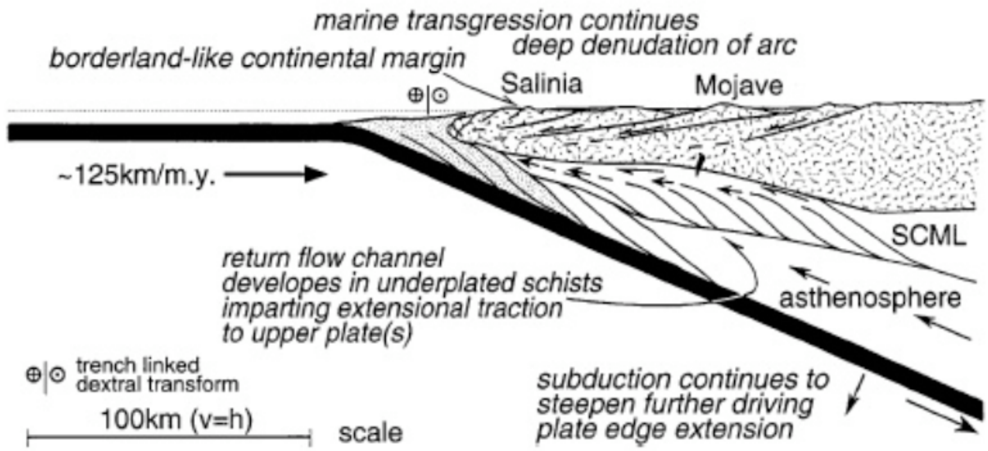

Figure 38. Interpretation of lower crustal anisotropy based on Saleeby model. Under plated schist associated with relative motion of the Farallon slab and NA plate develops a fabric that can explain tangential energy in receiver functions.

c. Viscosity of the Lower Crust and Mantle

Fay and Bennett have used vertical motion of long-term, low-noise GPS time series to constrain the viscosity of the lower crust/upper mantle. After taking into account vertical uplift from glacial rebound they model expected vertical motions from major past earthquakes (Owens Valley, Kern County,) to infer viscosity structure (Figure 39). Their preferred model is one where the lower crust has higher viscosity than the mantle e.g. (1021 Pa-s versus 1020 Pa-s). However no single layered model fits all data, and lateral variations in viscosity, or effects from more recent events may need to be taken into account. Similar 2-layer viscosities are assumed by Johnson. They use lower crustal and uppermost mantle viscosity of 1020-1021 Pa-s with mantle viscosity of about 1018-5x1018 Pa-s.

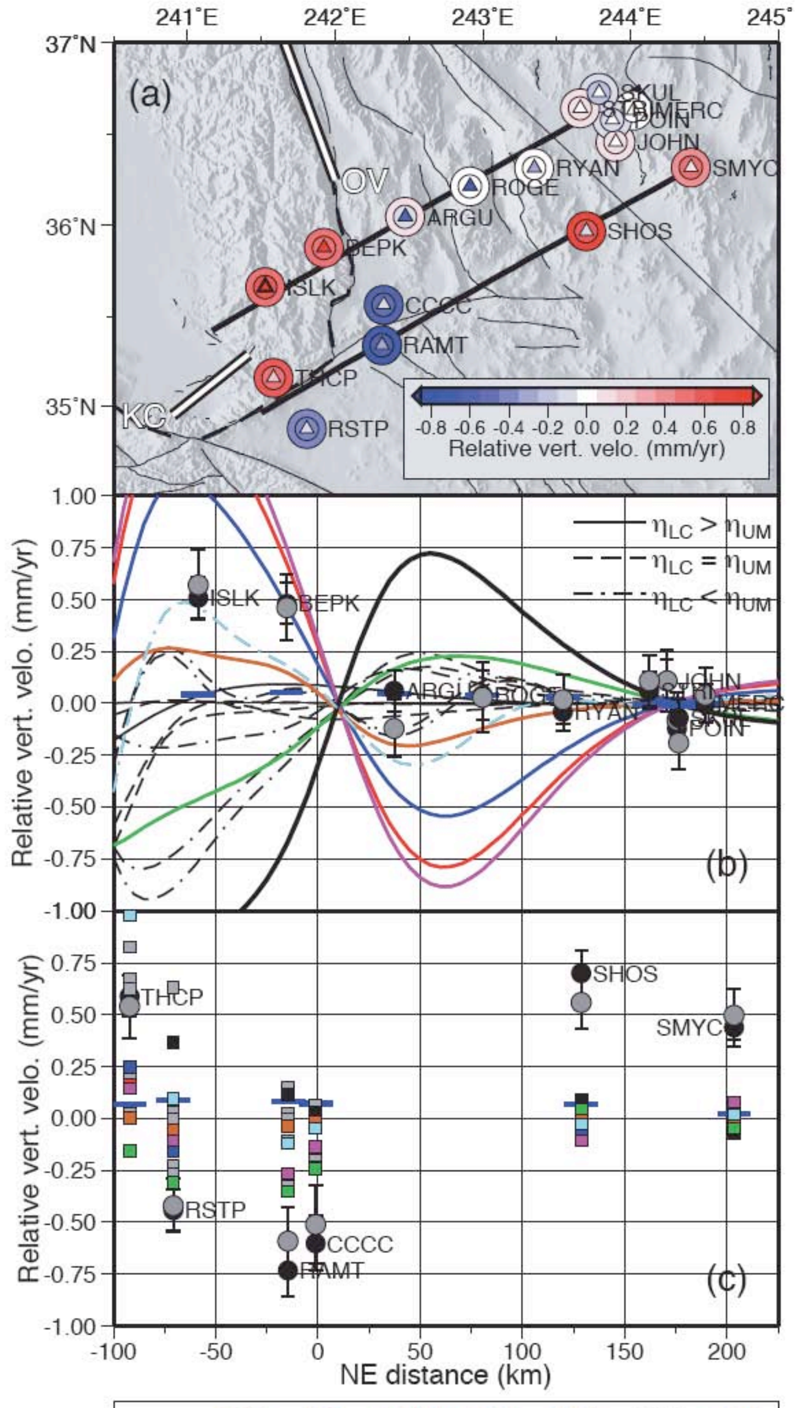

Figure 39. Post-earthquake (Owens Valley and Kern County) vertical motions compared with modeled values based on assumed viscosities of the Lower Crust (LC) and Upper Mantle.

d. Dynamic Models of Lithospheric Deformation

Becker's group is developing finite element models (SMOG3D) to understand driving forces, fault strength and rheology. They model curved faults with large off-fault strain similar to that observed geodetically (Figs 40 and 41) and the interaction of the San Andreas, San Jacinto (SJF) and Elsinore (ELS) faults and conclude that if only fault strength is varied to accommodate the geodetically observed distribution of slip-rates, the strength of the ELS must be larger than that of the SJF, which must be larger than that of the SAF Indio by at least a factor of 3 and 2, respectively. The results show that the models can be used to test several suggested forces acting upon southern California faults include in crustal as well as mantle tractions.

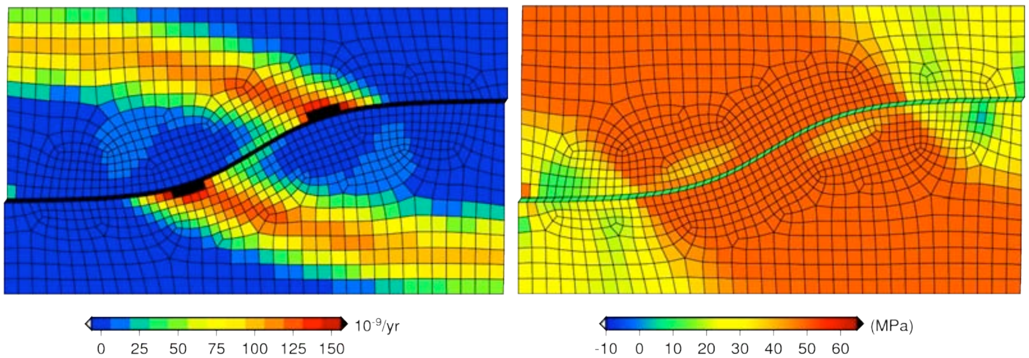

Figure 40. Finite element model used to describe stress and strain in southern California. Left panel shows square root of the second (shear) invariant of the strain tensor at 5 km depth. Color scale emphasizes off-fault strain (nano-strain/yr). Shear strain is off scale in the fault zone and would otherwise dominate the plot. Right panel shows square root of the second invariant of the stress tensor at 5 km depth.

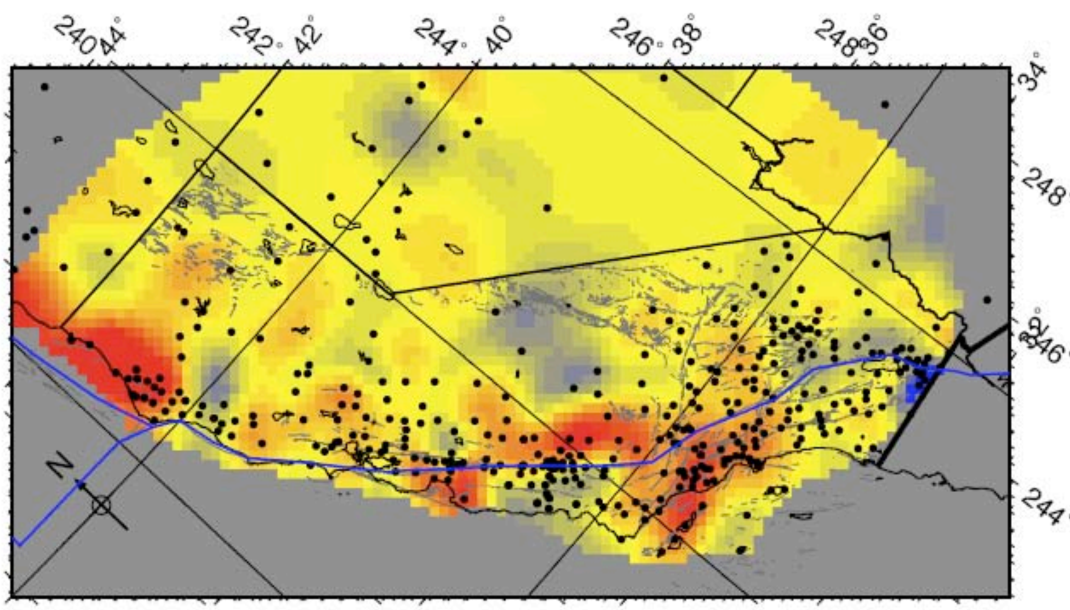

Figure 41. Dilatational strain inferred from high-quality GPS sites against which models are tested.

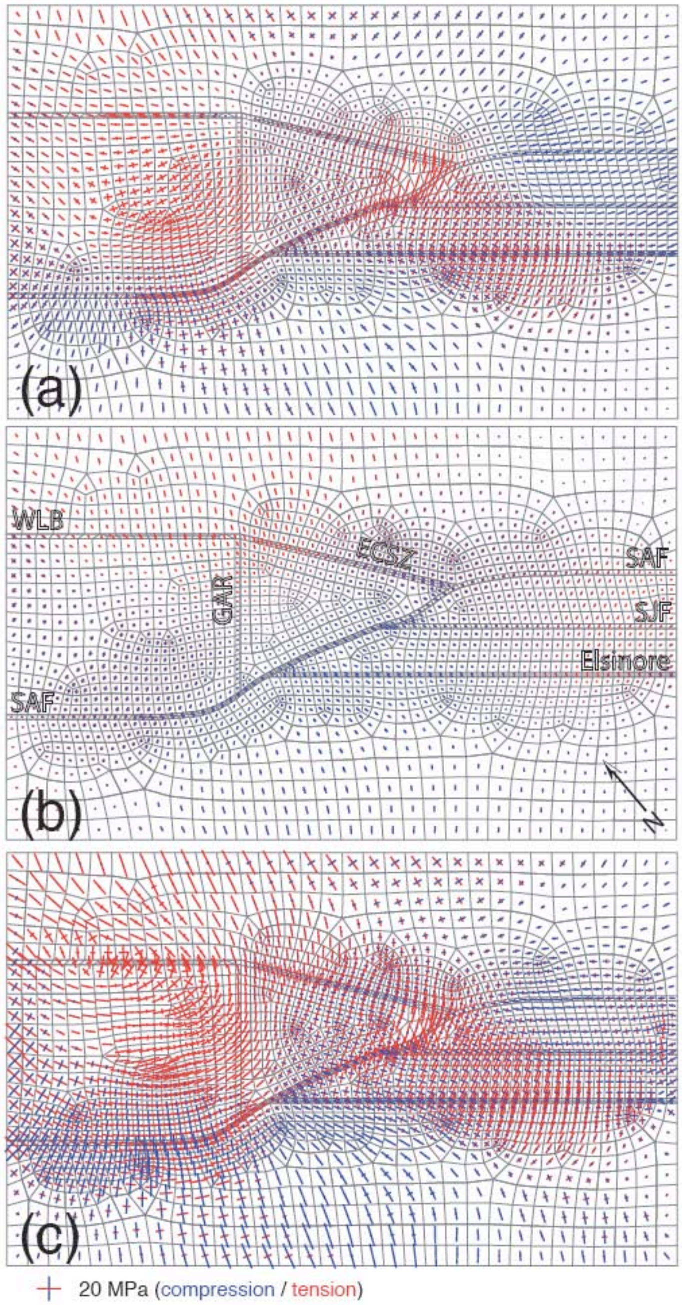

Figure 42. Estimated stress field, from body forces associated with topography, Moho variation and mantle loads inferred from tomography. Horizontal deviatoric principal stress field at 7.5 km depth caused by buoyancy heterogeneity. Blue bars indicate compression, red indicate tension. (a) Stress field caused by lateral variation in crustal thickness. Moho depth taken from receiver function studies [Zhu and Kanamori, 2000; Yan and Clayton, 2007] (b) Stress field caused by anomalous upper mantle density structure and tractions caused by density driven upper mantle flow [Fay et al., 2008]. SAF, San Andreas fault trace. (c) Total stress field (c = a + b) caused by crustal and upper mantle density variations. In the vicinity of the eastern and central Transverse Ranges the stress field is dominantly N-S compression and E-W tension.

Becker and coworkers are also characterizing stress based on relative plate motion traction, mantle flow, including that driven by body forces associated with topographic and crustal thickness variations. They find that tractions proportional to excess elevation and excess Moho depth result in tensional stress in the vicinity of the Transverse Ranges. The largest magnitude of this stress is of ~10-20 MPa in the east where the crust appears in isostatic equilibrium. Tractions on the crust derived from upper mantle flow driven by upper mantle density [Fay et al., 2008] produce compression throughout the Transverse Ranges, and tension in the southern Walker Lane Belt and Salton Trough area. Principal stress magnitudes are of order 5 MPa (Figure 42b). These stresses are known only to within a multiplicative constant that maps upper mantle seismic anomalies to density anomalies [Fay et al., 2008], and for the case shown here are smaller than the stresses caused by topography (Fig. 42a) by a factor of 2 or more.

They vary faults strengths to compare with the geodetic strain field and 'tentatively' conclude that a non-uniform distribution of fault strengths, possibly a consequence of differing fault maturity and offset, is required to produce the compressional stress to counter the tensional stress produced by the Transverse Ranges. They suggest it is necessary to consider the entire (simplified) fault system because the kinematics and stress at any one point is nonlinear and dependent on the material properties at that point and everywhere else in the system, the objectives of their continuing research. The variation of absolute stress for comparison with seismicity and stress drops is an outstanding SCEC goal. It will be important to compare this approach with the more comprehensive upper crustal model of the Hager group that incorporates the CFM, CBM and USR.

e. References

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5. Earthquake Forecasting and Predictability

The Earthquake Forecasting and Predictability (EFP) focus group coordinates two types of research projects. The first type encourages the development of earthquake prediction methods to the point that they can be moved to testing within the framework of the Center for the Study of Earthquake Predictability (CSEP). The other type of research project encouraged by EFP are those that are far from being ready for testing within the CSEP framework, but that aim to obtain fundamental knowledge of earthquake behavior that may be relevant for forecasting earthquakes.

Several proposals supported the CSEP testing centers and implementation of CSEP tests. Gerstenberger's "CSEP Forecast Test Methodology: Development and Participation" supported travel for collaboration and meeting participation for the New Zealand testing center. Wiemer's "Travel funds for CSEP integration & development" provided similar support for the testing center in Zurich. Jordan's "Alarm-based Evaluation of Earthquake Forecasts" supported the development of appropriate statistical tests for alarm-based earthquake forecasts. Schoenberg's "Spontaneous and triggered earthquakes in diverse tectonic zones of the globe" leads to submission to CSEP of both long-term and short-term global earthquake forecasts based on earthquake branching models and estimates of tectonic deformation (Figure 43).

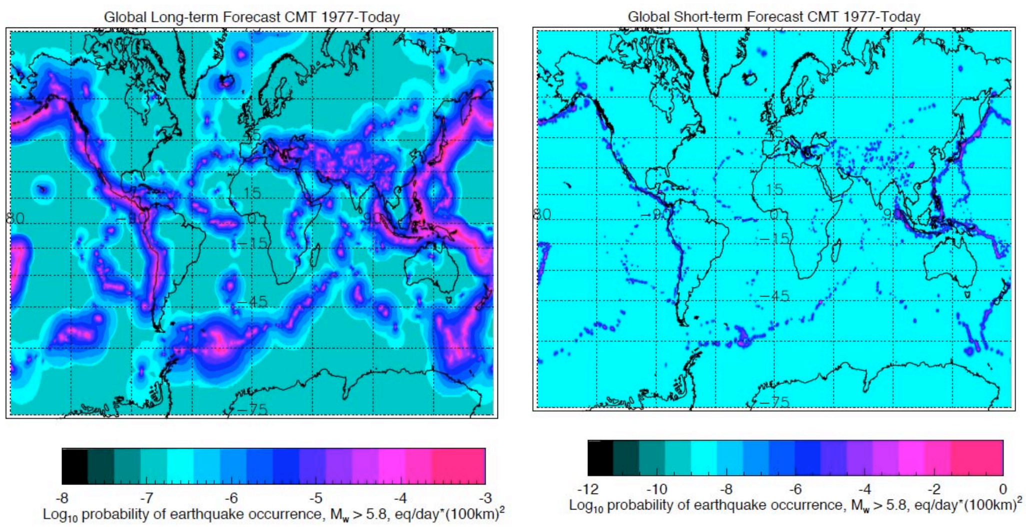

Figure 43. Long-term and short-term global earthquake forecasts. (Left) Global earthquake long-term potential based on smoothed seismicity. Earthquakes (Mw ¸ 5:8) from the CMT catalog since 1977 are used. Earthquake occurrence is modeled by a time-independent (Poisson) process. Colors show the long-term probability of earthquake occurrence. (Right) Global earthquake short-term potential based on smoothed seismicity. Earthquakes (Mw > 5.8) from the CMT catalog since 1977 are used. Earthquake occurrence is modeled by a temporal process controlled by Omori's law type dependence. Colors show the long-term probability of earthquake occurrence.

Shen's "Improvement and earthquake predictability test of the load response ratio method" carried out retrospective tests of the Load/Unload Response Ratio (LURR) method for intermediate-term earthquake forecasting, based on the rate and state of Coulomb stress changes induced by earth tides. This proposed method of earthquake prediction introduced by scientists in China has received much favorable attention there, although some studies by US scientists have brought those results into question. The retrospective tests had positive results for earthquakes in California, although different events required different friction parameters, and some earthquakes had a larger signal related to stress magnitude while others had a larger signal related to stress change (Figure 44). The method did not work for the 2008 M7.9 Wenchuan earthquake in China. The real test will come when this method is moved into the CSEP environment, where the method will be subjected to prospective testing with fixed parameters.

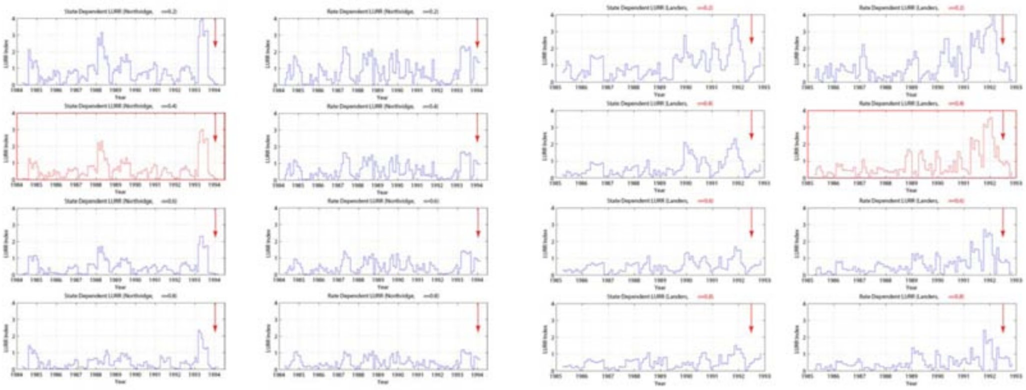

Figure 44. Retrospective test of the Load/Unload Response Ratio (LURR) method for intermediate-term earthquake forecasting, for the Northridge (left) and Landers (right) earthquakes. The triggering criterion is either “stress state” or “stress rate”, and the Coulomb friction coefficient μ= 0.2, 0.4, 0.6, or 0.8. Significant LURR “anomalies” appeared a few months before the mainshock for some of the test runs but not the others.

Other work placed observational constraints on physical models of earthquake occurrence. Bürgmann’s “Interaction and Predictability of Small Earthquakes at Parkfield” found that the recurrence time of repeating events at Parkfield shortened after nearby larger earthquakes, placing constraints on the stress magnitude necessary for triggering. Brodsky’s “Triggerability: A tool to connect aftershocks and long-range triggering” studied evidence for dynamic triggering of aftershocks by demonstrating a continuous relationship between peak dynamic stress and triggering rate in the near and far field. Zaliapin’s “Modeling seismic moment rate in San Andreas Fault -- Great Basin system: Combination of seismological and geodetic approaches” reconciled apparent differences in moment rate from seismicity and geodetic information, through detailed geodetic velocity and strain rate analysis and statistical modeling of seismic moment rate. These topics were addressed in a debate at the SCEC annual meeting in September, 2008.

The multi-disciplinary nature of EFP led to support of geological studies, including support of SoSAFE-related projects. Scharer’s “Slip per event at the Frazier Mountain paleoseismic site” better constrained the earthquake and slip history of the San Andreas fault near Ft. Tejon. Rockwell’s “SoSAFE: Confirming and Extending the Event Record at Hog Lake, San Jacinto Fault” was postponed until the summer of 2009. Stirling’s “Age of precariously balanced rocks at near fault sites in New Zealand: Reduction of age uncertainties” found that precariously balanced rocks in temperate environments New Zealand may have reached their precarious state much more quickly than precarious rocks in desert environments. Additionally, in support of SoSAFE, Cochran’s “Seismology Rapid Response Test During the SoSAF Shakeout” tested how rapidly portable seismometers could be deployed after a southern San Andreas event.

Earthquake Simulators

Several investigators have conducted research using Earthquake Simulators, including Ward's "ALLCAL -- An Earthquake Simulator for All of California", Tullis' "Quasi-Dynamic Parallel Numerical Modeling of Earthquake Interactions Over a Wide Magnitude Range Using Rate and State Friction and Fast Multipoles", and Dieterich's "Physics-Based Simulation of Earthquake Occurrence in Fault Systems". These simulators are numerical models aimed at generating catalogs of simulated earthquakes over a variety of spatial and temporal scales. The aim of these studies is to gain some understanding of the behavior of real earthquakes by studying the behavior of simulated earthquakes. For example, one line of inquiry is to see if patterns of simulated seismicity in space and time occur that might also be discovered in real seismicity. If so, forecasting future earthquakes might be done by recognizing ongoing patterns in past and current seismicity.

The "SCEC Earthquake Simulators Workshop 2" was held in June 2008. At this workshop, participants compared the results of their simulators for two benchmark problems outlined at the previous workshop, and discussed possibilities for future benchmark tests.

6. Ground Motion Prediction

The primary goal of the Ground Motion Prediction focus group is to develop and implement physics-based simulation methodologies that can predict earthquake strong motion waveforms over the frequency range 0-10 Hz. At frequencies less than 1 Hz, the methodologies should deterministically predict the amplitude, phase and waveform of earthquake ground motions using fully three-dimensional representations of the ground structure, as well as dynamic or dynamically-compatible kinematic representations of fault rupture. At higher frequencies (1-10 Hz), the methodologies should predict the main character of the amplitude, phase and waveform of the motions using a combination of deterministic and stochastic representations of fault rupture and wave propagation.

Source characterization plays a vital role in ground motion prediction and significant progress has been made in the development of more realistic implementations of dynamic and dynamically-compatible kinematic representations of fault rupture within ground motion simulations. Verification (comparison against theoretical predictions) and validation (comparison against observations) of the simulation methodologies continues to be an important component of this focus group with the goal being to develop robust and transparent simulation capabilities that incorporate consistent and accurate representations of the earthquake source and three-dimensional velocity structure. The products of the Ground Motion Prediction group are designed to have direct application to seismic hazard analysis, both in terms of characterizing expected ground motion levels in future earthquakes, and in terms of directly interfacing with earthquake engineers in the analysis of built structures. Activities in these areas are highlighted by the projects described below.

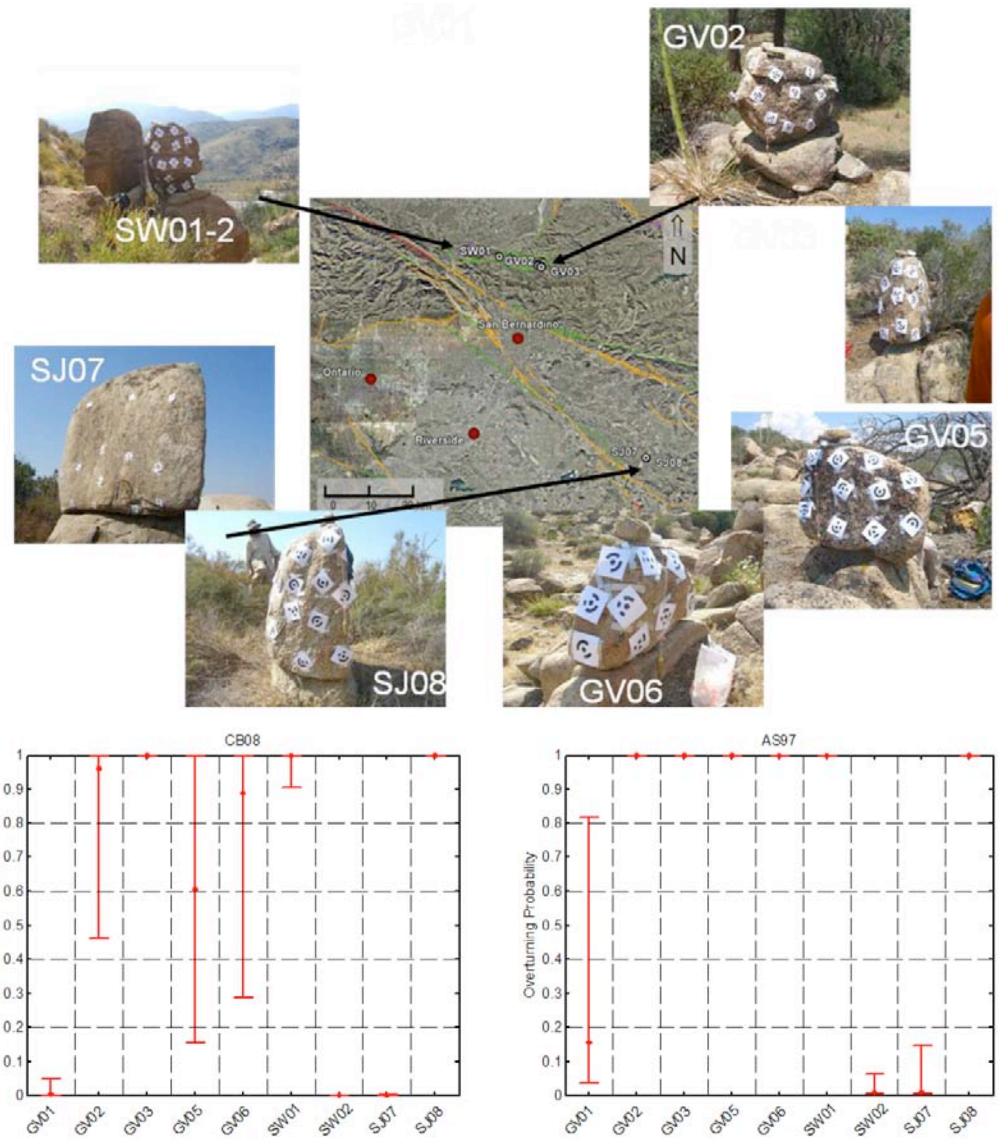

Figure 45. Top panel shows PBRs investigated in the vicinity of San Bernardino. The SW and GV sites lie very close to the Cleghorn, North Frontal Thrust, and San Andreas Faults while the SJ (San Jacinto) PBRs are very close to the San Jacinto Fault (within ~ 5 km). Bottom panels show PBR overturning probabilities assuming 10,000 year residence times when exposed to the UCERF 2 (Field et al. 2008) earthquake rupture forecast. Results for the Campbell and Bozorgnia [2008] and Abrahamson and Silva [1997] GMPE are shown.

a. Ground Motion Simulations and Model Validation

Precariously Balanced Rocks. *(Purvance, Anooshehpoor, Brune, and Jordan).* Recent work has developed refined fragility estimates of precariously balanced rocks (PBRs) in the San Bernardino region to test if their existence is consistent with current seismic hazard models. Figure 45 indicates the locations of PBRs chosen for this analysis. These include PBRs at sites very close to the Cleghorn and North Frontal Thrust Faults (sites SW at Silverwood Lakes and GV at Grass Valley) along with sites near to the San Jacinto Valley section of the San Jacinto Fault and between the San Jacinto and San Andreas Faults (sites SJ). Pictures of the PBRs at these sites are also presented with targets affixed, which are utilized for accurate shape determination via photogrammetry. These PBRs have all be field tested via forced tilting tests as outlined in Purvance et al. [2008] in an effort to more accurately delineate their fragilities. Rood et al. [2008] presents the only residence time study of PBRs in this region, indicating initial residence time estimates of 23-28 ka for Grass Valley PBR pedestals and 50 ka for one PBR. Thus there is evidence that the Grass Valley PBRs have resided in their current positions for many earthquake cycles.

The estimated PBR fragility models have been exposed to suites of ground motions produced by ensembles of earthquakes taken from the UCERF 2, along with the GMPE of Abrahamson and Silva [1997] and the NGA relation of Campbell and Bozorgnia [2008]. Monte Carlo simulations have been undertaken using the recurrence intervals and maximum magnitudes of events, sampling the GMPE for the magnitude/distance pairs. Since the PBR overturning fragilities depend on both the high- and lower-frequency ground motion amplitudes, PGA and spectral acceleration at 1 Hz have been used to estimate the overturning probabilities. Figure 45 presents the overturning probabilities for each PBR when exposed to the UCERF 2 where the ground motions have been estimated based on the CB08 and AS97 GMPE.

The ground motions are assumed to be statistically independent from earthquake to earthquake in these analyses and 10,000 year residence times have been assumed ubiquitously. The AS97 GMPE produces significantly higher rates of overturning when compared with the CB08. However, in both cases, a number of the PBRs should have overturned with high probability if exposed to the earthquakes represented by the UCERF 2. These results suggest that either the recurrence intervals of some earthquakes as indicated in the UCERF 2 are unrealistically short or that the Campbell and Bozorgnia [2008] GMPE predicts unrealistically large ground motions amplitudes in the near field of large earthquakes. Moreover, further constraints on ground motion levels from PBRs may soon be available (Figure 46).

Ambient Noise Analyses. *(Beroza, Ma and Prieto).* Beroza, Ma and Prieto have developed the capability to use the ambient seismic field to predict ground motion. Despite the complex nature of the ambient field, it has a weak coherence that can be extracted even in the presence of multiple scattering. In particular, the correlation of diffuse wavefields recorded at two receivers can be used to extract the impulse response (i.e., the Green's function) for an impulsive excitation at one receiver, as recorded at the other. The top panel of Figure 47 from Ma et al. [2008] compares all three components of the ambient-noise Green's functions at station FMP with theoretical, finite-element Green's functions calculated by applying a smooth vertical force with Gaussian time dependence at station ADO for SCEC CVM 4.0 and CVM-H5.2 community velocity models. The fit is limited primarily by our imperfect and incomplete knowledge of crustal structure.

Figure 46. The Echo Cliffs precariously balanced rock (see discussion in the Geology section) in the western Santa Monica Mountains. stands at just over 14 meters in height, and has a 3 to 4 second oscillatory period, corresponding to that of a 30 to 40 story building. This rock withstood ground motions during the 1994 Northridge earthquake estimated to have been 0.2 g (PGA) and 12 cm/sec (PGV) at this site. This rock, discovered in March 2009, may provide constraints on future ground motion simulations, especially for long-period shaking that is relevant for tall buildings in the Los Angeles area. Dylan Rood (LLNL & UCSB) and David Haddad (ASU) provide scale (from Hudnut et al., 2009 SCEC Annual Meeting abstract).

They have also used the ambient field to document basin amplification for seismic stations in the Los Angeles basin. Figure 48 [Prieto and Beroza, 2008] compares the response to a horizontal impulse, using station BBR as a virtual earthquake source, at seismic stations across metropolitan Los Angeles with seismograms of the February 10, 2001 (Mw 4.6) Big Bear earthquake, which is within 4 km horizontally and 10 km vertically of station BBR. The horizontal impulse is applied in the fault normal direction, following the earthquake mechanism given by Graves (2008), who independently modeled ground motions. Both the duration and relative amplitudes of ground motions across the Los Angeles Basin are recovered from ambient-noise observations.

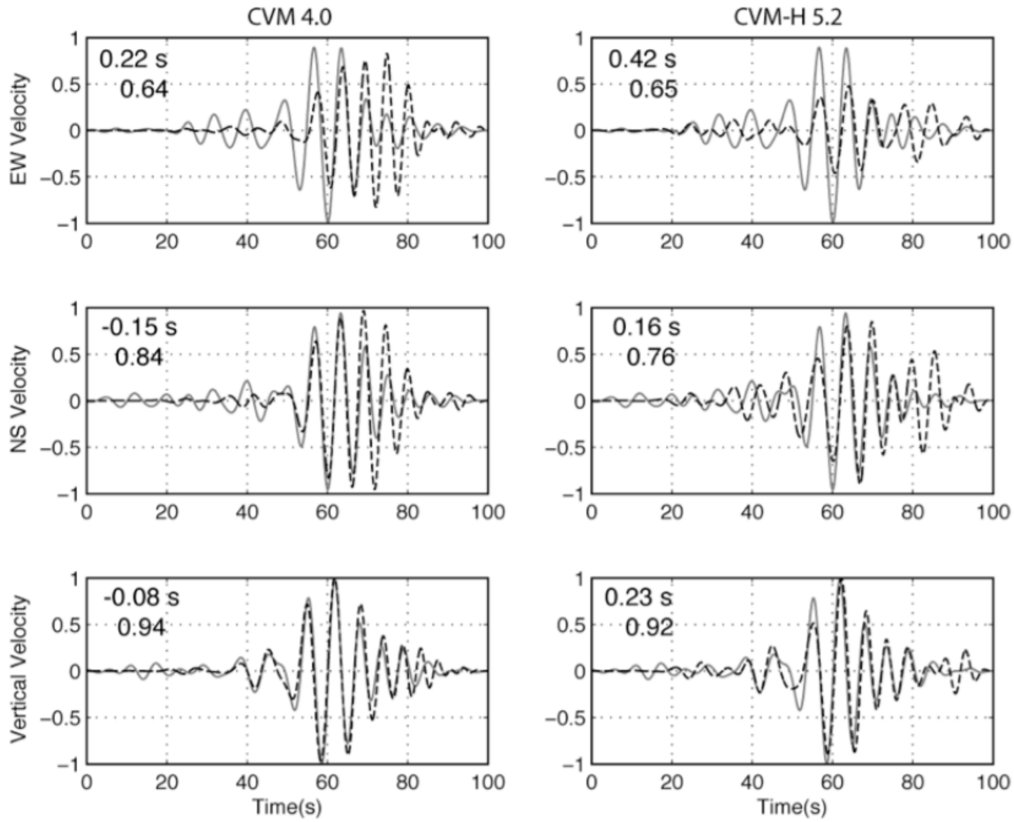

Figure 47. Top panel shows comparison of ambient field (gray) and synthetics (black dashed) at FMP for a vertical force at ADO filtered between 0.1 and 0.2 Hz. Time lag and correlation coefficient are shown in upper left.

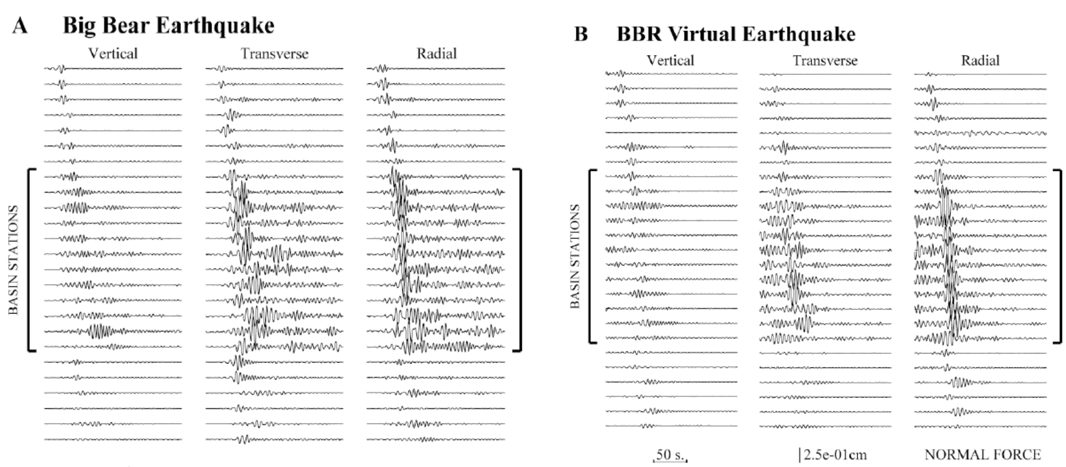

Figure 48. A) Earthquake record section of ground displacements for sites around the Los Angeles Basin. Records are plotted roughly with increased epicentral distance. The large brackets indicate basin sites. B) Same as A but for impulse response records for a horizontal force for station BBR. Note the amplification in the Los Angeles basin for both the impulse response as well as the earthquake records.

Parametric Correlations in Kinematic Ruptures. *(Archuleta and Schmedes)*. Liu et al [2006] have proposed a hybrid low/high frequency method for the prediction of broadband ground-motion time histories that utilizes correlation of the kinematic source parameters as suggested by previous models of dynamic faulting. For any point on the fault the choice of the source parameters is based on statistical distributions. The method computes 1D and 3D synthetics for a given station using a standard representation theorem that convolves the spatial varying slip rate function on the fault with the computed Greens functions of the medium between the fault and the station and integrates this combination over the fault. To produce more accurate high-frequency amplitudes and durations, we correct the 1D synthetics using a randomized, frequency dependent perturbation of azimuth, dip, and rake. To correct the 1D synthetics for local site response and nonlinear soil effects we use a nonlinear propagation code and a generic velocity structure appropriate for the site. Finally, we combined the low frequencies from the 3D calculation with the high frequencies from the 1D calculation using a wavelet-based approach at a specified cross over frequency.

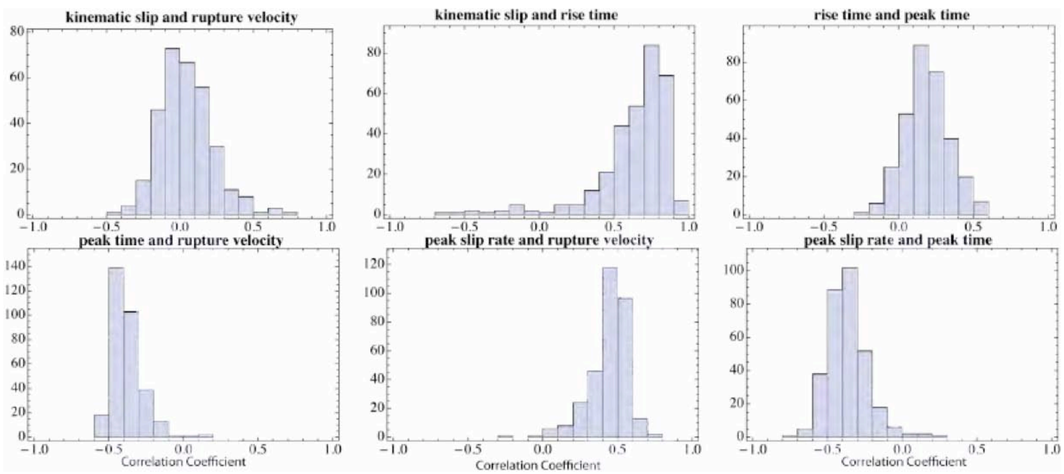

Figure 49. Histograms of computed spatial correlation coefficients for 315 ruptures and different parameter pairs. This result indicates that there is no correlation between slip and rupture velocity.

Current work is aimed at the refinement of the method using dynamic modeling. The focus here is on the spatial interdependency of the kinematic parameters. Spatial correlation coefficients have been computed for different parameter pairs and 315 spontaneous rupture models, including three dynamic Shakeout ruptures computed by Luis Dalguer [2008, pers. Comm.]. Selected histograms are shown in Figure 49. The first important result is contained in the first row, which shows the correlation of final slip with the ratio of rupture velocity over shear wave velocity. The distribution is centered on 0, hence for most ruptures there is no correlation between these two parameters. Therefore, for a given slip distribution on the fault there are many fundamentally different spatial distributions of rupture velocity possible, which translates into great variability in the possible ground motion. This result argues against using slip as a controlling parameter for rupture velocity. If a positive correlation between slip and rupture velocity is assumed, areas of large slip are sampled in a shorter time (faster rupture), which yields strong peaks in the ground motion. Hence, if such a correlation is wrongly assumed one might over-predict ground motion.

Validation of Synthetic Ground Motions. *(Bazzurro, Tothong, Shome, Park, and Gupta).* This study focuses on the statistical comparison of the characteristics of ground motion intensity measures at a given site derived from numerical simulations, ground motion prediction equations (GMPEs) and observed records. The analysis utilizes both elastic and inelastic response quantities. The simulations analyzed for this project were generated in 2005 and are for the 1989 Loma Prieta earthquake and a scenario based on the 1906 San Francisco earthquake [Aagaard et al., 2008a and 2008b].

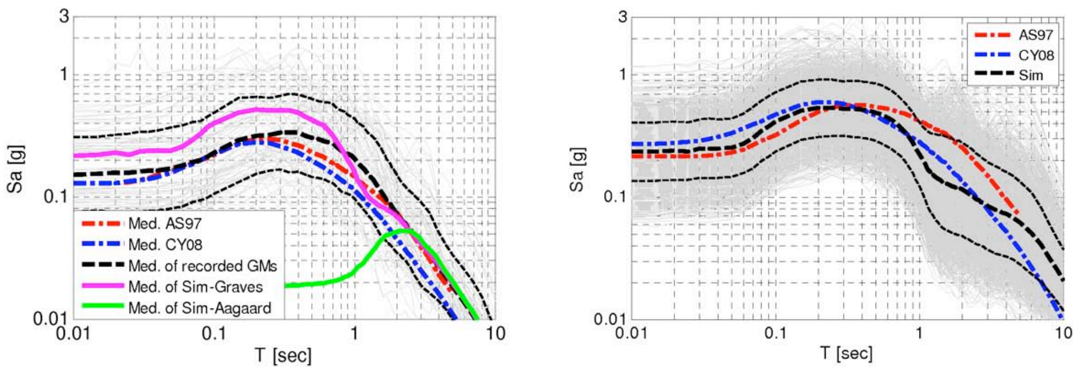

Figure 50. Left panel shows geometric mean response spectra of 83 recorded motions (gray lines) from 1989 Loma Prieta earthquake along with their geometric mean (thick dash-dash line) and +/-one sigma (thin dash-dash lines) compared with the geometric mean of the predicted spectra from both the GMPEs and the simulations. Right panel compares simulated and GMPE predictions for 1906 earthquake scenario.

Figure 50 compares 5% damped elastic response spectra from the earthquake simulations with that predicted from the GMPEs of Abrahamson and Silva [1997] and Chiou and Youngs [2008]. The left panel is for the 1989 Loma Prieta earthquake, which also includes the median of the actual observations, and the right panel is for the 1906 scenario. For the Loma Prieta earthquake, the simulation predicts higher motions on average for periods less than about 1 sec. Between 1 and 2 seconds the simulated motions under-predict the median observations, and then above 2 sec the simulations are at the same level as the median observations. For 1906, the simulation and GMPE predictions are quite similar except for the dip in the simulations seen between periods of 1 and 4 seconds. As discussed in the next section, recent refinements to the simulation methodology have been focused on correcting the deficiencies illustrated by these comparisons. These include the implementation of a more accurate non-linear site response model, and the use of a sharper slip rate function, both of which significantly improve the fit to the Loma Prieta observations (Figure 52).

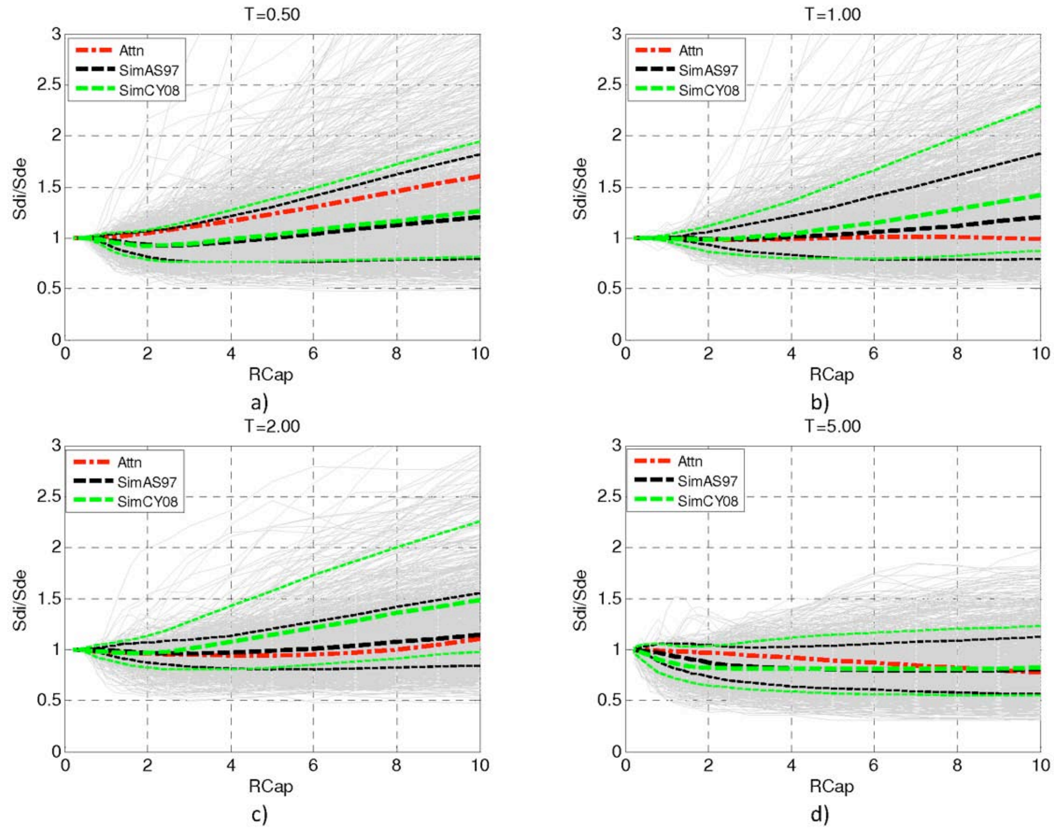

Figure 51. Comparison of inelastic displacement ratio for multiple periods between simulated records for the 1906 earthquake scenario and those predicted by the GMPE of Tothong and Cornell [2006].

Figure 51 compares the inelastic response for the 1906 simulation. The results are displayed as the ratio of inelastic to elastic spectral displacement plotted as a function of the expected level of nonlinearity (RCap). At longer periods, the simulation is consistent with the empirical prediction from Tothong and Cornell [2006]; however, at shorter periods the simulations show lower inelastic response ratios than the empirical model. Interestingly, Baker [2007] used a similar procedure to analyze simulations for a Mw 7.15 Puente Hills scenario generated using the same methodology employed for the 1906 simulation and also found good agreement at the longer periods. However, at shorter periods Baker [2007] found that the simulations predicted higher inelastic response ratios than the empirical model. This apparent discrepancy can be explained by examining the scenario specific rupture characteristics employed in each simulation. The Puente Hills scenario analyzed by Baker [2007] was a high dynamic stress drop event that produced quite strong short period motions [Graves and Somerville, 2006], and consequently generated large inelastic response ratios at the shorter periods. On the other hand, the 1906 scenario is modeled as a low dynamic stress drop event (due to the presence of surface rupture), which consequently produces relatively weak short period motions and lower inelastic response ratios.

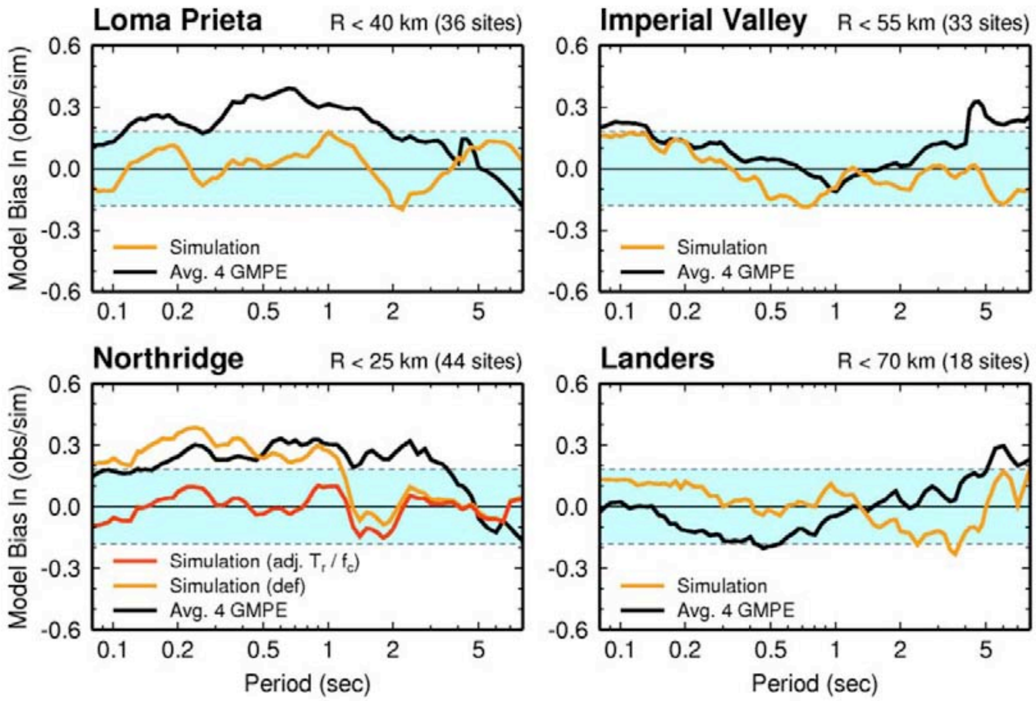

Figure 52. Mean model bias of average horizontal component spectral acceleration for simulations of four large California earthquakes. Blue shading indicates +/-20% variance. The black lines are predictions from empirical ground motion attenuation models.

The results from this study highlight the benefits of utilizing statistical analyses to validate and guide the improvement of the simulation methodologies. In addition, they also illustrate the need to consider potential biases introduced by event- and/or scenario specific characteristics included in the simulations.

Broadband Simulations. *(Graves and Pitarka).* Current work on this project is aimed at refinements to the hybrid broadband ground motion simulation methodology of Graves and Pitarka [2004], which combines a deterministic approach at low frequencies (f < 1 Hz) with a semi-stochastic approach at high frequencies (f > 1 Hz). The high frequency approach assumes a random phase omega-squared radiation spectrum and generic ray-path Green's functions. The low frequency motions are computed using a 3D viscoelastic finite difference algorithm. Fault rupture is represented kinematically and incorporates spatial heterogeneity in slip, rupture speed and rise time.

Recent source characterization improvements are guided by rupture model inversions and dynamic rupture simulations. The prescribed slip distribution is constrained to follow an inverse wavenumber-squared falloff and the average rupture speed is set at 80% of the local shear wave velocity, which is then adjusted based on the slip distribution such that the rupture propagates faster in regions of high slip, and slower in regions of low slip. The slip rate function is a Kostrov-like pulse having a rise time proportional to the square root of slip, with the average rise time across the entire fault constrained empirically. Recent observations from large earthquakes show that surface rupturing events generate relatively weak high frequency ground motions compared to buried ruptures. Dynamically, this behavior can be reproduced by including a zone of velocity strengthening in the upper few km of the rupture. Kinematically, this leads to a reduction of rupture propagation speed and a lengthening of the rise time, which we model by applying a 70% reduction of the rupture speed and increasing the rise time by a factor of 2 in a zone extending from the surface to a depth of 5 km.

Another refinement is the use of near surface response factors developed from equivalent linear response analysis. These factors are based on Vs30 as implemented in the empirical model of Campbell and Bozorgnia [2008]. First, ground motions are simulated for a reference site condition, which is typically set at Vs30 = 865 m/s for the high frequency portion of the simulation. Next, using the peak ground acceleration (PGAR) measured from the reference waveform, the reference Vs30 (VREF) and the site Vs30 (VSITE), a frequency dependent amplification spectrum is constructed. This amplification spectrum is then applied to the Fourier amplitude spectrum of the simulated waveform. Inverse transformation back to the time domain yields the site-specific broadband waveform. Non-linear effects are incorporated through the use of PGAR, which adjusts the level of amplification depending on the strength of the reference motions. For large PGAR, the amplification functions can be less than one, particularly at high frequencies. Although the factors are strictly defined for response spectra, the application in the Fourier domain appears to be justified since the functions vary slowly with frequency. The use of Vs30 is attractive because this parameter is readily available and the amplification functions are easy to compute and apply to large-scale simulations.

The fidelity of the simulation technique is demonstrated in Figure 51, which compares the spectral acceleration goodness-of-fit against the strong motion recordings from the Imperial Valley, Loma Prieta, Landers, and Northridge earthquakes.

b. Dynamic Rupture Effects on High Frequency Ground Motions

Rough Faults. *(Dunham and Rice).* This work utilizes numerical simulations to explore how ruptures propagate along rough faults [Belanger and Dunham, 2008]. Measurements indicate that natural fault surfaces are rough at all scales; more specifically, deviations from planarity are evident at all wavelengths with an amplitude-to-wavelength ratio that is scale independent (i.e., fault surfaces are self-similar fractals). Part of the effort over the past year has been devoted to development of a numerical method that offers more flexibility in terms of incorporating other bulk rheologies (including plasticity) and geometrical complexity of faults. This has led to the development of a block-structured finite difference code that is capable of handling curved boundaries/faults. Irregular geometries in the physical domain are mapped onto a rectangular computational domain via a coordinate transformation; the governing equations are solved in the computational domain. For these simulations, band-limited self-similar fault profiles are generated with the maximum roughness wavelength corresponding to the fault length and the minimum taken to be about ~10 times larger than the grid spacing to ensure proper numerical resolution of all modeled roughness wavelengths. The top panels of Figure 53 shows an example of a synthetically generated fault surface as well as the location of a station where synthetic seismograms are computed; rupture is nucleated in the center of the domain.

One important result shown by the simulations is that increasing the fault roughness, while keeping all other parameters (initial stresses, friction law parameters, etc.) fixed, ultimately inhibits rupture propagation by creating extremely large stress perturbations. These stress perturbations are, for sufficiently short roughness wavelengths, capable of completely relieving normal stress over small portions of the fault, at least when assuming linear elastic material response as was done in these simulations.

In addition to influencing rupture propagation, roughness alters the characteristics of radiated ground motion. This is most easily illustrated for faults with a single Fourier mode of roughness at a given wavelength (bottom panels of Figure 53). One might speculate that faults with a single Fourier mode of roughness will only excite waves at a single frequency; these would appear as a single peak in ground motion spectra. However, this is not the case. Instead, the frequency of waves also depends upon the speed of the rupture relative to the station. That is, the excited waves exhibit a Doppler shift; if the rupture is receding from the station, then the frequency decreases as a function of time, as illustrated in Figure 53. Hence, there is no single, distinct peak in the Fourier spectrum.

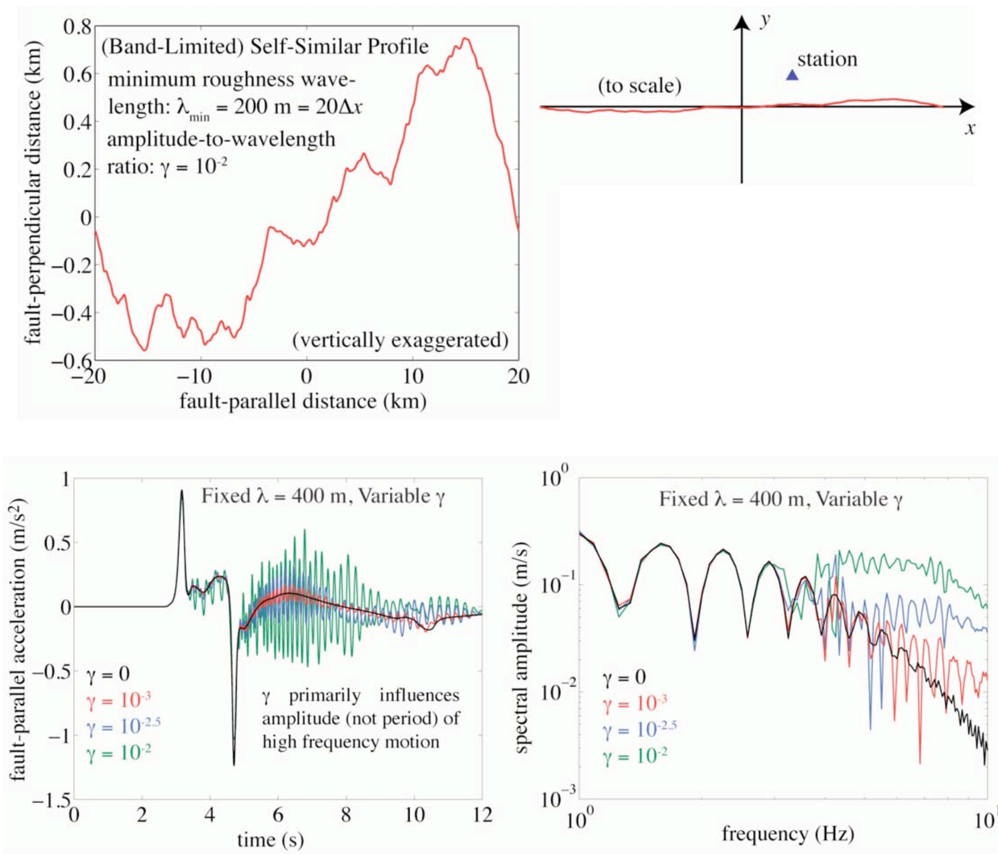

Figure 53. Top panels show non-planar fault model used to explore influence of fault roughness on rupture propagation and production of high frequency ground motion. Bottom panels show Ground acceleration and its Fourier transform for ruptures on sinusoidal faults having various levels of roughness for a given wavelength. Note how the period of the high frequency oscillations in the seismograms increases with time. This is the Doppler shift caused by the rupture propagating away from the station.

Heterogeneous Initial Stress. *(Ampuero, Ruiz, and Mai).* The main goal of this project is to design efficient procedures to generate realistic initial stress conditions for dynamic earthquake source simulations tailored to ground motion prediction. The scope of the work this year was to formulate a stress generation procedure based on additive residual stresses from background Gutenberg-Richter seismicity, and explore its properties through extensive 2D simulations. Of particular interest was to examine the ability of the model to radiate high frequencies with ω^{-2} spectral decay throughout the whole rupture surface. This is a major improvement with respect to usual dynamic models in which high frequencies come mainly from stopping phases at arbitrarily abrupt rupture ends.

In crack models, the two major mechanisms to produce rupture speed jumps and strong high-frequency radiation are abrupt heterogeneities of fracture energy and inverse square root concentrations of initial stress. The latter, which is the focus of the current study, arises naturally at the edge of previous ruptures. In this study, it is assumed that the heterogeneous fault stress emerges from the background seismicity. A large number of such initial stress distributions are generated by stochastically varying the locations of the hypocenters in the background seismicity. These initial stresses are then taken as initial conditions for 2D rupture simulations on a planar fault governed by slip-weakening friction. The problem is solved numerically with a spectral boundary integral equation method. Finally, the statistical properties of the resulting ruptures are examined, in particular macroscopic source properties such as the far-field radiation spectra derived from the seismic potency rate functions.

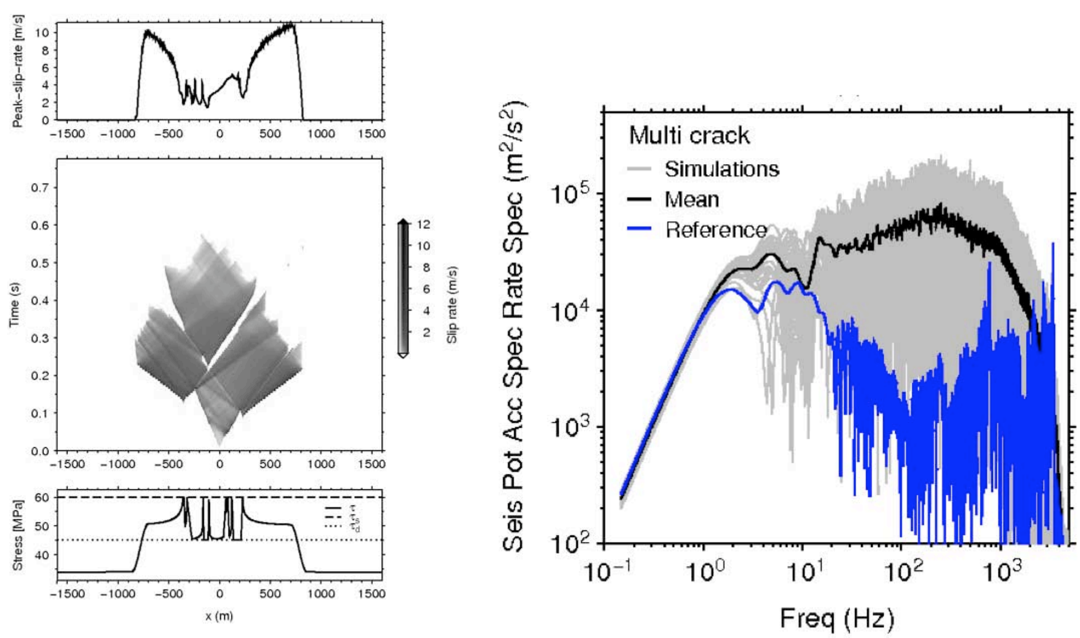

Figure 54. Example of 2D dynamic rupture under heterogeneous initial stress containing a multiple initial cracks (left panels). Each panel on the left shows the assumed initial stress (bottom), the resulting space-time distribution of slip rate (middle) and the spatial distribution of peak slip rate (top). Right panel shows spectra of far-field acceleration derived from the seismic potency rate of 30 simulations with the multi-crack model. The reference model (blue) has uniform initial stress.

This process involves the fitting of a basic spectral model to estimate seismic potency, corner frequency and high-frequency spectral fall-off exponent. Three models are considered: (1) a reference model with very smooth initial stresses, (2) a single-crack model with only one pair of initial stress concentrations from a single previous rupture and (3) a multi-crack model. The single-crack and multi-crack models generate spectra with the usual $\omega-2$ high-frequency decay (Figure 54). In contrast, the reference model is deprived of high frequencies, its spectrum falls off as $\omega-3$. The multi-crack model is richer in high frequencies than the single-crack model, it generates higher corner frequencies for the same event magnitude (Figure 54). The enhanced high-frequency content is generated by the multiple strong phases present all along the rupture.

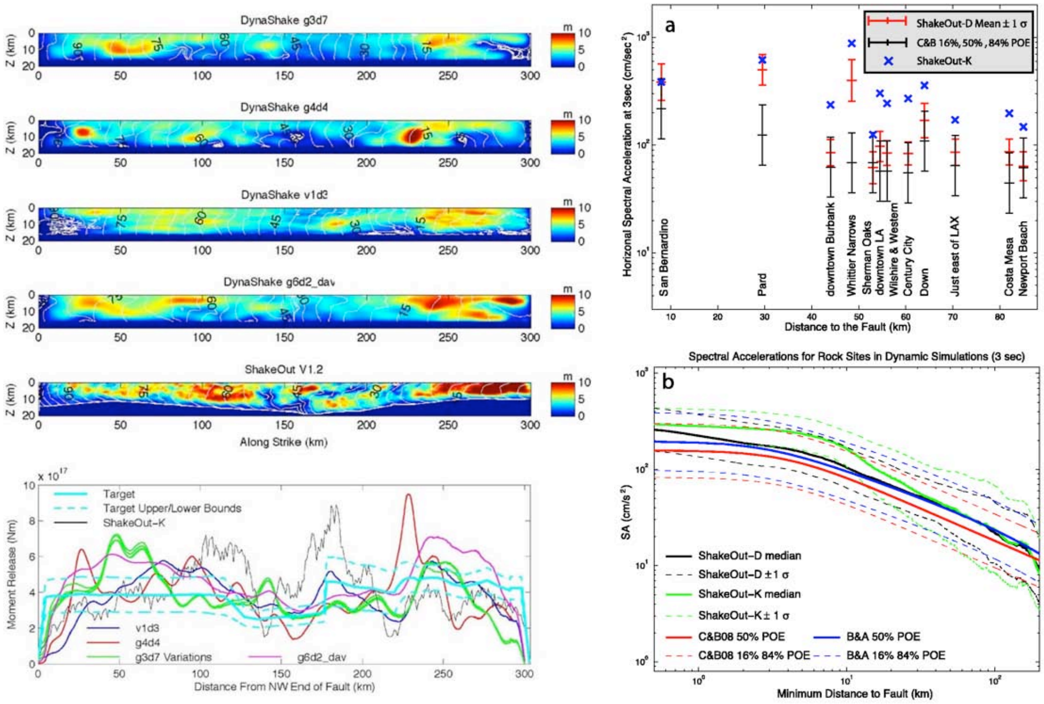

Figure 55. Left panels show slip distributions for 4 of the 7 ShakeOut-D sources and ShakeOut-K. The white contours and contour labels depict the rupture times. The bottom left panel shows distributions of depth-integrated moment density along the fault. Right panels show comparison between 3s-SA at rock sites (top) for 12 selected sites and (bottom) for the mean of ShakeOut-D, for ShakeOut-K, and for CB08 and BA08.

c. Large Scale Ground Motion Simulations

Spontaneous ShakeOut Rupture. *(Olsen, Day, Dalguer, Mayhew, Cui, Cruz-Atienza, Roten, Maechling, Jordan, Okaya, and Chourasia)*. This collaborative effort simulated ground motion in southern California from an ensemble of 7 spontaneous rupture models of large (Mw7.8) northwest-propagating earthquakes on the southern San Andreas fault (ShakeOut-D). Each ShakeOut-D dynamic source was modeled via a slip-matching technique constraining the initial (shear and normal) stress conditions. This technique allowed us to iteratively perform kinematic and dynamic simulations to find initial distributions that approximately conform to the kinematic ShakeOut static slip distribution. The distributions of depth-integrated moment density (left panels of Figure 55) all reproduce the ShakeOut scenario relatively well. Nonetheless, as Figure 55 illustrates, 4 of the 7 dynamic rupture models vary greatly in their fault-plane spatial-temporal distributions of final slip and rupture time, even though averages are nearly identical. The remaining 3 ShakeOut-D sources are variants of the rupture model ‘g3d7’, with initial stress conditions that yield similar slip (but somewhat different slip-rate distributions).

The right panels of Figure 55 compare 3s-SA values for the mean of the ShakeOut-D ensemble with those of our ShakeOut-K simulation, at all rock sites within 200 km of the fault rupture. The rock-site distance dependences of ShakeOut-K and ShakeOut-D are very different. While the medians agree well for distances less than about 1 km and larger than about 30 km from the fault, the ShakeOut-K medians are up to 60% larger than those from ShakeOut-D between 1 km and 30 km from the fault. The larger values for ShakeOut-K in this range must reflect characteristics of the ShakeOut-K source model that differ systematically from the ShakeOut-D ensemble. A possible source of this difference would be the presence of strong rupture-induced directivity in ShakeOut-K, which has rupture velocities that are often near or above the Rayleigh velocity. In contrast, rupture-front coherence, and therefore directivity effects, are likely to be substantially reduced by the complex dynamic ruptures that emerge in the ShakeOut-D simulations. Moreover, the ShakeOut-D sources satisfy local energy conservation, which puts constraints on possible rupture velocities, for example, the preclusion of rupture velocities between the Rayleigh and S velocities. ShakeOut-K, being kinematically prescribed, need not obey these energy constraints.

Graves et al. [2008] demonstrate that predicted ground motions in Los Angeles are significantly reduced if one introduces relatively moderate reductions in the average rupture speed of the ShakeOut-K scenario. It is possible that this sensitivity reflects, in part, the presence in ShakeOut-K of segments rupturing at velocities between the local Rayleigh and S-wave velocities, i.e., the range that is energetically precluded. Dynamically simulated sources will naturally avoid the energetically-precluded regime.

Kinematic ShakeOut Comparison. *(Bielak, Graves, Olsen, Taborda, Ramirez-Guzman, Day, Ely, Roten, Jordan, Maechling, Urbanic, Cui, and Juve)*. This project involves a verification of three simulations of the ShakeOut scenario, an Mw 7.8 earthquake on a portion of the San Andreas fault in southern California, conducted by three different groups at the Southern California Earthquake Center using the SCEC Community Velocity Model for this region. Two of these sets were obtained using the finite difference method, and the third, the finite element method. Qualitative and quantitative comparisons were performed. The results are in good agreement with each other: only small differences occur both in amplitude and phase between the various synthetics at ten observation points located near and away from the fault, as far as Santa Barbara. Using the goodness-of-fit criteria proposed by Anderson [2004], all the comparisons scored above 8, with most above 9.2. This score would be regarded as excellent if the measurements were between recorded and synthetic seismograms. Results are also very good for comparisons based on the misfit criteria of Kristekova et al. [2006]. Results from these two criteria can be used for calibrating the two methods for comparing seismograms. In those cases in which noticeable discrepancies occurred between the seismograms generated by the three groups, we found that they are the product of intrinsic differences between the numerical methods used and their implementation. In particular, we found that the major source of discrepancy lies in the difference between mesh and grid representations of the same material model. These differences notwithstanding, the three schemes are consistent, reliable, and sufficiently accurate and robust for use in future large-scale simulations.

Figure 56 shows snapshots at different times of the magnitude of the horizontal velocity at the free surface, calculated as the square root of the sum of squares of the two horizontal components, for the three groups. Although smaller and larger values are present in the results, the color limits in the figure were set to 0.05 and 2.0 m/s for visual convenience. Other than the differences derived from URS/USC using a smaller domain, all triplets are in good agreement with each other at all times. Discrepancies are practically unnoticeable unless one zooms in and examines the triplets carefully. Those small differences are more visible in wave fronts with amplitudes close to the lower limit of the color scale. See, for example, the back front moving along to the right side of the fault by 60 and 90 s, the frontal wave at 120 s, or the remaining trapped waves in San Fernando Valley by 150 s. Still, these differences are insignificant. One can confidently say that, judging by this comparison, the results of the three sets are, from a regional perspective, equivalent.

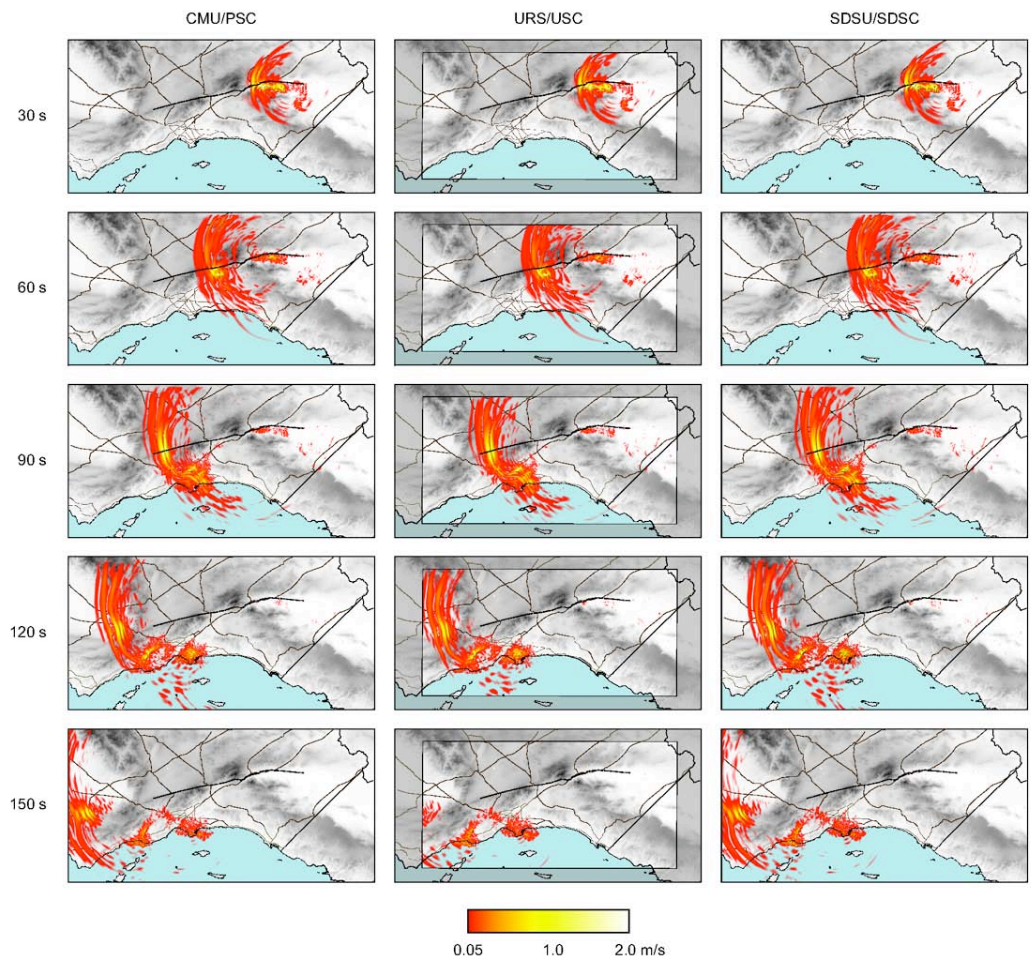

Figure 56. Snapshots of surface horizontal magnitude velocity for the three simulation sets at different times. Left to right shows Carnegie-Mellon group's simulation running at the Pittsburgh Supercomputing Center, URS group's simulation running at USC, and San Diego State's group running at San Diego Supercomputing Center.

d. References

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7. Seismic Hazard and Risk Analysis

The purpose of the Seismic Hazard and Risk Focus Group is to apply SCEC knowledge to the development of information and techniques for quantifying earthquake hazard and risk. Projects in this focus group can have relationships with most of the other focus groups. The strongest linkages are with the Ground Motion Prediction Focus Group, as well as to SCEC special projects such as the Extreme Ground Motion Project, and to PEER special projects such as the Tall Buildings Initiative. Projects that involve interactions between SCEC scientists and members of the community involved in earthquake engineering research and practice are especially encouraged in SHRA. The following three SCEC reports summarize some of the activities in SHRA during 2008-09. A very large number and variety of SCEC projects relate in some way to the goals of SHRA. This report briefly reviews a selection of projects that span this wide range of topics.

a. The Earthquake Source

Seismic Energy, Stress Drop, and the Limits of Strong Ground Motion. *(Beroza).* A long-standing discrepancy exists in studies of the radiated seismic energy. Some studies find that the scaled energy - the ratio between seismic energy and seismic moment - varies systematically with earthquake size, while others find that it does not. The scaling of seismic energy is an important issue for both the physics of earthquake faulting and for strong ground motion prediction. For earthquake physics, a break in scaling might be diagnostic of a characteristic length scale in the faulting process. For strong ground motion prediction, if large earthquakes radiate seismic energy more efficiently than do small earthquakes, then they have the potential to generate more intense strong ground motion. It is this latter issue that is important for the extreme ground motion project.

This study used an empirical Green's function (eGf) method on the seismic coda in order to investigate possible scaling of the radiated seismic energy with earthquake size. Path effects in the spectra of earthquakes were corrected using a stack of closely located, small earthquakes as an eGf. This approach was applied to four earthquake sequences in western North America that span a magnitude range from Mw 3.0 – Mw 7.1. The estimates of scaled energy are consistent with independent measurements, where available. No dependence in individual seismic energy estimates on source-station distance was found, which validates the eGf approximation. Energy estimates for the larger events compare with those made independently. A constant scaled energy of 2.4 × 10-5 provides a reasonable fit to all the data, with no systematic variation of the scaled energy with seismic moment required (Figure 57).

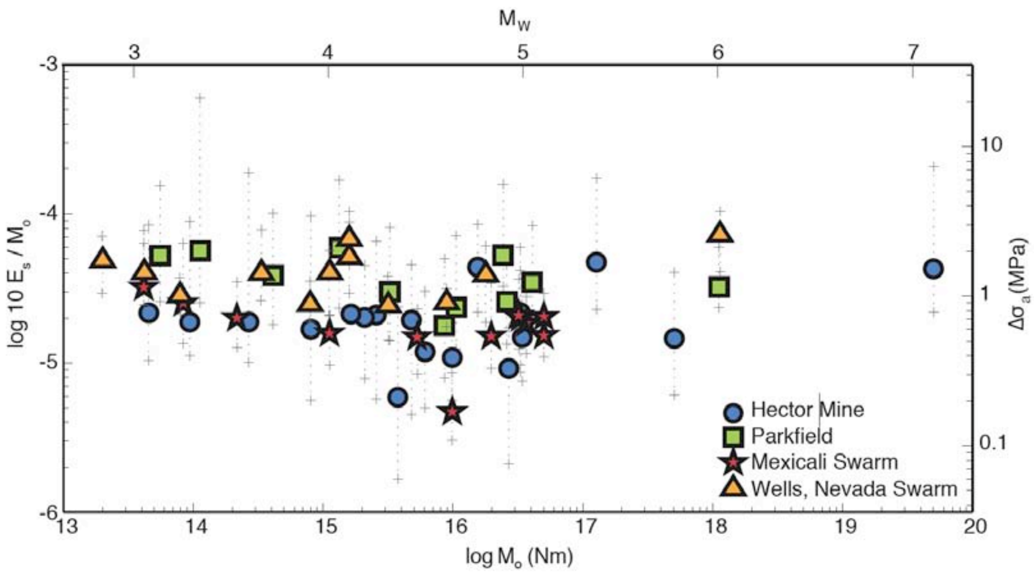

Figure 57. Scaled energy for four earthquake data sets. Large symbols show mean value of scaled energy for each location and event. Grey error bars show 5% and 95% intervals on the interstation scatter. Estimates from this study fall within the range of previous results.

Constant Stress Drop from Small to Great Earthquakes in Magnitude-Area Scaling. *(B. Shaw).* Earthquakes span a tremendous range of scales, more than 5 orders of magnitude in length. This study addressed the question whether earthquakes are fundamentally the same across this huge range of scales, or whether great earthquakes are different from small ones. All of the leading magnitude-area scaling relations used in the most recent US national seismic hazard maps assume a breakdown of the scaling seen in small earthquakes, with stress drops increasing for the largest earthquakes. This poses a challenge for earthquake physics and for seismic hazard estimation: what is different in the physics of great earthquakes, and how can we extrapolate from the much more numerous moderate and destructive large earthquakes to the rare and devastating great earthquakes if the physics differs? The study showed that the simplest hypothesis, that earthquake stress drops are constant from the smallest to the largest events, when combined with a more thorough treatment of the geometrical effects of the finite seismogenic layer depth, gives a magnitude area scaling which matches the data very well, and better than the currently used scaling laws which have non-constant stress drop scaling (Figure 58).

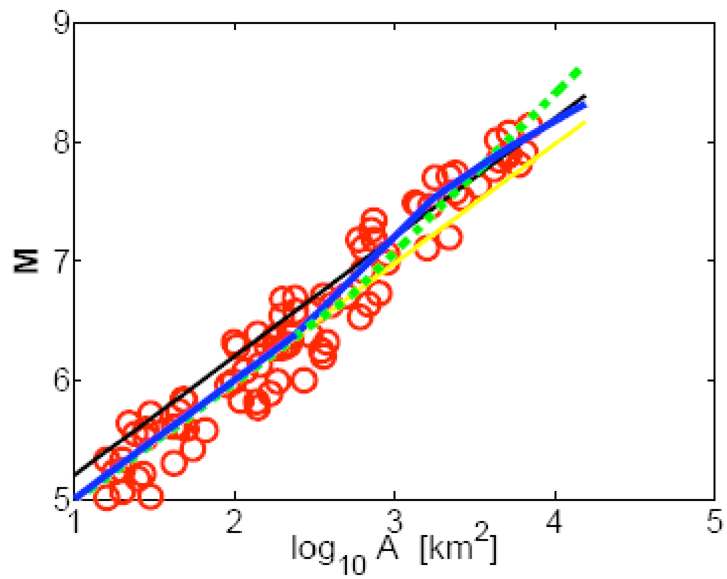

Figure 58. Magnitude area relations for large strike-slip events. Red dots denote magnitude and area of events from [Hanks and Bakun, 2008] database. Solid yellow line is linear [Wells and Coppersmith, 1994] magnitude-area relation, solid black line is linear Ellsworth-B [WGCEP, 2003] magnitude-area relation. Dashed green line is [Hanks and Bakun, 2002] bilinear relation. Blue line is our new proposed scaling relation. Note excellent agreement of solid blue line with data across the whole range of magnitudes. From [Shaw, 2009]

b. Earthquake Ground Motion

The highlights of the 2008-09 research into ground motions are described in the Ground Motion Prediction Report. Important topics at the interface between strong motion seismology and earthquake include the study by Tothong et al. on validation of synthetic ground motions via spectral response quantities, described in that report, and the study on nonlinear response described below.

Nonlinear Site Response Uncertainty in "Rupture-to-Rafters" Broadband Ground Motion Simulations. *(Assimaki).* To quantify the conditions under which nonlinear effects significantly affect the ground surface response, two indexes were developed to describe the near surface soil stratification and the characteristics of input seismic motion at each site during each scenario. Note that the site conditions describe which layers are susceptible to nonlinear effects, while the amplitude and frequency content of input motion identify whether the seismic waves will “see” the soft layers and whether they “carry” sufficient energy at the corresponding frequencies to impose large strains in the soft layers. More specifically, the intensity of incident seismic motion was described by the level of PGA (Peak Ground Acceleration) on rock outcrop (i.e. on ground surface for BS boundary soil conditions), and the frequency content of ground motion was characterized relative to the amplification potential (or transfer function) of the soil profile by means of the so- frequency index which is defined as the normalized cross correlation between the linear elastic transfer function of the profile and the Fourier amplitude of the input seismic motion (Figure 59).

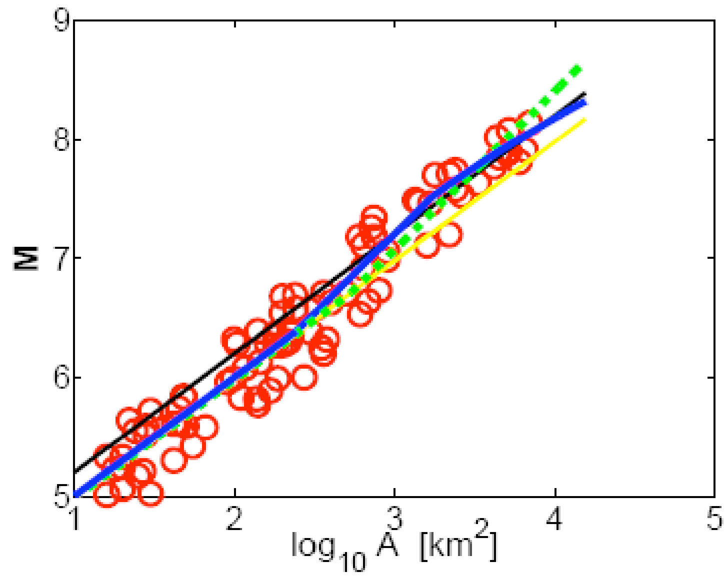

Figure 59. Contour maps of the prediction error (ERR) as a function of the peak ground acceleration (PGARO) on rock-outcrop and frequency index (IF) for selected sites.

c. Modeling of Earthquake Occurrence

ALLCAL – An Earthquake Simulator for All of California. *(S. Ward)*. This physics-based earthquake simulator produces spontaneous, dynamic rupture on geographically correct and complex system of interacting faults. ALLCAL computations now involve a truly 3-dimensional fault system including thrust faults and variable slip down dip. Fault geometry, fault rake, fault slip rate, fault strength and a two parameter velocity weakening friction law are all that ALLCAL requires to generate spontaneous dynamic rupture catalogs that include all fault stress interactions. Fault geometry, rake and slip rate are considered to be data, so fault strength and the two frictional parameters are the only adjustable quantities in the simulator.

The primary product of earthquake simulators is a long series of earthquakes that act as surrogates for real, but time limited catalogs. ALLCAL simulations provide all details of every rupture. For example, earthquake scaling laws, M_{max} and b-value that are input into most earthquake hazard estimates are outputs of the simulator. Agreements between observed and synthetic scaling relations such as Area versus Moment, give evidence that ALLCAL results are meaningful. The earthquake potential for California derived from the earthquake simulator is shown in Figure 60.

The model is tuned with real earthquake data. Largely, the tuning is accomplished by comparing computed earthquake recurrence intervals versus magnitude to observed intervals. Paleoseismic data constrain earthquake simulators in two ways: 1) through input of measured slip rates, and 2) by comparison of computed recurrence interval and slip per event with field measurements provided through projects like SoSAFE. While fault slip rate is a direct constraint, slip per event and recurrence interval are applied indirectly. In the simulator, these observables spring from the fundamental physics of the system through fault slip rate, fault strength and friction law parameters. Like slip rate, fault strength is thought to be preserved through many earthquake cycles. Strong fault segments tend to have larger slip per event earthquakes with longer recurrence intervals, but the correlation is imperfect because of the non-linear nature of the system and the complex memories of all preceding earthquakes. For these reasons, iterative segment strength adjustments are made to the model to match reasonably well paleoseismic recurrence data.

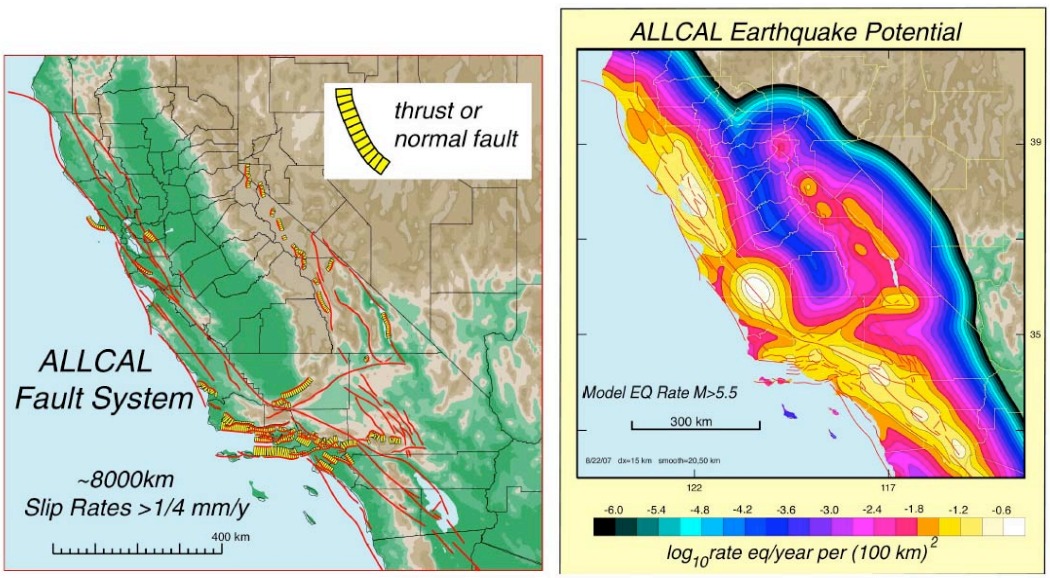

Figure 60. Earthquake potential (right) derived directly from the ALLCAL earthquake simulator (left). In the simulator, earthquakes occur only on the specified faults. Earthquake hazard and potential have been windowed off fault. Instead, geodetic information is used to fill in off fault hazard.

Modeling Seismic Moment Rate in San Andreas Fault – Great Basin System: Combination of Seismological and Geodetic Approaches. *(Zaliapin, Anderson, Kreemer, Pancha)*. It has been shown that the geodetic and seismological estimations of moment release may differ significantly on a regional level: the ratio between the observed and geodetically predicted moment releases varies from 0.1 to 100. Such discrepancies can be explained by the heavy-tailed distribution of seismic moment [Zaliapin et al., 2005a,b; 2006; 2007].

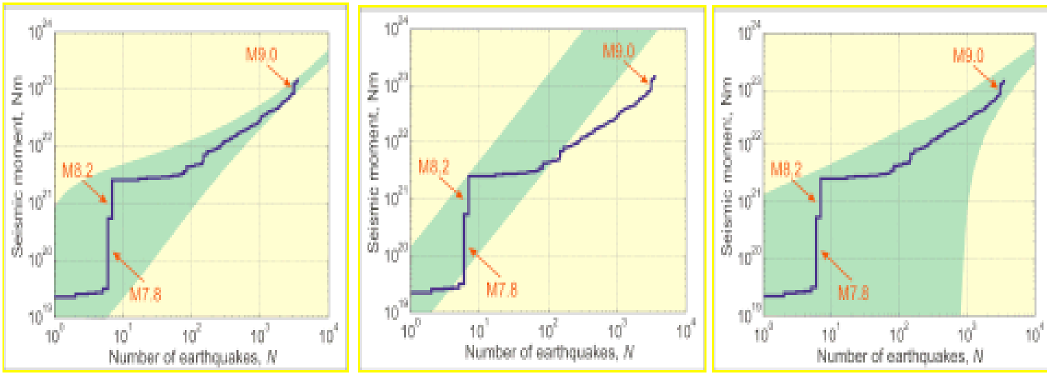

Figure 61. Alternative models for seismic moment release: tapered Pareto model (left panel), pure Pareto model (center panel), and the classical Normal model (right panel).

The practical necessity of the tapered Pareto distribution is illustrated in Figure 61, which at compares the long-term moment distribution predictions based on Normal, Pure Pareto, and tapered Pareto distributions and the observed world-wide seismic moment release during 1976-2008 according to the NEIC catalog. The tapered Pareto model (left panel) correctly accounts for short-term and long-term moment release. The pure Pareto model (center panel) overestimates the long-term release, and the classical Normal model (right panel) underestimates the short-term release. The validity of a moment release model is based on the seismic coupling ratio that is defined as the ratio between the observed and predicted moments. Under this study's approach, the predicted moment is the geodetic long-term moment release according to our strain model. The currently accepted probabilistic approximation to the long-term release is given by the expected moment according to the tapered Pareto distribution. It has been shown by the PIs during previous SCEC projects that the approximation is very close for large regions and long time-intervals. This year investigation has shown though that this approximation overestimates the moment release in small regions, which is illustrated on the left side of Figure 61.

The currently accepted model for moment release gives wrong estimations within small regions. Each point in the figure corresponds to an observed regional seismic coupling; shades depict the model predictions. To account for this discrepancy, the investigators suggest a modified model that takes into account the fact that the observed number N of earthquakes in a region is also random and obeys a heavy-tailed discrete distribution. The distribution of N is chosen based on the observed seismicity within the SAF-GB region. The results of this modified model are illustrated on the right side of Figure 62.

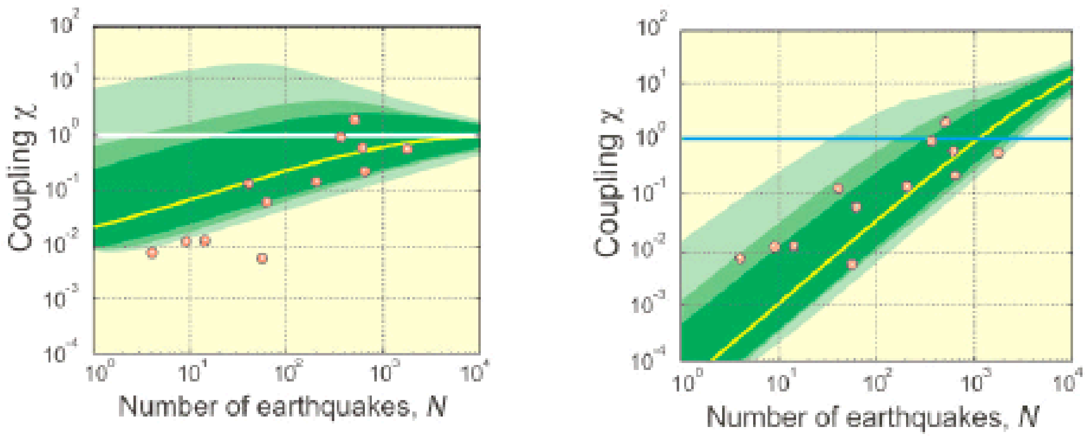

Figure 62. Distribution of seismic coupling ratio, defined as the ratio between the observed and predicted moments, for tapered Pareto distribution (left) and modified tapered Pareto distribution (right).

d. Building Response and Loss Estimation

Response of Steel Buildings to the Ground Motions of the ShakeOut Scenario. *(Krishnan, Muto, Graves).* The scenario earthquake, chosen based on a wide variety of observations and constraints, was a magnitude 7.8 earthquake on the San Andreas fault with rupture initiating at Bombay Beach and propagating northwest through the San Gorgonio Pass a distance of roughly 304 km, terminating at Lake Hughes near Palmdale, sections of the San Andreas fault that last broke in 1680, 1812, and 1857. Through community participation in two Southern San Andreas Fault Evaluation (SoSAFE) workshops organized by the Southern California Earthquake Center (SCEC), a source model specific to the southern San Andreas fault was constructed with constraints from geologic, geodetic, paleoseismic, and seismological observations.

Using this source model, Rob Graves simulated 3-component seismic waveforms on a uniform grid covering southern California (Graves et al. 2008). Peak velocities of the synthetic ground motion were in the range of 0-100 cm/s in the San Fernando Valley, and 60-180 cm/s in the Los Angeles basin (Figure 63). Corresponding peak displacement ranges were 0-100 cm and 50-150 cm. For the shakeout drill, USGS commissioned the investigators to provide a realistic picture of the impact of such an earthquake on the tall steel buildings in southern California. They selected 784 sites across southern California to place 3-D computer models of three steel moment frame buildings in the 20-story class (an existing building designed according to the 1982 UBC, the same building redesigned using the 1997 UBC, and a hypothetical L-shaped building also designed according to the 1997 UBC, and analyzed these models subject to the simulated 3-component ground motion, orienting them in two different directions, considering perfect and imperfect realizations of beam-to-column connection behavior.

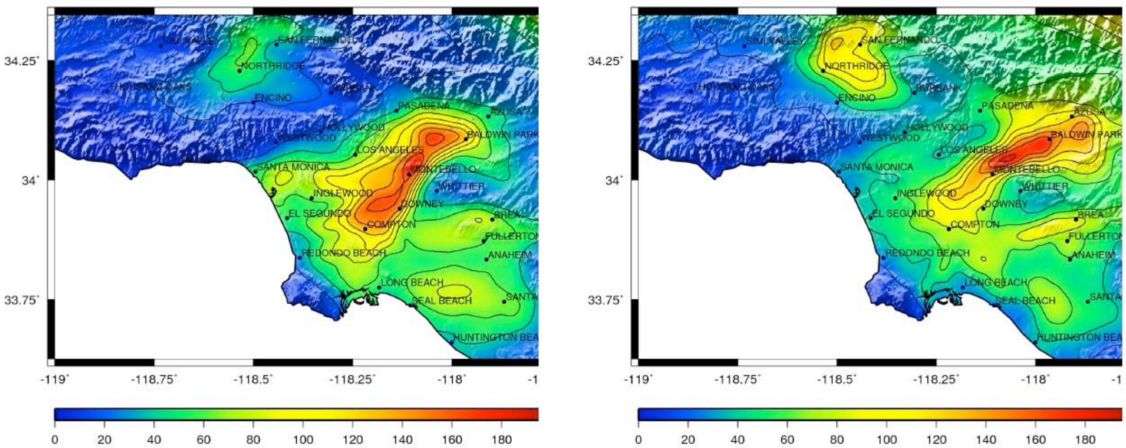

Figure 63. San Andreas fault shakeout scenario earthquake simulation: Peak ground motion under a S-to-N rupture (east and north components of velocity in cm/s.)

Figure 64 shows a map of average peak interstory drift ratios for the 12 structural models considered in this study (3 buildings x 2 orientations x 2 connection susceptibility assumptions). Structural models hypothetically located at 784 analysis sites spread across the Los Angeles basin were analyzed. The results indicated that 7% of these could be immediately occupied after the earthquake (IO, blue zone); 34% would have damage requiring building closure, but no loss of life (LS, green zone); 35.8% would have serious damage resulting in loss of life, but collapse would be prevented (CP, yellow zone); 10.5% would have to be red-tagged and may be on the verge of collapse (RT, red zone); and 12.7% would have collapsed (CO, pink zone).

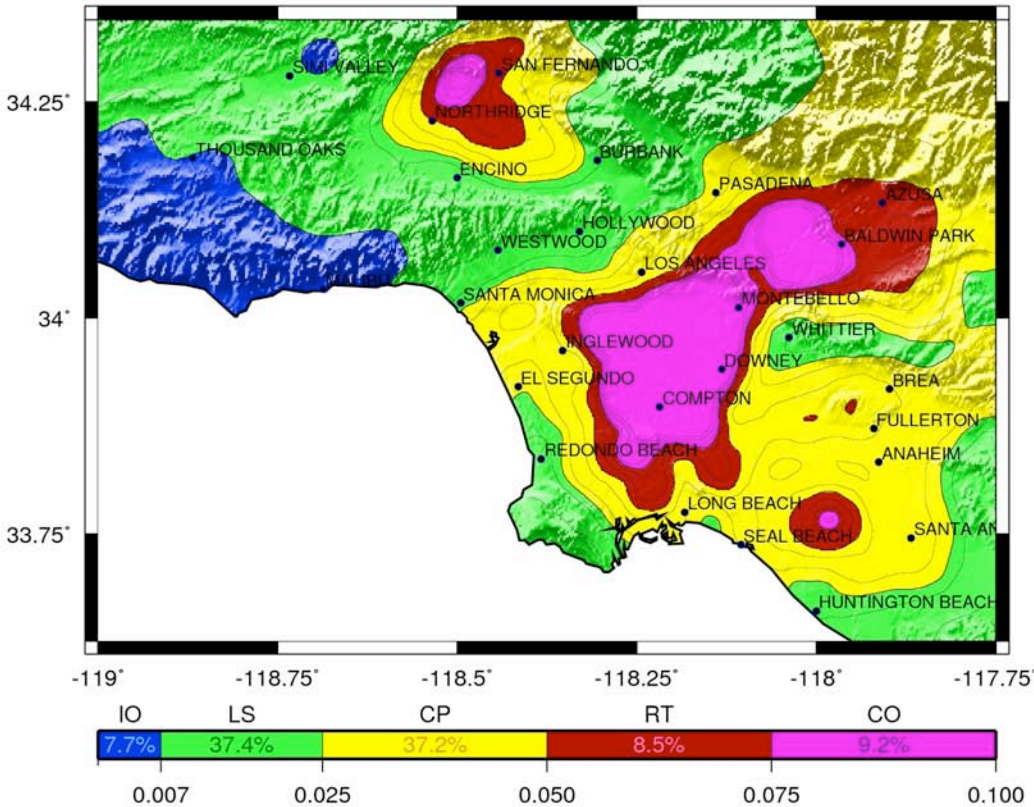

Figure 64. Distribution of peak interstory drift ratios, demarked into building damage states.

Implementation of HAZUS® to Evaluate Societal Impacts Associated with the Uniform California Earthquake Rupture Forecast (UCERF) Model & the Next Generation of Attenuation (NGA) Relationships. *(Seligson)*. The objectives of the reframed study were two-fold; to re-visit HAZUS® loss estimates for a Puente Hills scenario earthquake (studied extensively under SCEC funding in 2004-2005) relative to 1) recently developed physics-based ground motions developed by Rob Graves, and 2) recent enhancements made to HAZUS® inventory data for southern California for the “ShakeOut” earthquake scenario.

Figure 65 provides a comparison of HAZUS® total direct economic losses estimated for the various M7.15 Puente Hills scenario ground motions(for the area within the Graves’ study limits), using the enhanced “ShakeOut” inventory data. Within HAZUS®, total direct economic loss includes building and content losses, as well as inventory loss and income losses (which includes relocation costs, income losses, wage losses and rental income losses). For the physics-based ground motions, losses are largest for V2 and V5, the scenarios with the shortest rise time (V2) and the largest rupture velocity (V5). The only attenuation-based ground motions producing losses on the same order of magnitude as the largest physics-based ground motions are BJF 1997; the NGA ground motions produce losses approximately half as large as the largest physics-based ground motions.

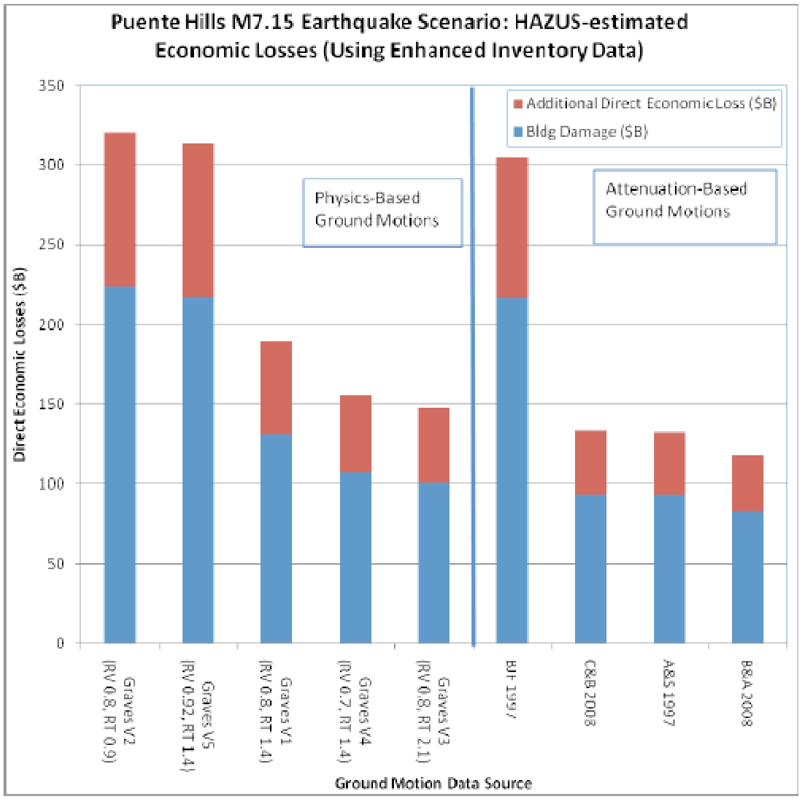

Figure 65. Comparison of Total HAZUS®-estimated Direct Economic Losses (within the Graves' grid limits) for the M7.15 Puente Hills Scenario Earthquake for various Sources of Input Ground Motion Data

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C. Special Projects

In addition to the disciplinary groups, and cross-cutting focus groups, SCEC has undertaken a number of special projects, which are focused on problems with well-defined short-term research objectives, but are nevertheless consistent with SCEC goals. These include the *Southern San Andreas Fault Evaluation (SoSAFE)*, the *Collaboratory for the study of Earthquake Predictability (CSEP)*, the *Working Group on California Earthquake Probabilities (WGCEP)*, the *Extreme Ground Motion Project (ExGM)*, and the *Community Modeling Environment (CME)*.

1. Southern San Andreas Fault Evaluation

The Southern San Andreas Fault Evaluation (SoSAFE) Project is in its third year of work towards better defining the past 2000 years of earthquake occurrence, as well as slip rates along this hazardous and intensively scrutinized fault system. The information obtained is enhancing our ability to forecast the occurrence of future destructive earthquakes along the fault system and to better predict aspects of fault system behavior. Work conducted by SoSAFE researchers is being funded by the USGS Multi-Hazards Demonstration Project (MHDP) through SCEC. SoSAFE paleoseismologists are now making systematic use of the NSF-funded B4 Project LiDAR data set along the entire southern San Andreas and San Jacinto, throughout the B4 coverage area. The SoSAFE Project furthermore links with NSF's GeoEarthScope and its funding of geochronological support, using radiocarbon and other new dating facilities and methods. GeoEarthScope has recently also acquired LiDAR along many other major faults, hence SoSAFE work with B4 data has proven to be pioneering integrative science within the SCEC framework.

On January 8-9, 2007 for the sesquicentennial commemoration of the great 1857 Fort Tejon earthquake on the southern San Andreas fault, the Southern California Earthquake Center (SCEC) held a SoSAFE science workshop. Four SoSAFE workshops have been held so far - one at each SCEC Annual Meetings; 2006, 2007, and 2008; the latest one was held jointly with Fault Systems in early 2008.

The next SoSAFE workshop will be held at the SCEC Annual Meeting in 2009. Discussion at the upcoming SoSAFE workshop in Sept. 2009 will consider the future direction of this special project in this context, as did the Sept. 2008 workshop. The leadership transition from Ken Hudnut, who led SoSAFE from its inception in Sept. 2006 through March 2009, to Co-Leaders Tom Rockwell and Kate Scharer, has begun and the new Co-Leaders will lead the upcoming workshop.

Coordinated studies employ novel dating methods and emphasize cross-validation of methods and field sampling techniques to gain a better understanding of actual uncertainties in geologically estimated slip rates over time spans of up to several tens of thousands of years. For example, studies on the San Andreas and San Jacinto faults have used cosmogenic and U-series dating, as well as soils analysis.

Another SoSAFE highlight is the exciting result from Zielke and Arrowsmith [2008] that numerous, subtle 5m offsets are present along the Carrizo Plain section of the San Andreas fault (Figure 65). These offsets are about half the ~10 m slip attributed to the 1857 Fort Tejon earthquake by Sieh [1978]. This new result agrees well with new paleoseismic recurrence from the Bidart fan paleoeseismic site [Akciz et al., 2009]. The net impact of these findings is that great earthquakes on the southern San Andreas fault are about twice as frequent as previously thought (Figure 66). Slip-rate studies within the Big Bend and south have focused on longer time-scales that integrate earthquake behavior. One of these sites, near Palmdale, promises to resolve a long-standing debate on the rate of slip (25 vs. 35 mm/yr) of the San Andreas through the Transverse Ranges [Sgriccia and Weldon, research in progress].

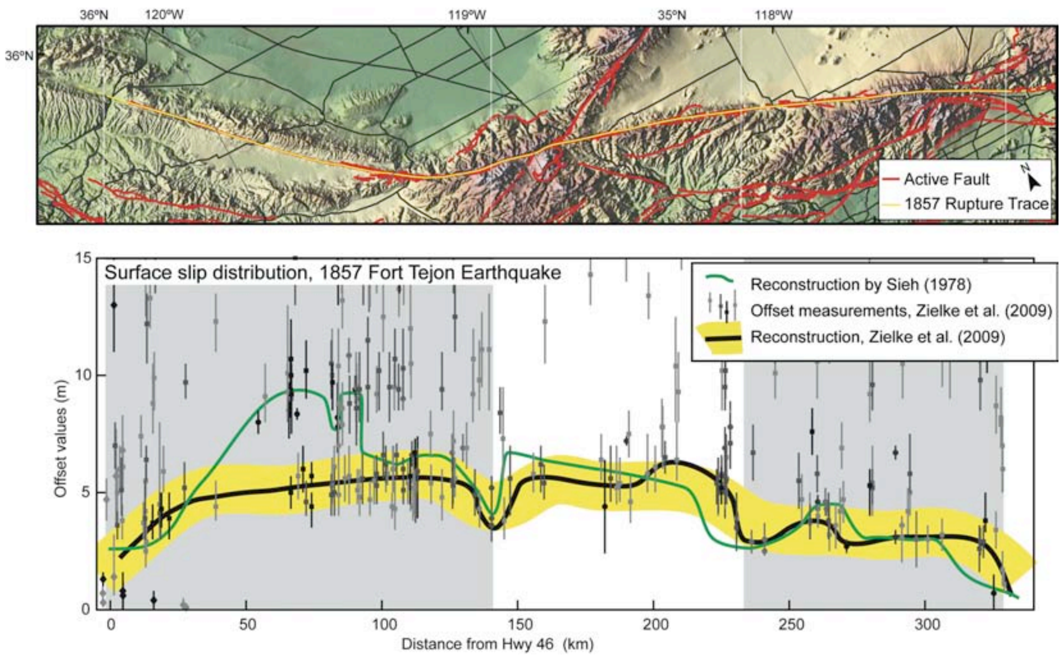

Figure 66. Results from Akciz et al. showing 1857 fault rupture yellow (upper panel). Lower panel shows previous slip reconstruction in Green [Sieh, 1978] and revised reconstruction in black [Zielke, Arrowsmith, Grant-Ludwig, and Akciz] of slip in the 1857 Fort Tejon earthquake.

In the San Andreas case, a group worked to re-examine the age of an offset alluvial fan at Biskra Palms Oasis that had been previously dated by similar cosmogenic methods. At this location, the geodetic slip rate is nearly twice as high as geologic; both rates are reasonably well constrained. This site therefore provides a testing ground for studying the uncertainties in all methods used, and in addressing possible slip rate variation through time. At Biskra Palms, two papers have reached the point of completion and will be published together soon in GSA Bulletin. – notably, both papers are first-authored by graduate students, Whitney Behr at USC and Kate Fletcher at U. C. Berkeley. In the slip rate studies on the San Jacinto, special emphasis is being given to the question of whether slip rates vary through time.

Figure 67. Old vs. new San Andreas Fault earthquakes and dates based on paleoseismological work at the Bidart fan. The revised record indicates more frequent earthquakes and is corroborated by geomorphic analysis of offset features.

Work at the Frazier Mountain site has been another major highlight of SoSAFE-funded research. SoSAFE has funded a series of other trenching studies at sites along the San Andreas and San Jacinto faults during the past two years and more in the present third year. In addition to workshops, numerous field site visits and field trips to foster collegial discussion at sites of active trenching and studies of offset channels have been conducted through SoSAFE as well. Part of the emphasis of the early 2008 workshop was on the in-field scientific review process, as well. Through these interactions, the paleoseismic community within SCEC has been able to reach consensus on a number of high priorities for future research. The highest priority identified at the first SoSAFE workshop, of obtaining more and better data in the northern Big Bend, has already been addressed well by the progress at Frazier Mountain.

In its first year, the SoSAFE group contributed heavily to definition of the ShakeOut earthquake scenario source description. Along with the more recent work highlighted here, these early successes of SoSAFE have been followed by much work that is still in progress.

We note that many other projects were also funded by the SCEC regular core funds, and also that many studies being conducted as part of the larger SoSAFE effort are also funded by the NSF and USGS NEHRP external program. SoSAFE workshops typically present research results from broad studies that are being conducted with support from these other sources as well as from the USGS MHDP special project funds.

Special project funding has been provided by USGS MHDP for the originally agreed-upon 3 years, and it should be expected to taper down after the end of the third year of funding. The USGS MHDP is necessarily moving on to emphasize other priorities, and the FY10 budget allocation for MHDP was not increased. Contingent on the amount of support the SoSAFE investigators are able to match against the USGS MHDP funds, the ramp-down rate may vary; that is, continued or increased matching would be taken as a healthy indication, and would encourage USGS to maintain ongoing support rather than ramp it down sooner.

2. Collaboratory for the Study of Earthquake Predictability

The special project Collaboratory for the Study of Earthquake Predictability (CSEP) is developing a global program of research on earthquake predictability through prospective, comparative testing of scientific prediction hypotheses in a variety of tectonic environments. CSEP is an open, international partnership, and our purpose is to encourage participation by scientists and research groups from other countries who are interested in the scientific study of predictability. To understand earthquake predictability, scientists must be able to conduct prediction experiments under rigorous, controlled conditions and evaluate them using accepted criteria specified in advance. Retrospective prediction experiments, in which hypotheses are tested against data already available, have their place in calibrating prediction algorithms, but only true (prospective) prediction experiments are really adequate for testing predictability hypotheses.

The CSEP core group at USC developed during the year 2007 the first two released versions of the CSEP Testing Center Software. At the beginning of 2008, the testing center (Schorlemmer & Gerstenberger, 2007) at USC was hosting several experiments for the testing area of California: First, CSEP inherited a variety of forecasts created for the RELM (Field et al., 2007) experiment (5-year forecasts). Second, two 1-day forecast models were installed in the testing center, ETAS and STEP. Third, for intermediate-term forecast testing, CSEP started a new 3-month model class and seven forecast models were installed in the testing center. CSEP was able to complete the initial phase of the collaboratory development in 2007 with an operational testing center and different experiments underway.

In 2008-09, CSEP kept the pace and expanded into all directions. New testing regions were established (Western Pacific, Japan, and a global testing program). New testing procedures were introduced and the testing center software was optimized for processing speed and memory usage. Several meetings were held at USC and INGV, Rome, and a collaboration between SCEC and the Earthquake Research Institute (ERI) of the University of Tokyo was established for erecting a testing center at ERI.

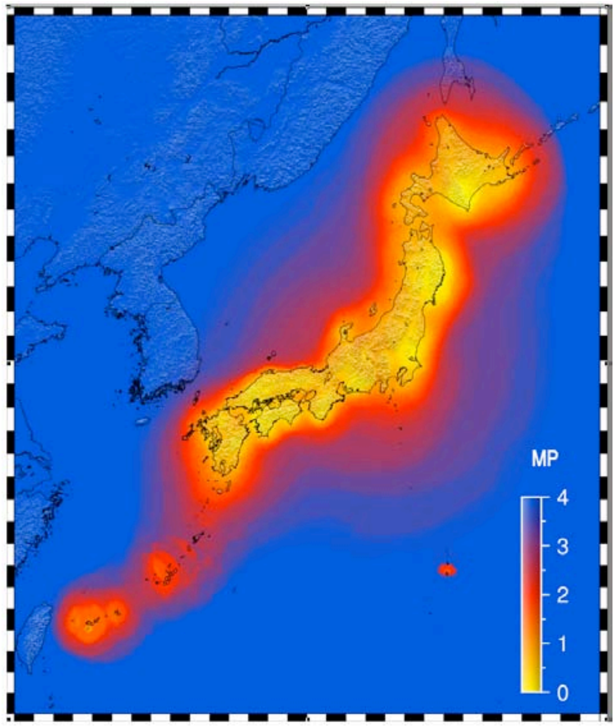

Figure 68. Probability-based magnitude of completeness of the JMA network on 1 April 2008.

a. Collaboration Between SCEC and ERI

D. Schorlemmer was invited as research fellow to spend the summer at ERI. During this visit, he conducted a full characterization of the network recording completeness of the network of the Japan Meteorological Agency (JMA), employing the PMC method (Schorlemmer & Woessner, 2008). The results of this study were used to define the Japanese testing region. Although the results confirmed that the JMA network is a high-quality network with a completeness magnitudes spatially below (Figure 68), the CSEP group in Japan (N. Hirata, K. Nanjo, H. Tsuruoka) decided to first mimic the experiments from California and to use the same magnitude ranges for forecasting and testing. Analogous to the procedure in Italy and California, the testing region was defined to capture not only Japan but also a region of approx. 100 km around it to allow testing of hazard-relevant forecasts.

ERI established an agreement with JMA for the use of the JMA catalog data for the forecast experiments in CSEP. This agreement also includes that CSEP researchers can freely use the JMA data for model development. ERI also invited software engineer F. Euchner from the European CSEP team at ETH to help installing the CSEP testing center software. The installation was finished during the visit of both CSEP members and the system went operational as a prototype on 1 September 2008, the Japanese Earthquake Preparedness Day, with three 1-year models: A "Relative Intensity" (RI) model provided by K. Nanjo, "TripleS" by J. Zechar, and "JALM" by D. Schorlemmer. All three models are essentially smoothed seismicity models, except for JALM, which additionally uses spatially varying b-values for forecast generation. Because the latency of the JMA catalog is up to 6 months before the final publication of earthquake locations, the CSEP group decided to first run a retrospective experiment to test the functionality of the Japanese testing center.

b. Other Testing Regions

Besides the new Japanese testing region, CSEP established two new testing regions for which experiments are hosted at the testing center at USC: The Western Pacific region and global testing (see Figure 69).

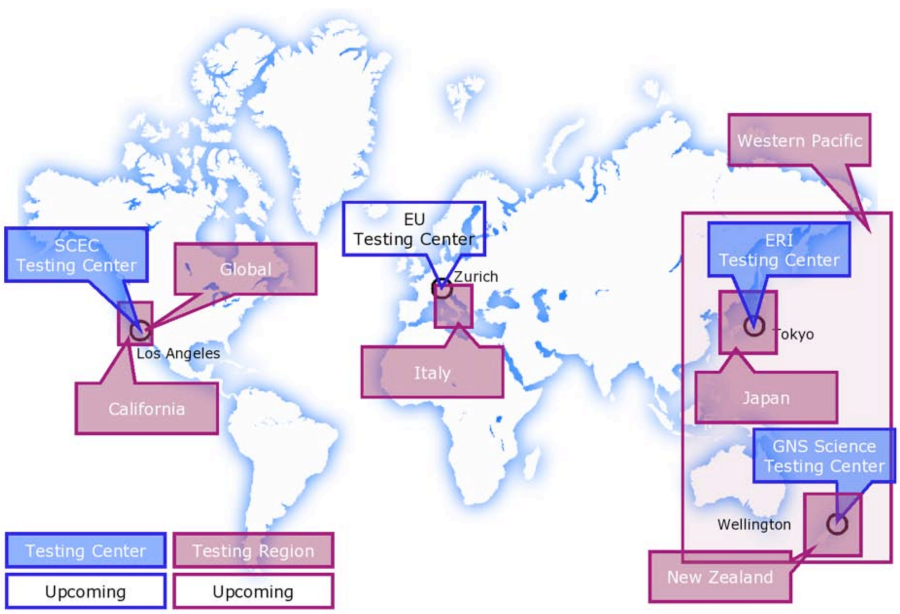

Figure 69. Distribution of CSEP testing regions and testing centers at the end of 2008.

Because Y. Kagan and D. Jackson were performing earthquake forecasting and testing in the Western Pacific region, CSEP decided to include this experiment in the testing center to ensure long-term processing of this ongoing experiment and to open this experiment to other researchers with competing models. Furthermore, this testing region can be considered a blueprint for global testing as it already covers 55% of global seismicity and only a global catalog can be used for the experiment. In addition to the models by Y. Kagan and D. Jackson, W. Marzocchi and A. Lombardi installed their Double-Branching Model, and J. Zechar provided the TripleS model. For historical reasons the Western Pacific region is divided into a northern and a southern part; CSEP decided to not change the original setup.

After successful implementation of the Western Pacific region, CSEP implemented a prototype global testing region. A consensus between modelers was reached to start global testing with a low-resolution but regular grid. Several other possibilities were discussed during the Global Testing Meeting, from high-resolution grids to a grid with varying resolution to allow for detailed forecasts in high-seismicity areas but to not force modelers to provide high-resolution forecasts in areas of sparse seismicity. Two models were submitted: TripleS and Double-Branching.

To prepare the future extension of the global program to high-resolution testing, a 0.1x0.1 degree grid was proposed but is still debated. The primary goal of such a regular high-resolution grid is to match with local testing regions such that each global model can be automatically used as a regional model. For this purpose, all local testing regions were designed to exactly match with this proposed global grid. The California, Italy, and Japan grid were originally defined in a way that they match, but the New Zealand testing was shifted by 0.5 degrees in latitude and longitude. Because only preliminary testing was underway in New Zealand, no experiment had to be stopped or canceled.

c. Developments in Italy

The Italian CSEP group organized a meeting on 27 October 2008 to solicit model submissions for the upcoming experiments and to reach a consensus of the rules for each of the proposed experiments. Because the RELM experiment received a high attention due to the large variety of submitted forecasts, the CSEP group decided to repeat such an experiment in Italy. For the RELM forecasts, researchers were able to use input data for their forecasts that are currently not provided by CSEP for models running in the testing center. This allows for the large variety of forecasts because geodetic and geologic data were also used. Furthermore, providing only a forecast (as numbers) is easier for modelers than to install codes in the testing center. Two experiments will be conducted, one for 5-year forecasts and the second one for 10-year forecasts. A deadline for model submission was set to July 2009 and testing is projected to start in August 2009. Besides the experiment for RELM-type forecasts, the European testing center will open for model installation. Defined experiments encompass 1-day, 3-month, and 1-year tests.

d. New Testing Procedures

In early 2008, the CSEP development team improved the testing codes implemented in the CSEP testing center software distribution for speed and memory usage. This, and the previous improvement accomplished in 2007, helped to reduce the computer time for performing all tests and to allow for easier recomputations.

On the scientific side, alarm-based testing was introduced using different testing procedures: Molchan Test (Molchan, 1990, 1991), ROC Diagram (Mason, 2003), and the Area Skill Score (Zechar & Jordan, 2008, 2009). Alarm-based testing was introduced to the testing regions of California, Western Pacific, and the global program. The new tests were formulated in a way such that they are also used for evaluating the rate-forecasting models (Schorlemmer et al., 2007); this provides further evaluations of the models and will help better understand the performances of the various models.

e. Software Development

The software development is the main focus of the current CSEP development as a functioning infrastructure is the base line for any CSEP related operation. The software development team decided to release new testing center software versions in a 3-month cycle. One month before the release, no new features will be added to the system and the particular system will be tested and checked for roughly one months. Only after successfully passing the acceptance tests for the software system, the new codes will be released.

A large portion of the time of the CSEP main developer M. Liukis was needed to support modelers installing their earthquake forecast codes in the system and to adapt the system capabilities to support the models such that they can be seamlessly integrated.

In parallel to the development of the operational system, J. Yu worked on the result viewing component of the CSEP website to improve the user experience for this website.

f. Results

In mid-2008, the first half of the RELM experiment was accomplished (2.5 years of the 5-year experiment). The CSEP group decided to prepare an intermediate report to inform the modelers and the wider scientific community about the results and the experiment. This report was presented at many meetings and was also submitted to the special volume of Pure and Appl. Geophys. about the Evison symposium held in early 2008 in Wellington, New Zealand, and covering many aspects of statistical seismology (Schorlemmer et al., in print).

In February 2008, a swarm of several M5+ earthquakes hit the Baja California area. Fortunately for CSEP, this swarm was in the southern part of the California testing region and offered a great opportunity to evaluate the two 1-day models for California. The surprising results was that, although the STEP models was more strongly focusing the projected aftershock area, the ETAS model clearly showed better performance. This because the STEP model's forecasts were off by some tens of kilometers to the east (see Figure 3). Discussion with the author M. Gerstenberger revealed that most likely a software bug caused the model to shift the forecast in the grid. As a consequence, M. Gerstenberger is working on a new version of the model for later submission. This result was also reported to the USGS that currently uses the STEP model for their “tomorrow's earthquake forecast” webpage.

g. Outreach and Communication

CSEP held three meeting during the year 2008: A testing meeting to discuss ongoing testing procedure developments and to agree on future tests to be implemented; a global testing meeting to prepare a global testing program; and a meeting in Rome to prepare testing in Europe, to solicit models, and to find a consensus in the testing rules for Europe.

Besides these meetings, CSEP was present at all major conferences and hosted several scientific sessions at these meetings. In 2008, CSEP sessions were held at the Evison symposium in Wellington, New Zealand and at the SSA annual meeting in Santa Fe, USA. Results of CSEP testing were presented at all of these meeting and a report about the first half of the RELM experiment was compiled.

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3. Extreme Ground Motion

Extreme ground motions are the very large amplitudes of earthquake ground motions that can arise at very low probabilities of exceedance, as was the case for the 1998 PSHA for Yucca Mountain. The Extreme Ground Motion (ExGM) project, is a three-year study, sponsored by the Department of Energy, that investigates the credibility of such ground motions through studies of physical limits to earthquake ground motions, unexceeded ground motions, and frequency of occurrence of very large ground motions or of earthquake source parameters (such as stress drop and faulting displacement) that cause them. A particular interest to ExGM, which applies more generally to the Fault and Rupture Mechanics, Ground Motion Prediction, and Seismic Hard and Risk Analysis focus groups, is why crustal earthquake stress drops are so sensibly constant and so much less than the frictional strength of rocks at mid-crustal depths. The main SCEC disciplinary and focus groups that work on this project are Geology – especially fault zone geology; Faulting and Mechanics of Earthquakes, Ground-Motion Prediction, and Seismic Hazard and Risk Analysis. Elements of this project are discussed above within these focus group reports.

a. 3D Rupture Dynamics Code Validation Workshop

Numerical simulations of earthquake rupture are used by SCEC researchers for a variety of purposes – from ground motion prediction, such as in the Extreme Ground Motion and PetaSHA DynaShake projects, to the basic goal of a better understanding of earthquake source physics. In either case, it is critical for the simulations to be numerically accurate and reproducible. For some types of geophysics and seismology problems, tests of numerical accuracy are simple, since the codes can be compared with analytical solutions. For dynamic earthquake rupture simulations however, there are no analytical solutions, and code testing must be performed by other means, such as with a code comparison exercise.

Within SCEC, rupture dynamics modelers who consider the physics of earthquakes will continue to use a range of computational methods to simulate earthquake behavior. No single numerical method has been shown to be superior for all problems. Therefore a number of numerical codes are being used, each with its own advantages. These include finite-difference, finite-element, spectral element, and boundary integral techniques. Whereas some of the methods are extremely accurate and computationally efficient at certain types of problems, for example investigating a range of earthquake friction mechanisms, others are better at simulating realistic fault geometry or the propagation of waves through the heterogeneous crust.

The November 17, 2008 3D Rupture Dynamic Code Workshop was led by Ruth Harris included approximately 34 participants, and was funded by the Extreme Ground Motion Project due to the need to have verified codes for simulations of dynamic rupture and ground motions at Yucca Mountain. The workshop was described in detail in the FARM focus group session, but here we note that inclusion of tests on a dipping normal fault was important for the Extreme Ground Motion project. Also relevant was the decision to work towards benchmark simulations that included the effects of realistic off-fault yielding as part of the rupture process.

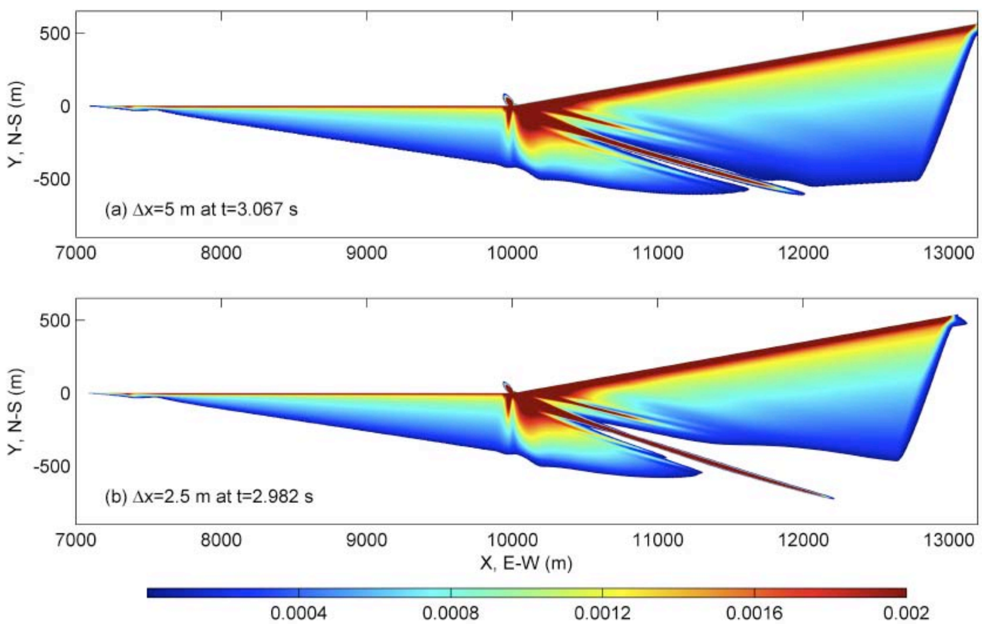

Figure 70. Distribution of off-fault plastic strain magnitude due to rupture on a fault with a kink (at x = 10 km, y = 0 km). Plastic strain localizes into bands and lobes near the kink, and the solution of the localization is apparently convergent when the element size is reduced. (From Duan and Day [2008]).

b. Non-Planar Faulting and Off-Fault Damage

Dynamic rupture modeling usually assumes planar faulting, but this clearly violates observations of faulting in the Earth. Non-planar faulting is interesting to the extreme ground motion because it may lead to strong high-frequency radiation in earthquakes. Another aspect of real faults that is increasingly being incorporated into models of dynamic rupture is the effect of off-fault yielding on earthquake rupture. This will have a strong effect on high frequency radiation as well, so the two issues are intertwined.

Duan and Day [2008] completed a study of elasto-plastic dynamics of non-planar faults. They examined inelastic strain near a fault kink and how it affects both rupture dynamics and seismic radiation from the kink. They found extensive inelastic deformation near a restraining bend, particularly on the side of the fault associated with rupture-front extensional strains (Figure 70). The extensive inelastic deformation reduced high-frequency radiation from the kink and the reduction is significant above several Hz. They also found that plastic strain sometimes localizes spontaneously during rupture along a planar fault; however, the details of the shear banding change with element size, indicating the challenge of numerically simulating inelastic off-fault deformation. They continue their work on this problem, and are including pore pressure effects, with an eye towards the specifics of the Solitario Canyon fault. They anticipate that off-fault yielding, and its effect on rupture, will help place upper bounds on ground motion.

Duan also worked on the challenging problem of modeling kinked faults, with both a material contrast and off-fault yielding. Previously, he had found that bi-material ruptures lead to asymmetric damage [Duan, 2008]. In this study he found that releasing bends suppress the bi-material effect, whereas restraining bends reinforce it.

Dmowska, Templeton, and Rice studied dynamic rupture with fault branching in a configuration of specific interest for the Solitario Canyon Fault. They also initiated more general studies on rupture through (or arrest at) complex fault junctions that involve branches and damaged fault bordering zones. The studies allowing for Mohr-Coulomb type elastic-plastic response in the simplified Drucker-Prager formulation. Their results on the effect of off-fault yielding, and fault branching, on ground motion for this specific configuration are shown in Figure 28.

Goldsby and Tullis continued their work to understand fault weakening mechanisms including: flash heating, silica gel lubrication, and thermal pressurization that may be operative at high slip speeds. All of these could have profound implications for the magnitude of stress-drop, and thus for the intensity of strong ground motion. This information is important for resolving questions concerning stress levels in the crust. If coseismic friction is low, and the magnitudes of dynamic stress drops are constrained to modest values by seismic data, then the tectonic stress acting on faults must also be modest. We may have a strong crust that is nevertheless able to deform by faulting under modest tectonic stresses if the strength is overcome at earthquake nucleation sites by local stress concentrations and at other places along the fault by dynamic stress concentrations at the rupture front. Thus, understanding high-speed friction is important not only for predicting strong ground motion, but also for answering major scientific questions receiving considerable attention and funding, e.g. the strength of the San Andreas fault and the stress-heat flow paradox.

c. Precariously Balanced Rocks

Where they are available, precariously balanced rocks (PBRs) have the potential to provide unique constraints on long-term levels of strong ground motion. So they are of particular interest to the Extreme Ground Motion project. A key issue in using PBRs for this purpose, is in determining how long they have been precarious. For that reason, a key concern of PBR research in 2008-09 was age dating.

Grant Ludwig and her collaborators [Grant Ludwig et al., 2007; Rood et al., 2007; Scholm et al., 2008] focused on constraining the age and exhumation or "renewal" rates of PBRs. They identified PBRs with good potential for dating at sites that are important for ground motion validation (Figure 71). In 2007 and 2008, they collected samples from 9 rocks at 6 sites for 10Be analysis, and obtained preliminary exposure ages of four PBRs near the southern San Andreas. In early 2009, they collected additional samples to refine model dependent (Figure 72) exposure ages of rocks at these sites, and to investigate activity of the Cleghorn fault at the critical Grass Valley site in order to interpret results relative to ground motions from San Andreas and/or San Jacinto earthquakes.

Figure 71. Rocks sampled at Lovejoy Buttes, Pacifico, Grass Valley and Beaumont South for 2007-2008 pilot study (Rood et al., 2008).

Scenario	E_A (m/Myr)	E_B (m/Myr)	T_{EXP} (yr)
1 FAST EXHUMATION ($E_A > E_B$)  Curvature = max +	2000	32	22000
2 EQUAL EXHUMATION RATES ($E_A = E_B$)  Curvature = 0	50	50	31000
3 SLOW EXHUMATION ($E_A < E_B$)  Curvature = max -	15	500	46000

Figure 72. (left). Model 10Be profiles for different exposure scenarios, erosion rates, and exposure times. In profiles (red), x-axes are 10Be concentration (N) and y-axes are depth/height (Z). Note curvature and magnitude of erosion rate differences that can be used to test geomorphic models and refine exposure times.

2009 will mark the 3rd year of the 3-year Extreme Ground Motion project. A final report summarizing the results of the project is planned to be submitted to SCEC for review by December, 2009.

d. References

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4. Community Modeling Environment

The Southern California Earthquake Center (SCEC) Community Modeling Environment (SCEC/CME) collaboration is an inter-disciplinary research group that includes geoscientists and computer scientists from University of Southern California, San Diego State University, University of Wyoming, Stanford University, San Diego Supercomputer Center (SDSC), the University of California at San Diego, Carnegie Mellon University (CMU), Pittsburgh Supercomputer Center (PSC), and USC Information Sciences Institute (USC/ISI). The CME collaboration develops computational models of earthquake processes and uses high performance computing (HPC) systems to run these predictive numerical models and produce physics-based seismic hazard estimates for California.

Many SCEC researchers use numerical modeling in their work. However, complex system science calculations such as seismic hazard analysis calculations for California require expertise in several geoscientific specialties as well as several computer science specialties. The CME collaboration enables SCEC to conduct computational research at scales and complexity levels that exceed what individual researchers or small research groups can typically accomplish.

Several recent scientific advisory and workshop reports including Living on the Active Earth (National Research Council – 2003) and Long Range Science Planning for Seismology (NSF – 2009) have discussed how numerical modeling techniques can be used to improve current seismic hazard analysis estimates. In order perform large-scale seismic hazard calculations, geoscientific expertise from SCEC collaborate with computer scientists that specialize in high performance scientific computing. The CME has produced a series of significant scientific results since its inception in 2001. In this SCEC/CME Project report for 2009, we present an overview of CME research activities and summarize some of the research results obtained by the group this year.

a. CME Science and Computational Goals

The scientific goals of the CME Project have been defined to support the scientific goals of the core SCEC program. Many of the SCEC 3 science objectives require the use of computer modeling and the CME is developing the scientific computing systems needed for SCEC reach those objectives. At the start of the CME program, SCEC researchers defined four SCEC Computational Pathways for seismic hazard analysis (Figure 73). These Pathways represent increasingly complex and computational expensive ways to calculate ground motion predictions. The CME scientific software and computer system developments are designed to help SCEC researchers perform one or more of the SCEC Seismic Hazard Computational Pathway calculations.

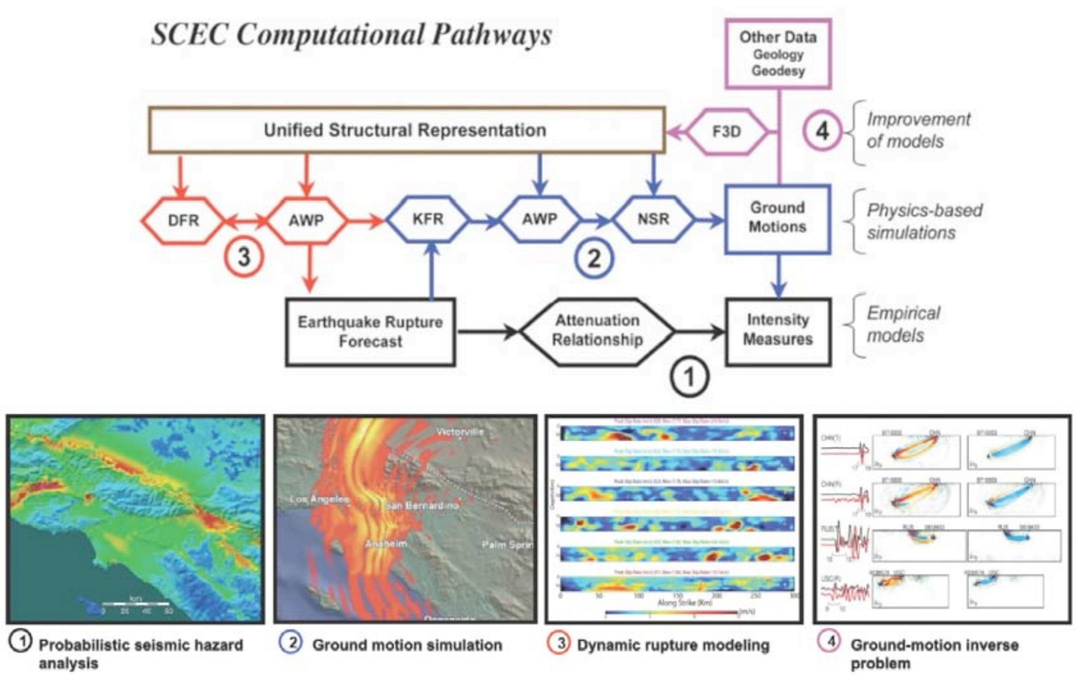

Figure 73. A wiring diagram for the SCEC computational pathways in seismic hazard analysis (upper diagram) and large-scale calculations (lower panels). The computational modules with three-letter abbreviations are described in Box 1. (1) High-resolution seismic hazard map for the Los Angeles region using the UCERF2 model. (2) Simulation of a M 7.8 earthquake on the southern San Andreas Fault for the 2008 ShakeOut exercise. (3) Dynamic rupture models for a M 7.8 earthquake on the southern San Andreas Fault used in the ShakeOut-D simulations. (4) Frechet kernels used in full 3D waveform tomography to improve seismic velocity models in Southern California.

The SCEC Computational Pathways calculations produce predictive seismological parameters with broad impact. These predictive seismic hazard parameters include scenario ground motion maps (used in emergency management exercises), scenario broadband seismograms (used in seismic engineering of tall buildings), and probabilistic seismic hazard curves (used in insurance loss estimations). Groups such as emergency management organizations, building engineers, and insurance organizations will benefit if SCEC science can improve these predictive data products. By integrating new SCEC science results into highly-scalable computational models and running seismic hazard calculations on national supercomputer facilities, the CME simulation results help the SCEC science program have an immediate societal impact.

The CME collaboration has identified four specific computational improvements that are needed to advance the SCEC science program towards its goal of improving ground motion predictions. The following four scientific and computational goals identify specific computational improvements that the CME is pursuing in order to improve the accuracy of ground motion predictions for California.

Goal 1: Improve the resolution of dynamic rupture simulations by an order of magnitude to investigate realistic friction laws, near-fault stress states, and off-fault plasticity.

Goal 2: Investigate the upper frequency limit of deterministic ground-motion prediction by simulating strong motions up to 3 Hz using realistic 3D structural models for Southern California.

Goal 3: Validate and improve the Southern California structural models using full 3D waveform tomography.

Goal 4: Transform probabilistic seismic hazard analysis (PSHA) by using wave propagation modeling rather than empirical attenuation relationships in PSHA calculations.

These goals provide the CME with specific scientific and computational improvements that are needed to improve seismic hazard numerical modeling efforts. In particular, these goals address the seismic hazard issues of broad impact including development of accurate source descriptions, verification and validation of 3D structural models, and the integration of state-of-the-art numerical modeling techniques into standard PSHA calculations.

b. CME Simulation Planning and Results

As SCEC researcher develops new insights into earthquake processes and improves earth structural models, these scientific improvements are integrated into computational models and used for large-scale seismic hazard simulations. The CME collaboration together with researchers from SCEC and other research organizations has performed a series of significant simulation results over the last several years.

The planning and performance of large scale simulations go through a similar process. First, CME geoscientists identify an important scientific issue relating to our understanding of seismic hazards in California that can be investigated through numerical modeling. Then, in situations where the computational requirements exceed the capabilities of our numerical modeling tools, CME researchers extending and improving current CME computational capabilities. Once all the seismological and high performance software is integrated to work together we consider it a computational platform. Then the computational platform must be re-verified and re-validated which is typically done by using the system to run reference problems with known good solutions. Once the platform is confirmed ready for use, the large scale simulations are run. Planning, development, testing, and running of a CME simulation often takes 6 months of consistent team work. Once the simulation is completed, researchers require additional time to analyze and publish the results. It is common for three or four such large simulations to be underway in the CME collaboration at any one time.

When the SCEC simulation goals exceed the capabilities of our current numerical modeling tools, we work with CME computer scientists to develop the required computational capabilities. The CME computer scientists have greatly improved the scalability of SCEC wave propagation codes. SCEC is now qualified to run on the world's largest supercomputers. The CME computer scientists have automated our distributed computing using scientific workflows that enable us to perform probabilistic seismic hazard calculations requiring 100M+ jobs and 100M+ files. By repeating the project phases including; a) definition of new scientific questions, b) HPC cyberinfrastructure development, and then c) integration of new scientific computational capabilities into a practical PSHA framework, the CME project produces important new results and establish the numerical

c. CME Communication, Education, and Outreach

The SCEC CEO Program helps the CME collaboration communicate SCEC and CME research results. CME collaborators participate in SCEC intern programs including UseIT and ACCESS. The 2009 UseIT program recently concluded another successful summer in the IT lab at SCEC (Figure 74).

ACCESS-G students working with CME are conducting projects on (a) Vector and tensor Visualization (McQuinn, Minster, Chourasia – UCSD/SDSC), (b) Building Response Animation (Fu, Krishnan - USC/Caltech), and (c) Data Management and Data Access Tools for SCEC simulation archives (Pechprasarn, Maechling – USC/USC) (Figure 75).

The CME helps to provide SCEC researchers with access to HPC systems. SCEC numerical modeling researchers can make use of the CME computer allocation on the USC High Performance Computing and Communication (HPCC) system. When the CME simulations need more computer power than available at USC, we move simulations to NSF TeraGrid facilities onto system that exceed 60K cores. Beginning in January 2009, the CME was awarded computer time and has begun to run simulations on a Department of Energy (DOE) Leadership class computer called Intrepid at Argonne National Laboratory's (ANL) which exceeds 130K cores. The CME's computational results and accomplishments have raised SCEC's profile in the national and international high performance computing community. SCEC's computational science program now approaches the scale of other large-scale HPC scientific users including high energy physics, chemistry, and atmospheric science.

Figure 74. The SCEC Undergraduate Studies in Earthquake Information Technology (UseIT) attracts students from around the country to study earthquake system science. Over 140 students have successfully complete their SCEC internship in the last 6 years of the program. The twenty three on the left are participating in the 2009 summer UseIT program are supervised by the PI and SCEC Educational specialist (Robert de Groot, PhD). The interactive 3D visual earth environment software developed by the group under the name SCEC Virtual Display of Objects (SCEC-VDO) has been used frequently to display earthquake information for the public media. The SCEC-VDO development has also been used in a USC multi-media literacy program conducted by the USC college of Letters, Arts, and Sciences in collaboration with the USC School of Cinematic Arts.

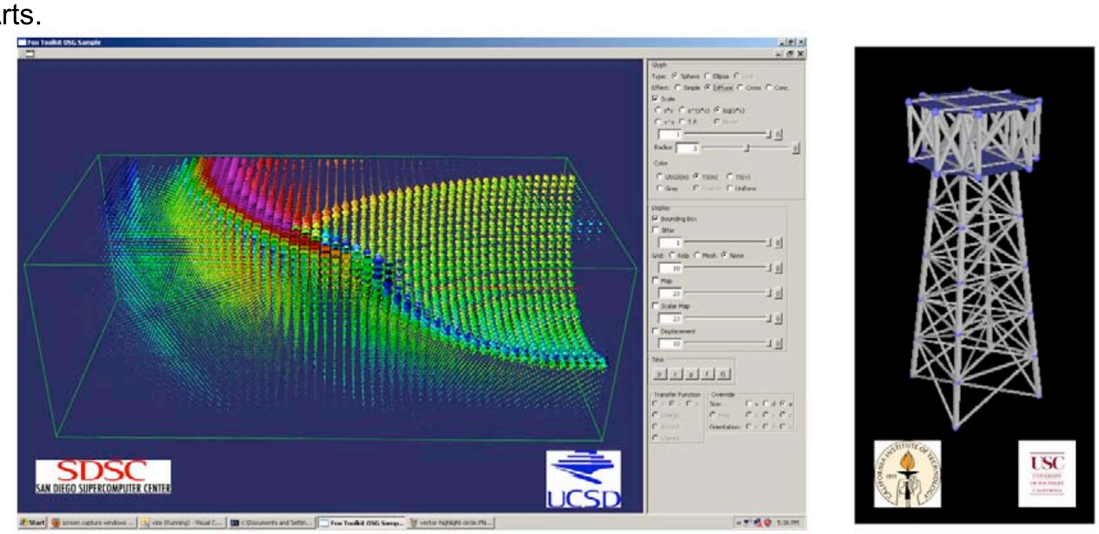

Figure 75. SCEC Access-G CME related projects include (left) development of new techniques for visualizing volumetric data from wave propagation simulations. Images shows acceleration vectors in a volume rendering of acceleration vectors during a SORD simulation (McQuinn, Minster, Chourasia - UCSD/SDSC) and (right) an animation frame from a 3D rendering of a Caltech Virtual Shaker structural response simulation (Fu, Krishnan - USC/Caltech).

CME project members regularly present SCEC research at computer science and HPC conferences such as Supercomputing and TeraGrid. This year, multiple articles about CME research were written and presented on NSF TeraGrid web sites including Texas Advanced Computer Center (TACC) and National Institute for Computational Sciences (NICS) at Oak Ridge National Laboratory. These articles about SCEC research were picked up and used by public science outlets including Live Science and US News and World Report. CME simulations are featured in a number of widely used scenario earthquake animations. CME ShakeOut simulation images were used in USGS literature and on public television. SCEC Intern animations from SCEC-VDO are distributed by new agencies from the news agency web sites. Visualizations of CME simulations produced by Amit Chourasia and others at San Diego Supercomputer Center (SDSC) continue to with awards for scientific visualizations including recent awards from DOE Scientific Discovery through Advanced Computing (SciDAC) in 2009 and ACM SIGGRAPH 2009.

SCEC, as a system science organization with broad research goals, has a wide variety of computational science research needs. SCEC's computer science capabilities, including the CME, rates with the best in any geophysical research group in the world. In particular, SCEC has developed one of the most scalable wave propagation codes (AWP-Olsen) and one of the largest and most complex scientific workflow systems (CyberShake1.0) in existence. Also, the CME work on full 3D Tomography has identified SCEC as one of the most data intensive computational groups in any NSF research domains. As the CME research program improves SCEC's scientific computing capabilities it helps to establish a leadership role for SCEC in national scientific computing.

d. SCEC Projects Organization

SCEC/CME activities were initiated in 2001 under a five-year NSF Information Technology Research (ITR) award. Through the CME ITR Project, SCEC was able to establish collaborative research activities with computer scientists and through these geoscience/computer science collaborations the scale and capabilities of the SCEC computational science program greatly increased. Since the NSF ITR program ended in 2006, CME activities have been supported through NSF OCI and EAR awards under Project names including PetaSHA-1, PetaSHA-2, PetaShake-1, and PetaShake-2. Detailed information about each of the awards is posted on the CME project web site (*http://www.scec.org/cme*).

Current funding for the CME is approximately 1.6M/year under two different NSF awards. These awards are (1) Petascale Cyberfacility for Physics-Based Seismic Hazard Analysis (PetaSHA-2) (EAR – 074493 – May 1, 2008 to April 30, 2010), and (2) Outward on the Spiral: Petascale Inference in Earthquake System Science (SCEC PetaShake Project) (OCI-0905019 - August 1, 2009 to July 31, 2011). The CME collaboration awards augments core SCEC research funds and provide a way for SCEC to rapidly migrate new research results into useful seismic hazard products.

CME Project funds are allocated to ten different research groups each of which has budget under the CME NSF awards. Some of the CME funded groups are led by computer scientists. The CME's collaborative work with computer scientists has been of great benefit to the SCEC computational modeling work. CME computer science groups have contributed great improvements in the scalability, automation, data management, and reliability of many SCEC simulations. We also believe there is wide recognition within NSF, and other scientific organizations, in the value of interdisciplinary collaborations between domain scientists and computer scientists. The CME collaboration provides an outstanding example of how such interdisciplinary groups can collaborate to good effect.

CME Projects are conducted under the scientific leadership of Principal Investigator (PI), Thomas H. Jordan. Day-to-day CME project operations are managed by Philip Maechling, SCEC IT Architect. The CME holds annual All-Hand Meetings (separate from the annual SCEC meeting) and collaborative CME project goals are coordinated by the CME senior scientists. CME Project coordination teleconference calls are held on a regular basis and CME Project results are posted on the CME web site and are presented as abstracts, posters, and talks at conferences including the SCEC annual meeting.

e. Anticipated Growth in Computational Science

Both the NSF and DOE are building very large-scale HPC systems, which will become available for open-science research within the next two years. The NSF is building a sustained Petaflops system that they call a Track 1 computer (Blue Waters at NCSA). DOE is deploying what they call Leadership Class Petascale computers for open-science research including Intrepid at Argonne National Lab and Jaguar at Oak Ridge National Lab. As these HPC systems become available, the sponsoring organizations will be very interested in using them to perform important scientific research. SCEC, as a large, deep, inter-disciplinary research consortium is one of the few groups capable of performing computational science at petascale. And current CME HPC capabilities have positioned SCEC as one of the few groups qualified to run on these largest systems.

Because this new class of supercomputers is about to become available, the time may be right to for SCEC to identify one or more seismological computational "Grand Challenges" and collaborate with geoscientific groups and HPC system operators to attempt some highly challenging, computationally intensive, and transformative research. If the SCEC science planning committee identified a computational challenge that is currently well outside the scale of any computer or research group, it might be possible to collaborate with the NSF and DOE to obtain the computer time needed attempt the computational challenge. As an example, SCEC researchers might decide what is needed to advance national seismological research is a full 3D velocity model from 0 to 100 km for all of North America using full 3D tomography. As another example of a "grand challenge" problem, SCEC researchers might decide there is great scientific value in a physics-based PSHA map for all of North America at 1 Hz. These calculations are currently well out of range of any group or any available NSF or DOE supercomputers. However, these calculations may not be out of range for long. Within 5 years, calculations at these scales may be possible if a consistent focused effort were made to achieve them.

The CME collaboration currently contains an exceptional group of HPC experts, and it is highly likely that these HPC experts would enthusiastically approach a large scale computational challenge if the anticipated scientific result has broad significance.

f. CME Research Using SCEC Computational Platforms

The science goal of the SCEC/CME collaboration is to transform seismic hazard analysis (SHA) into a physics-based science through high-performance computing (HPC). The CME is working to develop computational programs and techniques needed by SCEC to produce this transformation. SCEC's experience performing numerical modeling research has taught us that, in nearly all cases, several different codes must be run in order to produce a significant computational research result.

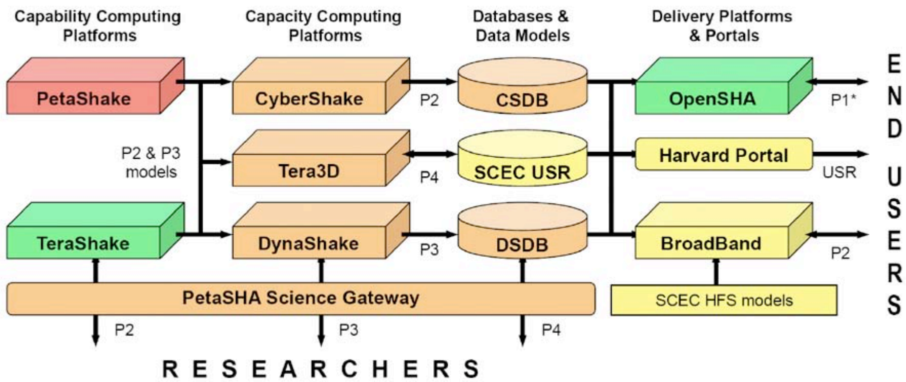

Figure 76. Computational platforms of the PetaSHA cyberfacility. Terashake and OpenSHA were developed under ITR funding (green). Cybershake and Dynashake and their databases, CSDB and DSDB, as well as the full-3D inversion platform, Tera3D (orange) are being developed under NSF/EAR funding. Petashake is a new petascale capability computing platform supported by NSF/OCI funding (red box). Other components supported by the SCEC base grants are shown in yellow. P1* and P2-P4 are the computational pathways diagramed in figure 1 and described in Box 1. The P2 and P3 models developed on PetaShake will be migrated to the capacity-computing platforms for full-scale production of seismic hazard maps. Researchers access codes and results from the PetaSHA science gateway, and users will access validated models and data products through the three delivery platforms: OpenSHA, Broadband, and the Harvard USR portal.

The CME uses high performance software and supercomputers that we call *computational platforms* to perform SCEC's computationally intensive seismic hazard research. We define a computational platform as a vertically integrated collection of hardware, software, observational data, structural models, and people that can perform a useful research calculation. A SCEC computational platform assembles and integrates all the software, hardware, middleware, input parameters, and structural models needed to perform a useful research calculation and it also includes all the observational data needed to verify and validate the functioning of the platform. A computational platform may require a large collection of software programs and these programs are carefully configured to work together.

The CME currently uses six computational platforms (Figure 76). Each platform performs a specific type of seismic hazard research calculation. The research capabilities of the computational platforms include: (1) Dynamic Rupture simulations (DynaShake Platform), (2) Earthquake Wave Propagation Simulations (TeraShake Platform), (3) Calculate high frequency synthetic seismograms (Broadband Platform), (4) Velocity Model Validation and Optimization (Full 3D Tomography (F3DT Platform)), (5) Traditional probabilistic seismic hazard analysis

(OpenSHA Platform), and (6) Physics-based PSHA using full 3D wave propagation (CyberShake Platform). Other computational platforms including highly scalable and capable wave propagation codes (PetaShake Platform) and data management tools (PetaSHA Science Gateway) are in development.

The CME collaboration seeks to perform very large-scale simulations that exceed the capabilities of our current computational platforms. To accomplish these research goals, we work to improve and optimize the computational platforms until they are capable of performing the desired research calculations. As we scale-up the CME computational platforms, our goal is to make effective use of NSF petascale computing for SCEC research when such computing resources become available. An NSF Track 1 computer system (Blue Waters – NCSA) capable of sustained Petaflops/s performance is expected to go online in 2011. Properly used, petascale computing will help study geosystems and other complex natural phenomena in more detail, at higher resolution, using more realistic physics, for larger geographical regions.

g. CME Scientific Research Results

CME project activities are science driven with CME research focused on science issues relating to seismic hazard analysis. CME research remains coordinated with SCEC science objectives because scientific needs precede CME software or system development. Given specific science goals, the CME evaluates its current software and computer tools to determine if it can perform the necessary computation. If the simulation exceeds the capabilities of our current platforms, we work on improving the scalability of the necessary platform until it is capable of running the needed simulation. We iterate between scientific software development, cyberinfrastructure development, and application of our Platforms to run milestone simulations. By combining software development, system improvements, and milestone research runs, the CME improves the capabilities of our computational platforms and produces significant research results.

Dynamic Rupture Research. The DynaShake Platform is designed to run large-scale (>300km rupture length) dynamic rupture simulations. The DynaShake Platform development is currently led by Steve Day and his team at SDSU. The DynaShake platform serves two important purposes in CME research. First, it is used to investigate the physics of fault ruptures. This is done by developing numerical models of rupture processes including friction laws on fault surfaces during an earthquake rupture. Second, DynaShake dynamic rupture simulations are also used to produce kinematic source descriptions by capturing rupture parameters produced by the dynamic simulation.

The DynaShake platform is used to investigate high-frequency seismic energy generation. The challenge is that the relevant phenomena (e.g., frictional breakdown, shear heating, effective normal-stress fluctuations, material damage, etc.) controlling ruptures are strongly interacting and span many orders of magnitude in spatial scale, requiring high-resolution simulations that couple disparate physical processes (e.g., elastodynamics, thermal weakening, pore-fluid transport, heat conduction). In dynamic rupture simulations, friction coefficient at sliding velocities above roughly 0.1 m/s are likely to be sharply weakened by flash heating of asperities. Compounding the computational challenge, natural faults are not planar, but instead have roughness that can be approximated by power laws with ratio of amplitude to wavelength typically in the range of roughly 0.01 – 0.001, potentially leading to large, multiscale fluctuations in normal stress. The capacity to perform 3D rupture simulations that couple these processes while capturing outer/inner spatial-scale ratios of 104 – 105 will enable significant advances in our fundamental understanding of high-frequency seismic wave excitation. The DynaShake software can simulate flash heating in a fully regularized form by embedding it in a rate- and state-dependent friction formulation using a well-verified and efficient numerical method. In this model, dynamic weakening will occur if the effective normal stress is reduced by shear heating of pore fluids the effect being controlled by the balance between pore pressurization by shear heating and depressurization by fault-normal Darcy flow. This effect can be included in simulations by coupling frictional dissipation with fault-normal heat conduction and pore-fluid diffusion models.

DynaShake-based dynamic rupture sources were used in both the TeraShake-2 research study (Olsen et al – 2007) and ShakeOut-D (Olsen et al – 2009). In 2007, the DynaShake development group developed a technique for constraining dynamic rupture simulations so that the final slip exhibited by the simulation matched slip (for example, surface or depth-averaged) proscribed by the modelers. Then, these DynaShake produced source descriptions were used in the ShakeOut-D study. The CME dynamic rupture research is also involved with the rupture research ongoing within SCEC. The DynaShake developers participated in the SCEC Dynamic Rupture Verification Exercise.

An important aspect of the CME dynamic rupture research is the development of pseudo-dynamic rupture generators. Due to the complexity and large computational requirements of dynamic rupture simulations, kinematic rupture descriptions will continue to be used in seismic hazard research for several years to come. Pseudo-dynamic rupture generators that produce kinematic rupture descriptions with parameters consistent with dynamic rupture simulations are being developed in order to integrate advances in our understanding of dynamic ruptures into seismic hazard calculations. Both the Broadband and the CyberShake Platforms use rupture generators to produce source descriptions. Improvements in rupture parameterization produced by the DynaShake Platform will provide guidance for constructing appropriate pseudo-dynamic source models for high-frequency ground motion simulations and will be quickly migrated to other computational platforms. CME DynaShake research and other rupture modeling researchers including Beroza (Stanford), Archuleta (UCSB), and Graves (URS) are developing pseudo-dynamic rupture generators designed to produce kinematic rupture descriptions that are consistent with results from large-scale dynamic rupture models.

The DynaShake platform can simulation large magnitude (M8.0+), long rupture surface (>300km), long duration (> 60seconds) dynamic ruptures needed for simulations of regional scale earthquakes and worst-case Southern California earthquakes. The most scalable dynamic rupture modeling software in the DynaShake platform is a finite difference dynamic rupture code (Day et al) that uses a regular grid. To model many earthquakes in Southern California, the dynamic rupture simulations must work properly for complex faults such as multi-segment dipping faults. A number of dynamic rupture codes that support complex fault geometries are under evaluation for this purpose including SORD (Ely - USC) and DR-FE (Ma - SDSU). The SORD code was developed to handle the sort of complex fault geometry noted above, while retaining very good computational scalability and sufficient flexibility to accommodate the appropriate rupture physics. The DR-FE code can simulation ruptures on complex fault geometries and it can also model wave propagation in models that contain other geometrical complexities including topography.

High Frequency Wage Propagation Simulations. The CME Collaboration has developed the TeraShake Computational Platforms in order to run deterministic wave propagation simulations on regional scales at frequencies above 1Hz. Civil and building engineers, important users of CME seismic hazard modeling results want synthetic seismograms containing higher frequencies (up to 10Hz) for use in seismic hazard analysis ground motion studies.

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In 2007 and 2008, three CME research groups (Graves, Olsen, and Bielak) ran wave propagation simulations at 1Hz for the ShakeOut scenario M7.8 event in a large southern California region. In 2009, CME researchers once again double the frequency at which wave propagation simulations are performed. The 2009 TeraShake Platform development focused on running 2.0Hz simulations of historical earthquakes (e.g. Chino Hills). The 2.0Hz synthetic waveforms produced by these simulations have been compared against observed seismograms for this event in order to validate the simulation.

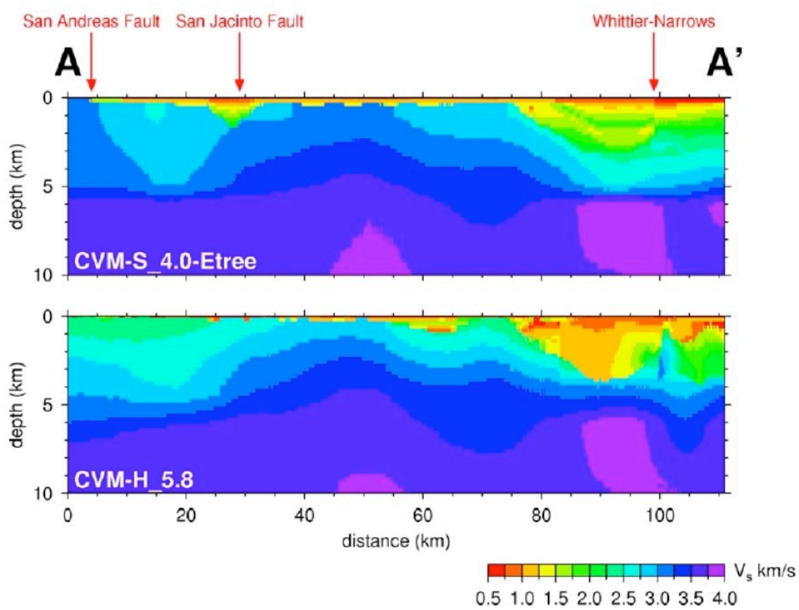

Figure 77. Comparable Vs profiles across the Los Angeles Basin are shown with CVM4.0 (top) and CVM-H (bottom). The differences between the CVM 4.0 and CVM-H velocity models contribute to uncertainties in high frequency simulations. The CME collaboration is working with both velocity models in order to determine which produces best match to observation or if a new combined or merged model will be required for 2.0 Hz and higher frequency deterministic wave propagation simulations for Southern California.

When simulation results match observational results, it indicates that each aspect of the simulation including the simulation software, the source description used, and the velocity model are valid for the region and frequencies involved. When earthquake wave propagation simulation results do not match observational results, differences are usually attributed to one or two inputs, either (1) the velocity model (e.g. CVM4.0), or (2) the source description. In order to identify the most accurate simulation configuration, we must analyze the sensitivity of our Southern California simulation results to the different 3D velocity models, which are available for this region including both the CVM4.0 and CVM-H. A comparison between the CVM4.0 and CVM-H 5.7 for a profile across the Los Angeles Basin indicating significant differences between the models that will affect ground motion simulations is shown in Figure 76.

In 2009, the CME has begun to integrate the SCEC CVM-H (v5.7 and later) into our numerical modeling work. The CME is running simulations using alternative velocity models and comparing the differences between simulation results. During this evaluation process, we identified the need for a numerical measurement that indicates how well seismograms match. Several characteristics of seismograms may be significant in a comparison including time of phase arrivals, amplitude and duration of motions, and frequency content. To improve the process of comparing seismograms, we have developed a Goodness of Fit (GOF) (Mayhew, Olsen – SDSU) algorithm that compares each of these aspects of two seismograms and produces a single numerical value on a 0-100 scale (a perfect match produces a 100 results) that is intended to represent how well the two seismograms fit. We are using this Goodness of fit measure to analyze the differences in simulation results between the CVM4.0 and CVM-H. Goodness of Fit results that compare observational data for the Chino Hills M5.4 earthquake to 2Hz simulation results are shown in Figure 78.

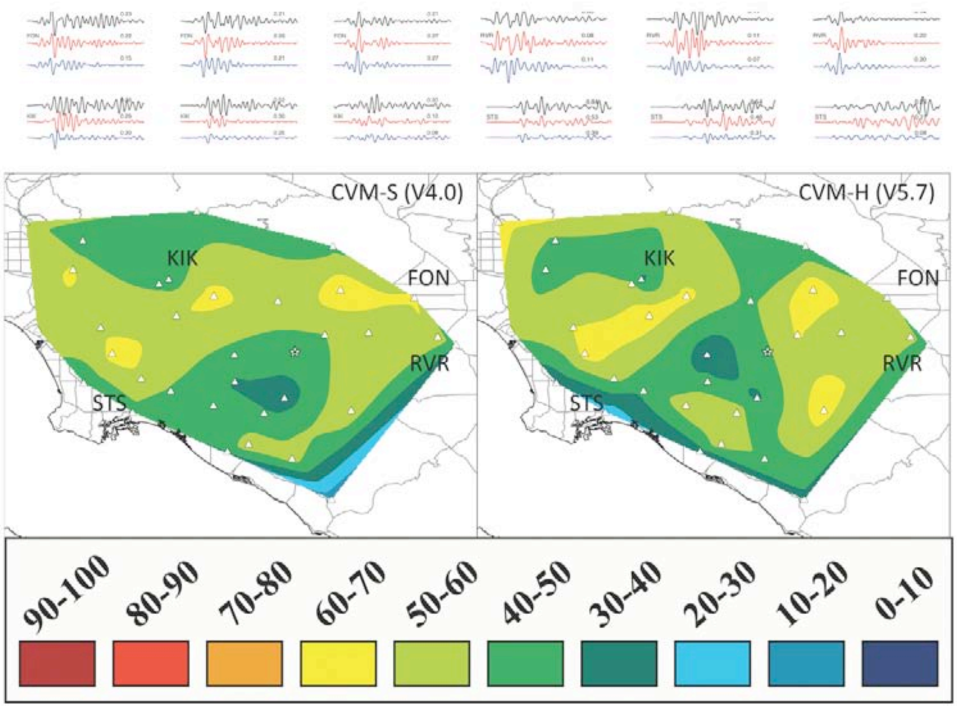

Figure 78. Validating regional scale wave propagation simulation results against observed data may require thousands of comparisons between observed and simulated data. The CME has developed an initial implementation of a Goodness of Fit (GOF) measurement system and is applying these new tools to help evaluate the 2Hz Chino Hills simulations. In this GOF scale, 100 is a perfect fit. The maps (left) show how GOF values vary geographically for AWP-Olsen, Chino Hill M5.4 event, and two different SCEC Community Velocity Models, CVM4.0 (left) and CVM-H 5.7 (right).

In HPC terminology, the largest and most parallel simulations are called ***capability*** simulations. In order to obtain computational time on the world's largest supercomputers, scientific groups must demonstrate their capability codes produce useful science results and make efficient use of the supercomputers. Under our current OCI PetaShake-2 award, the CME is working to improve the performance of our dynamic rupture and wave propagation codes so that we are ready to use the upcoming NSF Track 1 petascale computer (Blue Waters NCSA) when it becomes available in 2011.

The CME's most scalable code, the AWP-Olsen-Day-Cui software, is capable of scientific runs at using all available cores on the system at the same time on the nation's largest supercomputers including both NSF Track 2 machines (TACC Ranger - 50K cores) and NICS Kraken – 63K cores)) as well as DOE's leadership class computer (ANL Intrepid - 130K cores)). The CME capability computing developments have been led by Yifeng Cui (SDSC) who has improved the parallel performance SCEC software until it scales efficiently on more than 130,000 cores. The SCEC wave propagation software is in a small and select category of supercomputer applications that have been shown to produce well-verified scientific results at this scale. Scalability plots for three of the SCEC Computation codes (AWP-Olsen, Hercules, and SORD) are shown in Figure 79.

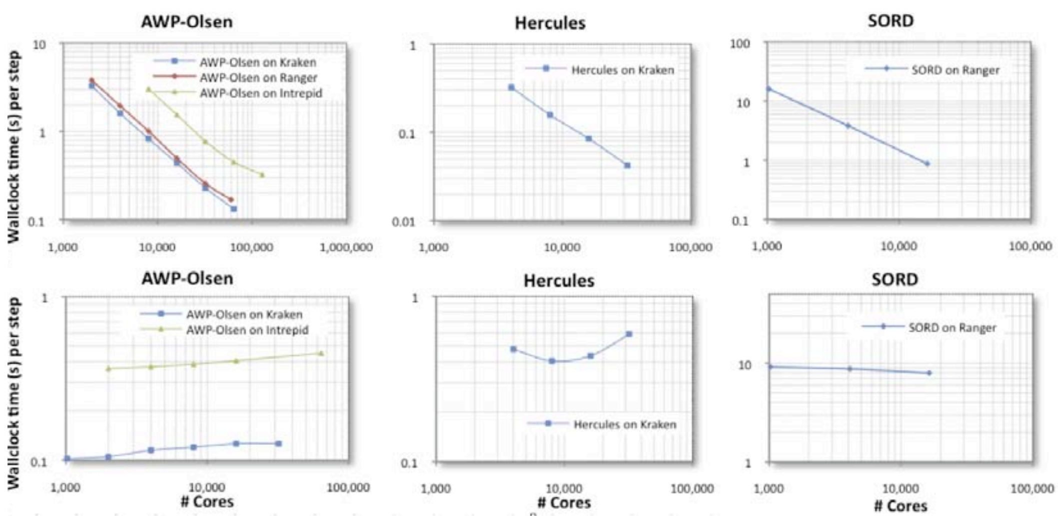

Figure 79. Plots show strong scaling (top) and weak scaling (bottom) for out two optimized codes AWP-Olsen (left) and Hercules (center). Yifeng Cui and his team at SDSC has optimized the AWP-Olsen software and it now shows excellent scaling up to 130k cores on DOE leadership class system Intrepid. Hercules shows excellent scaling up to 32k cores on NSF Track 2 system Kraken. We have begun optimization of SORD code (right) to support dynamic rupture and wave propagation simulations with more complex structural geometries including dipping faults and topography.

NSF's HPC organization, the TeraGrid, has supported our development of the TeraShake Platform and its highly scalable software. Over the last four years, each time a new NSF supercomputer became available, the NSF TeraGrid Advanced Support for TeraGrid Applications (ASTA) program collaborated with the CME by providing highly specialized HPC technical support to ensure our software ran efficiently on the new HPC system.

The NSF HPC community defined performance goals for hardware and software a few years ago as it embarked on the current NSF HPC development program. Science users together with NSF decided that the NSF HPC should enable scientific numerical modeling research at sustained Petaflops performance. Scientific applications groups such as SCEC expect to continue to improve our software until it is capable of sustained Petaflops performance. The CME has made outstanding progress in its code development. Current maximum sustained code performance for our CME software is approximately 50 TFlops indicating that we must improve the performance of our CME software by a factor of 20 to achieve this national scientific and HPC performance goal.

Full 3D Tomography (F3DT) Platform. The CME Full 3D Tomography (F3DT) Platform is a platform for executing Pathway 4 (inverse) calculations. The F3DT platform provides the means for updating the CVMs using seismic observations—an important validation step for predictive ground motion simulations.

In F3DT, the starting velocity model as well as the model perturbation is 3D and the sensitivity (Fréchet) kernels are computed using numerical simulations that incorporate the full physics of 3D wave propagation. F3DT can account for the nonlinearity of structural inverse problem through iteration. SCEC researchers have been developing F3DT algorithms that fall into two classes: the adjoint wavefield (AW) formulation, and the scattering integral (SI) formulation. The two are closely related, but their relative efficiency depends on the problem geometry, particularly on the ratio of sources to receivers. The SI method, which computes Fréchet kernels for individual measurements by convolving source wavefields with RGTs, is computationally more efficient than the AW method in regional waveform tomography using large sets of natural sources, although it requires more storage.

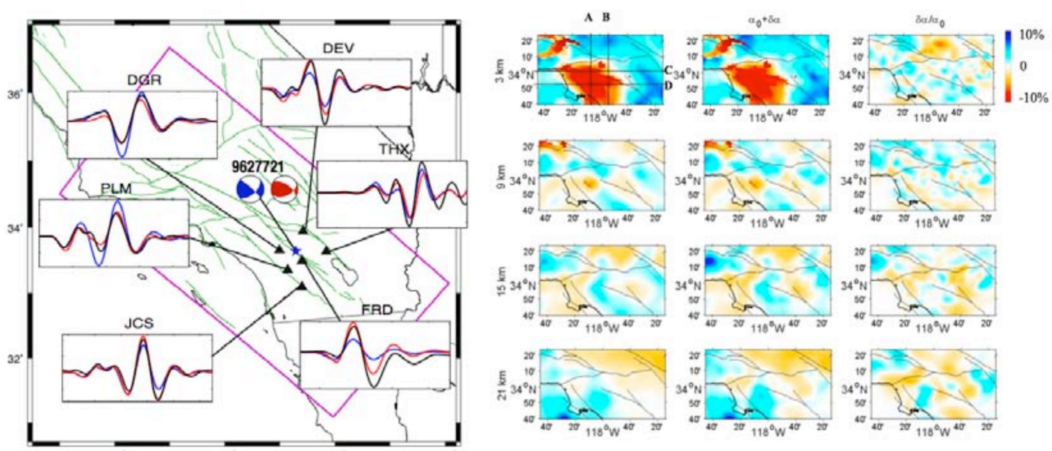

Figure 80. Full 3D Tomography (F3DT) Platform is used to validate and improve the 3D velocity models for California. The F3DT Platform can produce improved focal mechanisms (left) and improved 3D velocity models (right) by comparing simulation results to data. (Po Chen, U. of Wyoming)

A CME group led by Po Chen (University of Wyoming) and Thomas Jordan (USC) have successfully applied a scattering-integral (SI) formulation of F3DT to improve CVM3.0 in the Los Angeles region (Figure 80). They have inverted time- and frequency-localized measurements of waveform differences to obtain a revised 3D model that provides substantially better fit to the observed waveform data than the 3D starting model. In 2009, Po applied this technique to an inversion CVM4.0 for a 300km x 600km region of Southern California. In this work, performed largely on the DOE Incite computer Intrepid, he produced both a catalog of refined focal mechanisms and a perturbation model for CVM4.0 at 5 seconds period.

Other geoscience groups including SCEC members are also developing 3D inversion techniques including both the SI and the AW methods. Carl Tape (Harvard) and Jeroen Tromp (Princeton) are using the AW method to improve an earlier version of CVM-H. Greg Beroza (Stanford) and others are developing techniques that use ambient noise recorded at seismic stations to calculate kernels that can be used to improve velocity models at low frequencies.

F3DT inversions together with new seismic observations (including new earthquakes and new recording stations) can be used to improve velocity models. So, in the future, it is likely that ground motion modeling groups will base their seismic hazard calculations on the best available version of the SCEC CVM. This introduces the challenges of creating, maintaining, and using a time dependent community velocity model. The CME is working to support such a system in a number of ways. First, we have developed software tools capable of creating very large (>1B mesh points) velocity meshes from any of the current SCEC velocity models. Next, we are developing techniques to integrate inversion results into a velocity model and deliver the updated models for use in ground motion simulations. The CME is also working to define a "standard" inversion problem for California by defining an initial starting model, the region and maximum frequency, and validation criteria. The intent is for different groups to perform comparable inversion and then to compare the inversion results to determine whether the methods converge. In the long term, it should be possible to automate the inversion process, using the most efficient inversion technique available, and to repeat the inversion and deliver an updated and improved CVM whenever new observations are available.

OpenSHA Platform. OpenSHA is a Probabilistic Seismic Hazard Analysis (PSHA) computational platform. The CME developed the OpenSHA Platform in collaboration with USGS under the leadership of Ned Field (USGS). The OpenSHA Platform implements traditional PSHA calculations which use two critical inputs; (1) an Earthquake Rupture Forecast (ERF), and (2) a Ground Motion Prediction Equation (GMPE), typically an attenuation relationship. An ERF provides a list of possible future earthquakes, their magnitudes, and a probability that the earthquake will occur in a given time span (e.g. within 1 year). OpenSHA is object-oriented and it implements both (1) specific seismic hazard models such as earthquake rupture forecasts, and (2) specific seismic hazard algorithms such as attenuation relationships. Users can combine alternative models and algorithms to produce PSHA hazard curves and PSHA hazard maps for California.

OpenSHA is highly integrative platform because it relies on valid implementations of many modeling components include fault models, velocity models, rupture models, and ground motion prediction equations. In order to produce valid PSHA hazard curves maps, all of these seismic hazard modeling elements must work correctly. Despite this complexity, PSHA seismic hazard predictions are highly significant because they represent a critical interface between seismology and engineering. In the foreseeable future, it is likely that SCEC will continue to communicate our understanding of seismic hazards using PSHA techniques. As SCEC improves its understanding of earthquake processes, these scientific advances are used to improve PSHA results.

In 2007, a new Unified California Earthquake Rupture Forecast (UCERF2) was released by USGS. OpenSHA was used to define the reference implementation of this ERF and it also includes implementations of several recent (2008) attenuation relationships. OpenSHA was used by SCEC and the USGS in the development of UCERF2. Software implementations of the proposed forecast models were developed within OpenSHA (Figure 81). The OpenSHA software enabled UCERF2 scientists to easily test the prototype Earthquake Rupture Forecast models with established PSHA codes. OpenSHA proved a significant value during the development of UCERF2 and it will likely be used again during UCERF3 development.

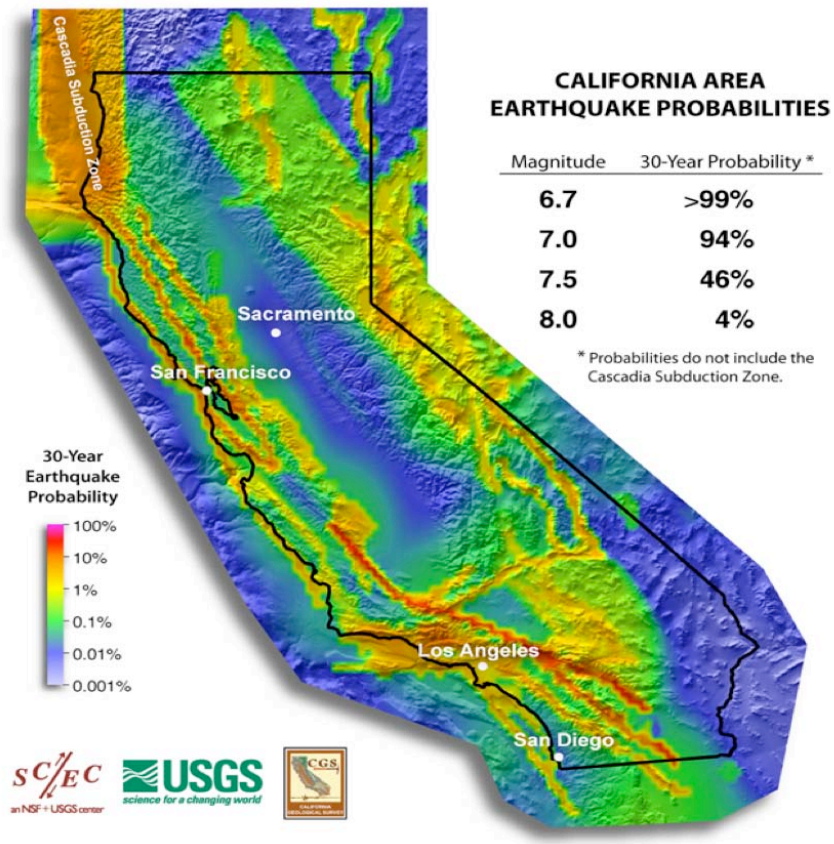

Figure 81. The colors on this California map represent the UCERF2 probabilities of having a nearby earthquake rupture (within 3 or 4 miles) of magnitude 6.7 or larger in the next 30 years. As shown in the table, the chance of having such an event somewhere in California exceeds 99%. The 30-year probability of an even more powerful quake of magnitude 7.5 or larger is about 46%. The CME OpenSHA computational platform was used in the development of the UCERF2 model with funding support from the California Earthquake Authority (an insurance consortium). The OpenSHA platform demonstrates the value of integrating geological and structure models with computational capabilities. New computational models can be added to the platform and immediately used in PSHA calculations with other existing PSHA components.

The OpenSHA development group is developing new capabilities so OpenSHA can support global seismic hazard calculations for use on the Global Earthquake Modeling (GEM) project.

GEM is an international collaboration working to produce a seismic hazard and loss calculations on a global scale. OpenSHA's object-oriented design, and its ability to perform very large-scale PSHA calculations using distributed computing, makes it an excellent basis for the large-scale PSHA calculations needed by GEM.

Physics-Based PSHA Curves Using UCERF2.0. Traditional PSHA calculations calculate ground motions at a site for a particular earthquake by using an attenuation relationship as a ground motion prediction equation (GMPE). This approach is computationally efficient but produces only an approximation of ground motions at the sites under study and these standard GMPE calculations do not produce seismograms so certain information about the ground motions is not available. PSHA researchers on the CME have implemented the CyberShake Platform in order to replace existing GMPE in standard PSHA calculations with 3D wave propagation modeling. Integrating 3D waveform modeling into standard PSHA calculations is an interesting scientific challenge as well as a very large computational challenge. The CyberShake PSHA technique promises to deliver new insights about how rupture directivity and sedimentary basin effects can modify hazard curves. CyberShake is the capacity-computing platform for executing and managing the large number of Pathway 2 simulations needed to construct physics-based PSHA maps.

A CME team led by R. Graves (URS) and Scott Callaghan (USC) developed the CyberShake Platform over the last few years. The current CyberShake implementation samples ~13,000 distinct sources in the UCERF2.0 ERF for Southern California. For each large (M > 6.5) source, the hypocenter, rupture rise-time and velocity distributions, and final slip distribution are varied according to a pseudo-dynamic model, producing a total catalog of more than 400,000 ruptures for each site. To make the calculations feasible, the Graves AWP codes has been modified and optimized to calculate "receiver Green tensors" (RGTs). Using seismic reciprocity, we can now efficiently post-process the RGTs to synthesize a site's ground motions for the full suite of rupture variations and, from this database, compute hazard curves for spectral accelerations below 0.5 Hz.

In previous years, the CME developed the basic CyberShake computational approach and calculated a number of PSHA hazard curves in order to validate our methodology. In 2009, based on satisfactory verification and validation results for a small number of trial CyberShake hazard curves, we scaled our CyberShake calculations up to produce a physics-based PSHA hazard map for part of Southern California. Using TeraGrid computer resources at TACC, we used the CyberShake computational platform to calculate physics-based (3D waveform modeling based) probabilistic seismic hazard curves. When then combined these hazard curves into the first ever physics-based PSHA map for Southern California as shown in Figure 82.

This CyberShake1.0 PSHA hazard map required an enormous calculation involving both parallel earthquake wave propagation codes and serial post-processing codes. The CME was able to perform this calculation by using a workflow system based on NSF-funded tools including Pegasus-WMS, Condor DAGManager, and Globus. The CyberShake1.0 Map calculation required more than 60 days of processing on one of the NSF's largest supercomputers and used more than 6 million CPU hours to complete.

This CyberShake 1.0 map represents the initial implementation of an important new technique for improving PSHA hazard curves. The official USGS PSHA hazard curves impact billions of dollars of construction each year. Improvements in PSHA hazard curves can have a very broad societal impact. Until now, physics-based PSHA calculations have been beyond the computational capabilities of SCEC and other seismic hazard research groups. The CME work has shown this type of calculation is possible. Now, we anticipate that SCEC researchers will help to evaluate the results and to determine whether the level of improvement produced by CyberShake justifies the computational effort needed by new PSHA technique.

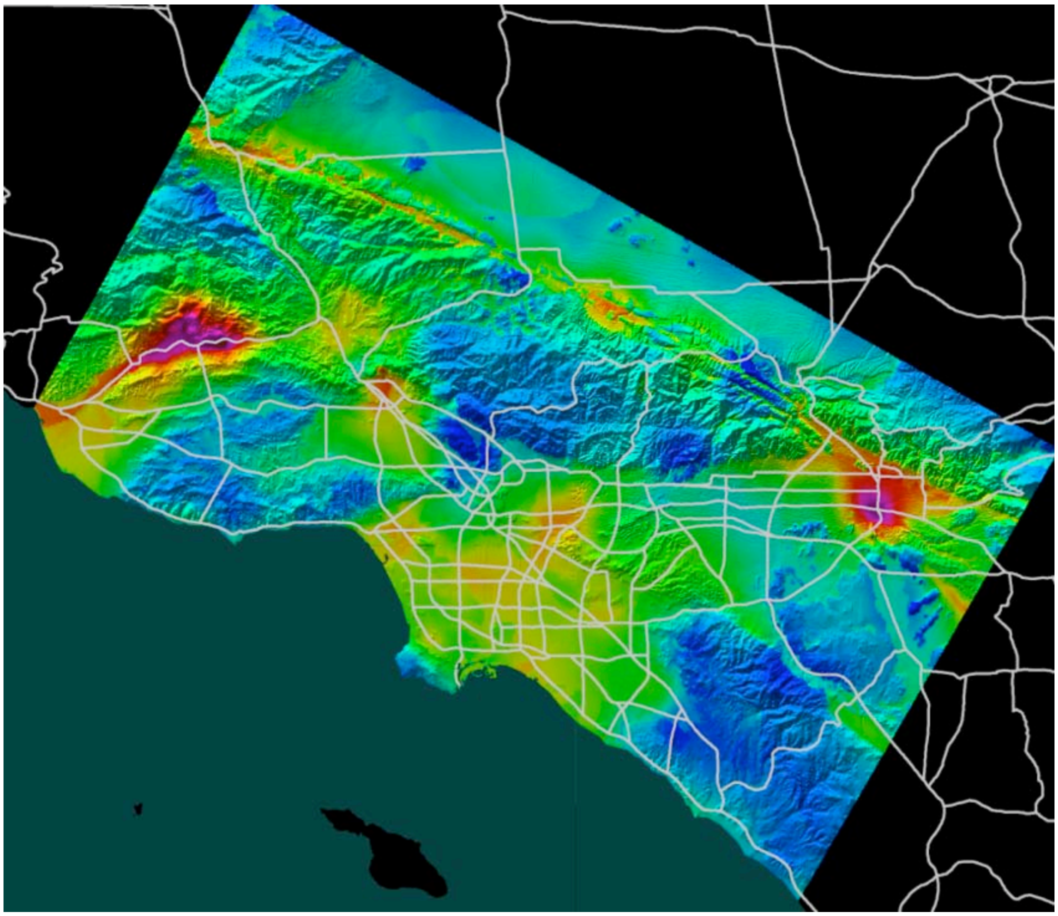

Figure 82. More than 220 CyberShake v1.0 physics-based PSHA hazard curves are assimilated into a background UCERF2 (2008) and NGA-based (2008) PSHA map (left) Peak SA3.0 (0.1 blue to 1.2 indigo) at 2% in 50 years tends to raise hazard estimates in the Los Angeles and Venture Basis and reduce hazard estimates for mountainous regions in southern California. The CyberShake capacity computational platform calculated this map over approximately 50 days of production runs on NSF Track 2 Ranger system. Scientific workflow technologies, including Globus, Condor, and Pegasus were used to submit, run, and monitor more than 100M tasks and 100M files during the calculation. The CME workflow system was able to use an average of 4000 cores at all times on TACC Ranger for 50 days in order to complete this calculation. This capacity run represents a transformative use of NSF HPC facilities by NSF/EAR research groups. The technologies developed by the CME collaboration run at this scale include general purpose geoinformatics and cyberinfrastructure tools valuable to both solid earth researchers are well as other domains including atmosphere, high energy physics, and medical research.

CyberShake's PSHA calculations integrate elements from most of the other CME ground motion modeling simulations. As the other CME computational platforms such as the DynaShake Platform, the TeraShake Platform, and the F3DT Platform produce improved ground motion modeling results, these improvements will be integrated into the CyberShake Platform so that CyberShake physics-based PSHA calculations continue to improve in accuracy and/or efficiency of calculation.

The CyberShake1.0 map calculation was possible only because of the advanced IT capabilities of the CME. Several computational trends for the CME indicating significant improvements during the last few years (Figure 83). These plots show that the CME has produced steady improvements in the scientific tools, the speed of processing, and the cyberinfrastructure used in the CyberShake Platform. The CyberShake1.0 calculations show how the CME applies HPC tools and techniques to PSHA enabling SCEC to produce improved seismic hazard information for southern California.

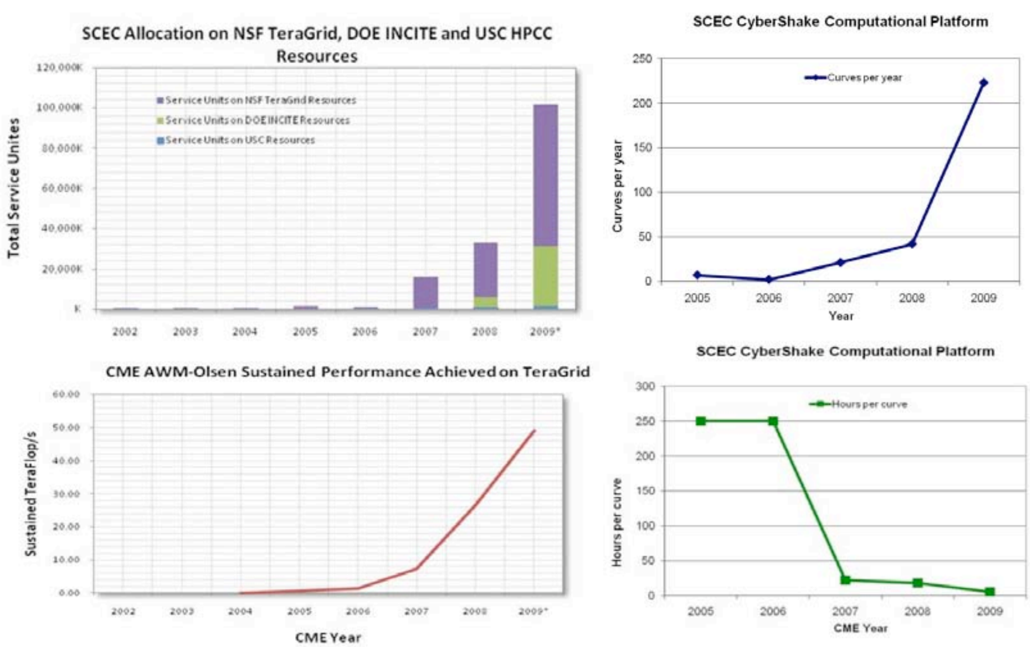

Figure 83. CME supercomputer allocations (top left) now include resources from NSF TeraGrid, USC HPCC, and DOE INCITE program. Peak performance of our capability code AWP-Olsen (bottom left) has risen as performance improvements and larger HPC system have become available. The number of physics-based PSHA hazard curves calculated with the CyberShake platform has risen by two orders of magnitude (top right), and the time required to calculate a hazard curve (bottom right) has fallen by two orders of magnitude.

h. Upcoming CME Research

The SCEC system science approach continues to integrate better physics into seismic hazard calculations and the CME continues to improve the efficiency of SCEC calculations on open-science high performance computers. The overall goal of improving seismic hazard calculations remains constant but the CME improvements change year by year. This upcoming year, the CME will run several large-scale scenario earthquake simulations for southern California that we call the Big Ten (Figure 84).

The Big Ten is a collection of large magnitude (>M7.5), high probability ruptures defined in UCERF2. All Big Ten events represent significant seismic hazards for Southern California. The Big Ten event set has been carefully selected to confront seismologists and numerical modelers with a wide variety of scientific and computational challenges. Issue the modeling groups must address include modeling of high frequency sources and wave propagation, use of multiple velocity models, simulation regions so large that earth curvature must be considered, modeling of topography, important of low minimum S wave velocities in velocity models, dipping faults, fault to fault stress transfer, and long rupture surface, long duration, M8.0+ events. The Big Ten simulations will involve all of the SCEC computational platforms. The Big Ten simulations are representative of earthquake simulations used in seismic hazard calculations and this CME research will help SCEC determine how to get valid scientific results from large seismic hazard calculations.

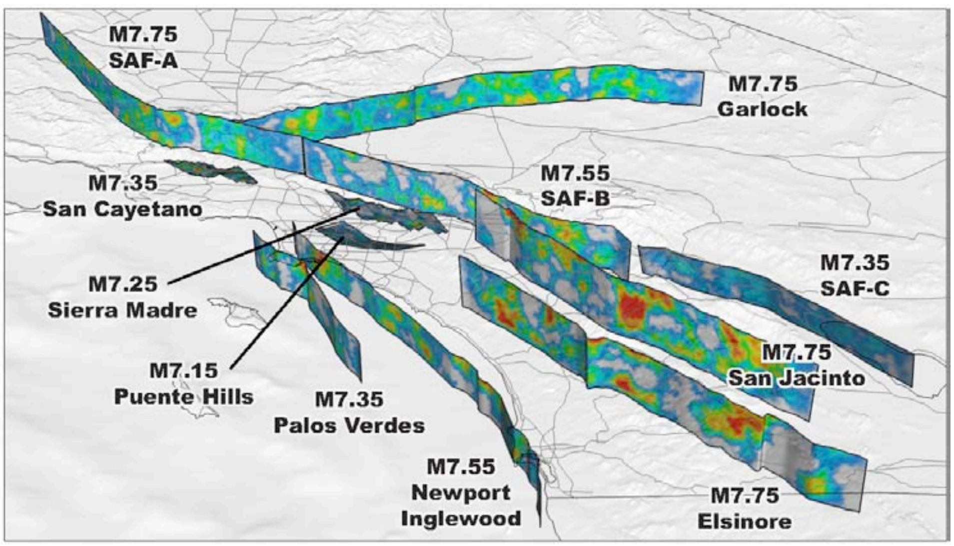

Figure 84. The Big Ten events are a collection of large magnitude, high probability ruptures defined in UCERF2.0. The CME will integrate new capabilities into our computational platforms including simulation of dynamic ruptures on dipping faults and higher frequency (>2Hz) wave propagation simulations. Once our computational platforms run at the required scale with the required capabilities, we will simulate the Big Ten events and analyze the impact of these scenario on seismic hazards in Southern California (Image: Ely, Jordan - USC).

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IV. SCEC Communication, Education, and Outreach

Introduction

The SCEC Communication, Education, and Outreach (CEO) program has four long-term goals:

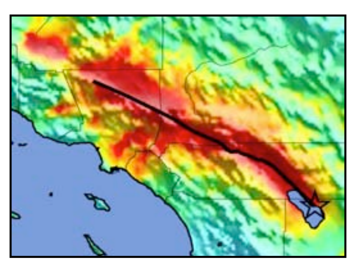
- Coordinate productive interactions among a diverse community of SCEC scientists and with partners in science, engineering, risk management, government, business, and education;
- Increase earthquake knowledge and science literacy at all educational levels, including students and the general public;
- Improve earthquake hazard and risk assessments; and
- Promote earthquake preparedness, mitigation, and planning for response and recovery.

These goals are pursued through activities organized within four CEO focus areas: ***Research Partnerships*** coordinated within the SCEC Seismic Hazard & Risk Analysis focus group; ***Knowledge Transfer*** activities with practicing professionals, government officials, scientists and engineers; ***Public Outreach*** activities and products for the general public, civic and preparedness groups, and the news media; ***Education*** programs and resources for students, educators, and learners of all ages, including the Experiential Learning and Career Advancement office which coordinates undergraduate and graduate internships and support for early career scientists. Many activities span more than one CEO focus area.

Partnerships are key to achieving SCEC's mission, research objectives, and outreach goals. These partners include other science organizations (e.g. IRIS, EarthScope, and UNAVCO), engineering organizations (e.g. PEER, CUREE, and EERI), education organizations (e.g. Los Angeles County Unified School District, Southern California County Offices of Education, museums, and the National Association of Geoscience Teachers), and public service / risk management organizations (e.g. California Office of Emergency Services, the California Earthquake Authority, FEMA, and the American Red Cross).

The following are highlights of SCEC's Public Outreach and Education activities in the last year.

Public Outreach Activities



Great (Southern & Statewide) California ShakeOut. A major focus of the CEO program in 2008 and 2009 has been organizing the inaugural ShakeOut drill for Southern California on November 13, 2008, and the first statewide ShakeOut drill planned for October 15, 2009. The purpose of the Shakeout is to motivate all Californians to practice how to protect ourselves during earthquakes ("Drop, Cover, and Hold On"), and to get prepared at work, school, and home.

<u>2008 Southern California ShakeOut.</u> In 2008, over 5.4 million participants (which exceeded the initial goal of 5 million people) registered to participate at *www.ShakeOut.org*, hosted and maintained by SCEC. Individuals, families, businesses, schools, and organizations joined

firefighters and other emergency responders (involved in the statewide "Golden Guardian" exercise the same week) in the United States' largest-ever earthquake preparedness activity. Registered participants received information on how to plan their drill, connect with other participants, and encourage a dialogue with others about earthquake preparedness. This was an unprecedented opportunity to educate the public.

The 2008 ShakeOut was based on a potential 7.8 magnitude earthquake on the southernmost San Andreas Fault. In the past this size of earthquake has occurred on that section of the fault every 150 years on average, yet the last was over 300 years ago! Dr. Lucy Jones (USGS) led a group of over 300 scientists, engineers, and others to study the likely consequences of this enormous earthquake in great detail. Many SCEC scientists have been involved including those who produced the ShakeOut Simulation. The final simulation used in analysis of losses was by Rob Graves (URS), and the visualization was by Geoff Ely (USC).

In addition to the ShakeOut drill, the City of Los Angeles and the Earthquakes and Megacities Initiative (of which SCEC CEO director Mark Benthien is the Los Angeles liaison) hosted an International Earthquake Conference November 12-14, bringing together over 45 international experts to discuss policy, planning, and preparedness with U.S. counterparts. More information is at www.iec.lacity.org. On Friday, November 14, the Art Center College of Design presented the "Get Ready Rally" at the new Nokia LA Live in downtown Los Angeles to engage the public in earthquake preparedness. Southern Californians were invited to celebrate the success of the Drill and share their experiences. The event included food, entertainment, and vendors.

Organizers and participants of the 2008 ShakeOut included Southern California Earthquake Center, U.S. Geological Survey, California Office of Emergency Services, City of Los Angeles, Caltech, Art Center College of Design, University of Southern California, State Farm, California Earthquake Authority, the California Seismic Safety Commission, American Red Cross, and businesses, schools and governments (in Riverside, San Bernardino, Orange, Los Angeles, San Diego, Imperial, Kern, Santa Barbara, and Ventura Counties), and *many other members of the Earthquake Country Alliance (ECA).*

2009 Great California ShakeOut. Immediately following the 2008 ShakeOut (initially conceived as a "once-in-a-lifetime" event), participants began asking for the date of the 2009 ShakeOut. After significant discussion among ECA partners and state agencies, the decision was made to organize an annual, statewide Shakeout drill to occur on the third Thursday of October (October 15 in 2009). This date is ideal for our school partners and follows National Preparedness Month in September, which provides significant exposure prior to the drill.

Over 6.9 million people participated in the 2009 ShakeOut. Many of the 2008 participants have registered again, along with new participants from all of California's the states 58 counties. This included 5 million K-12 participants (students and staff), nearly 1 million higher education participants, over 230,000 business participants, over 350,000 governmental participants (local, state, federal), and over 300,000 participants from other organizations.

Expanding statewide was much more complicated than simply deleting the word "Southern" from all materials and webpages. The 2008 ShakeOut was based on a single earthquake scenario, which does not apply to the entire state. Thus, 11 "ShakeOut Information Areas" (see map, next page) were created, based on earthquake hazards,

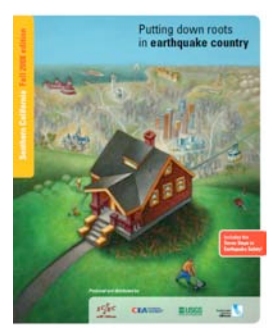
geography, media markets, and other factors, to provide local hazard information for participants throughout California. The redesigned *ShakeOut.org* website contains a description of each area's earthquake hazard and ShakeOut registration statistics down to the county level. Resources from the 2008 ShakeOut are being updated for a statewide audience, or "generalized" to be useful for any drill (anywhere and anytime).

In addition, expanding statewide required considerable partnership development with state agencies and regional alliances. As described below, the Earthquake Country Alliance, which has also expanded statewide, is the primary organization behind the ShakeOut, connecting four regional alliances. The group works together to coordinate messaging, develop resources, and recruit participation.

SCEC has also created and hosted the website for "New Zealand Great West Coast Shakeout" (*www.shakeout.org.nz*), held on September 18, 2009. Over 25% of the region's 30,000 residents participated, and expansion of the drill nationwide in coming years is being considered. Similarly, SCEC is consulting with the Central U.S. Earthquake Consortia to support a ShakeOut drill in 2011 or 2012 to commemorate the bicentennial of the New Madrid earthquakes.

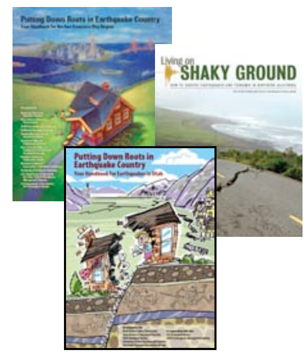
Putting Down Roots in Earthquake Country. In 1995 SCEC, the USGS, and a large group of partners led by Lucy Jones (USGS) developed and distributed 2 million copies of a 32-page color handbook on earthquake science, mitigation and preparedness. Funding was primarily from the National Science Foundation and USGS. The booklet was distributed through libraries, preparedness partners, cities, companies, and directly to individuals through SCEC.

The creation of the Earthquake Country Alliance in 2003 was concurrent with the desire to update *Putting Down Roots* in advance of the 10th anniversary of the Northridge earthquake. The process brought the ECA together to develop consensus messaging and notably introduced the "Seven Steps to Earthquake Safety," which has become a standard approach to organizing earthquake preparedness messaging. Since 2004, the booklet has undergone five additional revisions and printings, the latest of which was finalized in October, 2008, and included the ShakeOut Scenario and an overview of the Uniform California Earthquake Rupture Forecast study led by SCEC.



Putting Down Roots has been widely distributed through newspaper inserts, museums, schools, at events organized by SCEC and ECA partners, and via an online order form. Over 2.3 million copies have been distributed since 2004, and an additional 1.25 million copies in Spanish have been distributed. Printing and distribution of the booklet was made possible by generous support of the California Earthquake Authority and additional funding from the Federal Emergency Management Agency (FEMA), and the USGS. The handbook is available at *www.earthquakecountry.info/roots* as an online version and downloadable PDF, and printed copies can be ordered for free through an online request form.

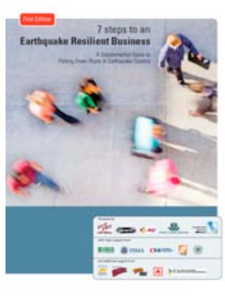
Putting Down Roots is the principal SCEC framework for providing earthquake science, mitigation, and preparedness information to the public. The "Roots" framework extends beyond the distribution of a printed brochure and the online version. For example, the Birch Aquarium in San Diego developed an earthquake exhibit that featured a "Seven Steps" display, similar to SCEC's "ShakeZone" exhibit at the Fingerprints Childen's Museum in Hemet, CA. The Emergency Survival Program (managed by LA County) based its 2006 and 2009 campaigns around the "Seven Steps." Many other adaptations of *Roots* and *Seven Steps* content have been developed by ECA and other partners.



The new version of Putting Down Roots was designed to allow other regions to adopt and adapt its structure to create additional versions. The first is a Greater San Francisco Bay Area version produced by a partnership led by the USGS with SCEC, local and state emergency managers, the Red Cross and many other organizations. Over 2.3 million copies have been printed, many distributed in newspapers, with funding from the California Earthquake Authority, USGS, FEMA, Red Cross, OES, CGS, and several others). In addition, a new booklet, *Protecting Your Family From Earthquakes– The Seven Steps to Earthquake Safety*, was produced in 2006 as part of the *Putting Down Roots* series, in two versions - English and Spanish in one booklet, and English, Chinese, Korean, and Vietnamese in another booklet. All Bay Area booklets can also be accessed from *www.earthquakecountry.info/roots*. All printings of the Bay Area version to date have been coordinated through SCEC.

Two other versions were produced over the last year, and can be downloaded from the *Roots* website:

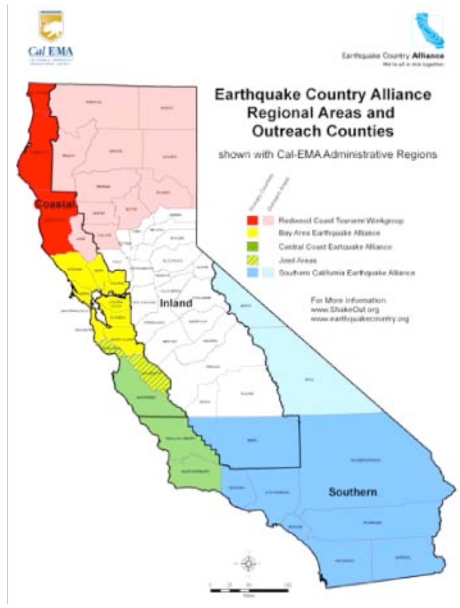
- The Utah Seismic Safety Commission in 2008 produced the first version of *Putting Down Roots* outside of California, and discussion for a Central United States version has been moving forward (though slowly).
- *Living on Shaky Ground*, an update to the well-known earthquake booklet for California's North Coast, now including the Seven Steps to Earthquake Safety, has been in development for several years and is subtitled "Part of the *Putting Down Roots in Earthquake Country* Series."



Finally, SCEC and ECA partners have developed a new supplement to *Putting Down Roots,* titled *The Seven Steps to an Earthquake Resilient Business,* an exciting new 16-page guide for businesses to develop comprehensive earthquake plans, printed in Fall, 2008. This booklet is the first non-regional publication, created as a supplement to all *Putting Down Roots* or other materials that include the *Seven Steps to Earthquake Safety.* It can be also downloaded and ordered from *www.earthquakecounty.info/roots*.

Earthquake Country Alliance. To coordinate activities for the 10-year anniversary of the Northridge Earthquake in January 2004 (and beyond), SCEC led the development of the "Earthquake Country Alliance" (ECA) beginning in summer 2003. This group was organized to present common messages, to share or promote existing resources, and to develop new activities and products. The ECA includes earthquake scientists and engineers, preparedness experts, response and recovery officials, news media representatives, community leaders, and education specialists. The mission of the ECA is to foster a culture of earthquake and tsunami readiness in California.

In 2006, the ECA launched the *Dare to Prepare* Campaign*,* to promote earthquake awareness and preparedness and to mark the 150th anniversary of the January 9, 1857, Ft. Tejon earthquake on the San Andreas Fault. With a strategy of getting southern Californians to "talk about our faults," the campaign acknowledged that "Shift Happens," and if you "Secure Your Space" you can protect yourself, your family, and your property. A new website (*www.daretoprepare.org*) was created, along with public events throughout the region (presentations, preparedness fairs, etc.) and a comprehensive media campaign with television, radio, and print promotion, public service announcements, on-air interviews and much more. A new Spanish-language website, *www.terremotos.org*, was also created and is hosted by SCEC.



The Earthquake Country Alliance is now the primary SCEC mechanism for maintaining partnerships and developing new products and services for the general public. Following the success of developing and implementing the 2008 Great Southern California, the ECA has now been expanded into a statewide organization and currently includes regional stakeholder alliances in southern California, the central coast, Bay Area, and north coast (see map). The statewide ECA, including state agencies, is currently planning the Great California ShakeOut, an annual statewide event in October.

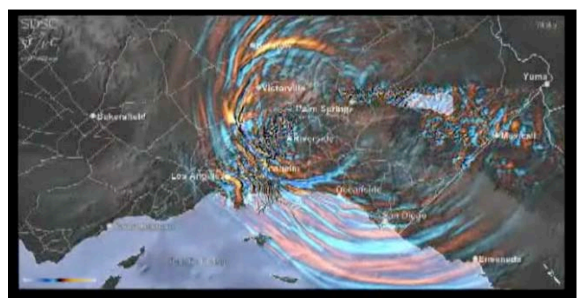
SCEC developed and maintains the ECA website (*www.earthquakecountry.info*), which provides multi-media information about living in earthquake country, answers to frequently asked questions, and descriptions of other resources and services that ECA members provide. The site is set up separately from the main SCEC web pages (though has attribution to SCEC) so that all members of the ECA see the site as their own and are willing to provide content. The site features the online version of *Putting Down Roots* and special information pages that all groups can promote, such as a special page about the "10.5" miniseries and a page about the "Triangle of Life" controversy (see assessments below). The site is being completely redesigned in fall of 2009 to complement the new design of the *ShakeOut.org* website.

Media Relations. SCEC engages local, regional and national media organizations (print, radio and television) to jointly educate and inform the public about earthquake-related issues. The goal has been to communicate clear, consistent messages to the public–both to educate and inform, and to minimize misunderstandings or the perpetuation of myths. In 2008, SCEC coordinated the major release of the Uniform California Earthquake Rupture Forecast, which involved a two-location press conference (with scientists at USC and at USGS in Menlo Park, with streaming video between the locations), a comprehensive website (*www.scec.org/ucerf*), a new USGS fact sheet, and other resources. SCEC CEO encourages scientists who are interested in conducting interviews with media reporters and writers to take advantage of short courses designed and taught by public information professionals.

Earthquake Country - Los Angeles. This video was produced by Dr. Pat Abbott of SDSU as the second in his "Written in Stone" series. The video tells the story of how the mountains and valleys of the Los Angeles area formed, including the important role of earthquakes. The video features aerial photography, stunning computer animations, and interviews with well-known experts. The video features 3D fault animations produced by SCEC interns from the Undergraduate Studies in Earthquake Information Technology (UseIT) Program. In addition to conducting several focus groups with teachers and preparedness experts, where the video was evaluated, SCEC has developed curricular kits for school and community groups to accompany the video, and has added captions in both English and Spanish. These kits have been duplicated in large quantities with funding from the California Earthquake Authority.

Emergency Survival Program. SCEC serves on the Coordinating Council of the Los Angeles County-led Emergency Survival Program, with emergency managers from all southern California counties, many large cities, the American Red Cross, and Southern California Edison. The primary role of the program is to develop a series of public information materials including monthly Focus Sheets, newsletter articles, and public service announcements related to a yearly theme. In 2006 and 2009 the program focused on earthquakes, with seven of the monthly focus sheets based on the "seven steps to earthquake safety" in *Putting Down Roots in Earthquake Country*. SCEC provided the Spanish version of the seven steps text, and coordinated the translation of the five other monthly focus sheets for 2006.

Use of SCEC Community Modeling Environment (CME) Products. Many SCEC CME products are being used in public presentations, webpages (*scec.org*, *earthquakecountry.info*, etc.), printed publications such as *Putting Down Roots in Earthquake Country* (English and Spanish), our "Earthquake Country – Los Angeles" DVD and in other venues to communicate earthquake hazards and encourage preparedness. These products, including the SCEC TeraShake and ShakeOut simulations, Puente Hills earthquake simulation, and Community Fault Model, have also had extensive media coverage through press briefings, reporters attending the SCEC Annual Meeting, and television documentaries, and have been used frequently as background imagery in many news stories. The visualizations were featured extensively in the National Geographic Channel documentary "Killer Quake," which presented SCEC TeraShake and Puente Hills animations, along with fault movies produced using SCEC's Virtual Display of Objects (SCEC-VDO) software. In June 2009 the Department of Energy honored the most advanced visualization to date of a magnitude 7.8 earthquake on the southern San Andreas Fault as one of this year's best scientific visualizations at the Scientific Discovery through Advanced Computing Conference. The new visualization was created by Amit Chourasia at the San Diego Supercomputer Center in collaboration with SCEC scientists *Kim Olsen, Steven Day, Luis Dalguer, Yifeng Cui, Jing Zhu, David Okaya, Phil Maechling and Tom Jordan.* The visualizations are featured at *http://www.wired.com/wiredscience/2009/08/visualizations/*.



Education Program

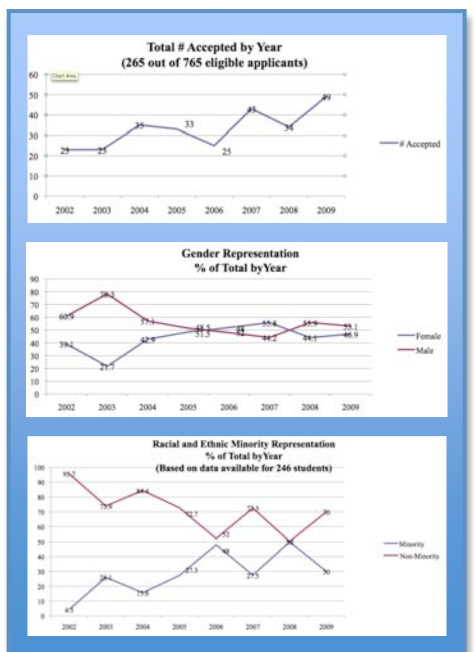
SCEC and its expanding network of education partners are committed to fostering increasing earthquake knowledge and science literacy at all grade levels and in a variety of educational environments.

The SCEC Education program uses the research literature (science education, learning psychology, sociology, etc.) and evaluation methodology to:

- Develop new materials and products (e.g. lesson plans, evaluation instruments, websites) where needed.
- Collaborate with partner organizations to enhance existing materials or products to meet the needs for SCEC's Earthquake Program mission.
- Utilize and promote existing materials that coincide with or complement SCEC's earthquake K-12 Education Program mission.
- Provide innovative experiential learning opportunities to undergraduate and graduate students during the summer and year-round.

SCEC Education programs include three internship programs, facilitated activities at museum exhibits, earthquake education workshops, public earthquake talks, and activities at conferences such as the National Science Teachers Association. SCEC Education programs and products are implemented in a variety of educational environments- any place, situation, or context where the transmission of knowledge to learners is taking place.

SCEC Experiential Learning and Career Advancement programs. Since 1994, SCEC has provided 338 internships to undergraduate and graduate students, with 265 internships since 2002 (charts included here are for 2002-2009 only). SCEC offers two summer internship programs (SCEC/SURE and SCEC/USEIT) and a year-round program for both undergraduate and graduate students (ACCESS). These programs are the principal framework for undergraduate student participation in SCEC, and have common goals of increasing diversity and retention. In addition to their research projects, participants come together several times during their internship for orientations, field trips, and to present posters at the SCEC Annual meeting. Students apply for both programs at *www.scec.org/internships*.



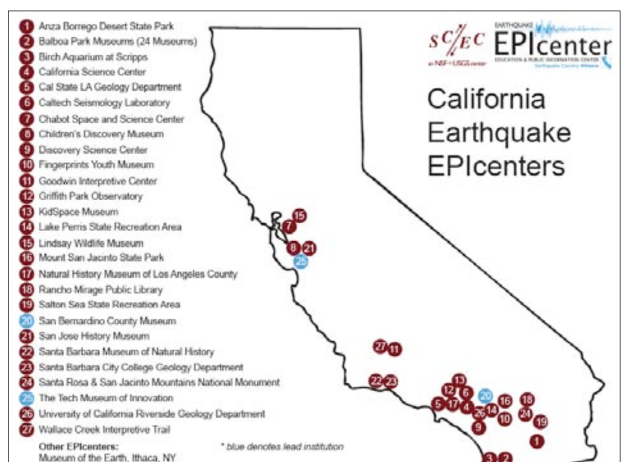
The SCEC *Summer Undergraduate Research Experience* (SCEC/SURE) has supported **172** students to work one-on-one as student interns with SCEC scientists since 1994 (100 since 2002). SCEC/SURE has supported students working on numerous projects in earthquake science, including the history of earthquakes on faults, risk mitigation, seismic velocity modeling, science education, and earthquake engineering.

The SCEC *Undergraduate Studies in Earthquake Information Technology* (SCEC/USEIT) program, unites undergraduates from across the country in an NSF REU Site at USC. SCEC/USEIT interns interact in a team-oriented research environment with some of the nation's most distinguished geoscience and computer science researchers. Since 2002, **145** students have participated.

Research activities are structured around “Grand Challenges” in earthquake information technology. Each summer the interns build upon the foundation laid by previous intern classes to design and engineer increasingly sophisticated visualization tools.

Our USEIT and CME experience has identified a “weak link” in cyberinfrastructure (CI)-related career pathways: the transition from discipline-oriented undergraduate degree programs to problem-oriented graduate studies in earthquake system science. We address this educational linkage problem through a CI-TEAM implementation project entitled the *Advancement of Cyberinfrastructure Careers through Earthquake System Science* (ACCESS). The objective of the ACCESS project is to provide a diverse group of students with research experiences in earthquake system science that will advance their careers and encourage their creative participation in cyberinfrastructure development. Its overarching goal is to prepare a diverse, CI-savvy workforce for solving the fundamental problems of system science. Undergraduate (ACCESS-U) internships support CI-related research in the SCEC Collaboratory by undergraduate students working toward senior theses or other research enhancements of the bachelor’s degree. Graduate (ACCESS-G) internships support up to one year of CI-related research in the SCEC Collaboratory by graduate students working toward a master’s thesis. **20** ACCESS internships have been awarded.

Earthquake Exhibits and Museum Partnerships. Recognizing the key role that museums have in engaging communities not often reached by schools, SCEC facilitates a network of museums and other locations interested in providing earthquake education programming. These organizations also serve as a distribution point for SCEC resources such as *Roots*. SCEC has worked with some of these partners for many years, and in summer 2008 they have been organized as Earthquake Education and Public Information Centers (Earthquake EPIcenters). The concept emerged during the planning of the 2008 Great Southern California ShakeOut, and the need to organize museums for the ShakeOut has evolved into a year-round interaction with the ShakeOut being the culminating community event for the year. The ShakeOut has provided a basis for institutions to share resources and expertise



EPIcenters share a commitment to demonstrating and encouraging earthquake preparedness. They help coordinate Earthquake Country Alliance activities in their county or region (including the ShakeOut), lead presentations or organize events in their communities, or in other ways demonstrate leadership in earthquake education and risk reduction. EPIcenters are found in a variety of public meeting places such as museums, science centers, libraries, and universities.

SCEC’s first major project in the development of a free choice learning venue was the *Wallace Creek Interpretive Trail***.** In partnership with the Bureau of Land Management (BLM), SCEC designed an interpretive trail along a particularly spectacular and accessible 2 km long stretch of the San Andreas Fault near Wallace Creek. Wallace Creek is located on the Carrizo Plain, a 3-4 hour drive north from Los Angeles. The trail opened in January 2001. The area is replete with the classic landforms produced by strike-slip faults: shutter ridges, sag ponds, simple offset stream channels, mole tracks and scarps. SCEC created the infrastructure and interpretive materials (durable signage, brochure content, and a website at *www.scec.org/wallacecreek* with additional information and directions to the trail). BLM has agreed to maintain the site and print the brochure into the foreseeable future. In 2009-2010, the website will undergo major revision to include new images created by using Light Detection and Ranging (LIDAR) techniques. A SCEC intern is creating a suite of activities to accompany the LIDAR images.

The *ShakeZone Earthquake Exhibit* at Fingerprints Youth Museum in Hemet, CA was developed originally in 2001 and was redesigned in 2006. The current version of the exhibit is based on SCEC's *Putting Down Roots in Earthquake Country* handbook. Major partners involved in the exhibit redesign included Scripps Institution of Oceanography and Birch Aquarium at Scripps. With funding from the United Way and other donors ShakeZone will be expanded in 2010 to include a section on Earthquake Engineering.

In 2006 SCEC has embarked on a long-term collaboration with the San Bernardino County Museum (SBCM) in Redlands, California. SCEC participated in the development and implementation of *Living on the Edge Exhibit*. This exhibit explains and highlights natural hazards in San Bernardino County (e.g. fire, floods, and earthquakes). SCEC provided resources in the development phase of the project and continues to supply the exhibit with copies of *Putting Down Roots in Earthquake Country*.

As a result of the successful collaboration on *Living on the Edge*, SCEC was asked to participate in the development of SBCM's *Hall of Geological Wonders*. To be completed in 2010, the Hall is a major expansion of this important cultural attraction in the Inland Empire. One of the main objectives of the Hall is to teach about the region from a geologic perspective. The museum is devoting a large space to the story of Southern California's landscape, its evolution and dynamic nature. SCEC has played an ongoing advisory role, provided resources for the development of the earthquake sections of the exhibit, and will have an ongoing role in the implementation of educational programming

The most recent debut of a SCEC earthquake display is the *Earthquake Information Center* at California State University, Los Angeles (CSULA). This exhibit, created in partnership with the geology department at CSULA, features two computer screens showing recent worldwide and local earthquakes. Located in the lobby of the Physical Science Building this exhibit also displays the seven steps to earthquake safety and components of a basic earthquake disaster supply kit. Many hundreds of students pass by the exhibit every day on their way to science classes.

K-12 Education Partnerships and Activities

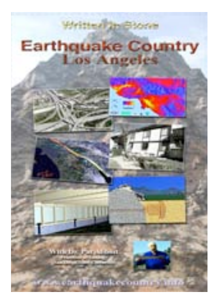
Partnerships with Science Education Advocacy Groups and Organizations with Similar Missions. SCEC is an active participant in the broader earth science education community including participation in organizations such as the National Association of Geoscience Teachers, the Coalition for Earth System Education, and local and national science educator organizations (e.g. NSTA). Improvement in the teaching and learning about earthquakes hinges on improvement in earth science education in general. Hence, SCEC contributes to the community through participation on outreach committees wherever possible, co-hosting meetings or workshops, and building long-term partnerships. An example of a current project is a partnership with EarthScope to host a San Andreas Fault workshop for park and museum interpreters that will be held in Spring 2009.

Teacher Workshops. SCEC offers teachers 2-3 professional development workshops each year. The workshops provide connections between developers of earthquake education resources and those who use these resources in the classroom. The workshops include content and pedagogical instruction, ties to national and state science education standards, and materials teachers can take back to their classrooms Workshops are offered concurrent with SCEC meetings, at National Science Teachers Association annual meetings, and at the University of Southern California. In 2003 SCEC began a partnership with the Scripps Institution of Oceanography Visualization Center to develop teacher workshops. Facilities at the Visualization Center include a wall-sized curved panorama screen (over 10m wide).

Sally Ride Science Festivals. Attended by over 1000 middle school age girls (grades 5–8) at each venue, Sally Ride Science Festivals offer a festive day of activities, lectures, and social activities emphasizing careers in science and engineering. Since 2003, SCEC has presented workshops for adults and students and participated in the Festival's "street fair," a popular venue for hands-on materials and science activities. At the street fair SCEC demonstrates key concepts of earthquake science and provides copies of Putting Down Roots in Earthquake Country. The workshops, presented by female members of the SCEC community share the excitement and the many career opportunities in the Earth sciences.

National Science Teachers Association and California Science Teachers Association. Earthquake concepts are found in national and state standards documents. For example, earthquake related content comprises the bulk of the six grade earth science curriculum in California. SCEC participates in national and statewide science educator conferences to promote innovative earthquake education and communicate earthquake science and preparedness to teachers in all states.

Development of Educational Products



Earthquake Country - Los Angeles Video Kit. The video, produced by Dr. Pat Abbott of SDSU, tells the story of how the mountains and valleys of the Los Angeles area formed, and the important role of earthquakes. The video features aerial photography, stunning computer animations (some produced by SCEC's UseIT interns), and interviews with well-known experts. SCEC developed an educator kit for school and community groups, available online and provided at SCEC's teacher workshops.

Plate Tectonics Kit. This new teaching tool was created to make plate tectonics activities more accessible for science educators and their students. SCEC developed a user-friendly version of the *This Dynamic Earth* map, which is used by many educators in a jigsaw-puzzle activity to learn about plate tectonics, hot spots, and other topics. At SCEC's teacher workshops, educators often suggested that lines showing the location of plate boundary on the back of the maps would make it easier for them to correctly cut the map, so SCEC designed a new (two-sided) map and developed an educator kit.

Use of SCEC Community Modeling Environment (CME) Products in K-12 Education. SCEC has included CME animations in its teacher education workshops since 2002 with the initial visualization of the Community Fault Model (CFM), and through 2008 with the latest TeraShake and ShakeOut animations. SCEC's "Earthquake Country – Los Angeles" DVD and *Putting Down Roots handbook* are used by teachers throughout Southern California, and both feature CME products. A compilation of CFM visualizations have also distributed on a CD at teacher conferences such as the NSTA annual meeting.

V. State of SCEC, 2009

Note: This report was presented by SCEC Director Jordan at the 2009 annual meeting.

This is SCEC's 19th Annual Meeting and the third community-wide gathering under the five-year SCEC3 program. The agenda features some very interesting presentations by keynote speakers, discussion sessions on major issues, many outstanding science posters, and a variety of IT demonstrations, education & outreach activities, and social gatherings. Four workshops and a student field trip are scheduled on the weekend before the meeting, and it will be followed by a special review of SCEC's Communication, Education & Outreach (CEO) program.

The week's activities will bring together one of the largest collaborations in geoscience (Figure 1): 466 people have pre-registered so far (compared to 453 last year), and 270 poster abstracts have been submitted—the most ever. This will be the first annual meeting for 121 of this year's pre-registrants, so we will welcome many new faces!

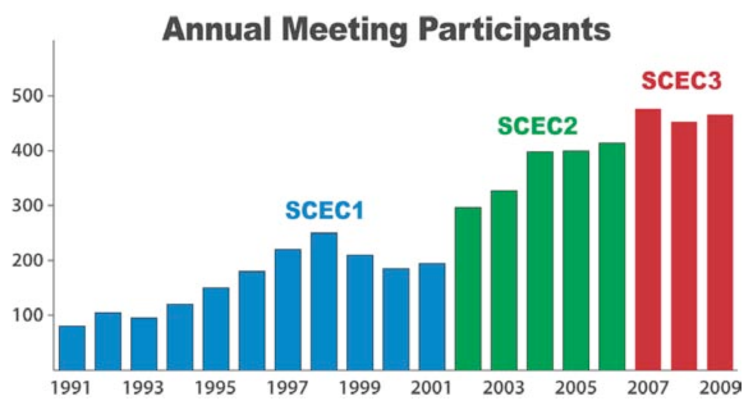


Figure 1. Registrants at SCEC Annual Meetings, 1991-2009. Number for 2009 (466) is pre-registrants.

Goals of the Meeting

Our annual meetings are designed to achieve three goals: to share scientific results and plans in poster sessions, at the meals, and around the pool; to mark our progress toward the priority objectives of the SCEC3 science plan given in Table 1; and to incorporate your ideas for new research into the annual planning process. A draft of the 2010 Science Plan, prepared by Deputy Director Greg Beroza and the Planning Committee, is included in this meeting volume.

A special goal of this year's meeting is to look beyond our annual cycle toward SCEC4, the next five-year phase of the Center's program. The SCEC4 planning process began at a leadership retreat in early June and will culminate with the submission of the SCEC4 proposal to the National Science Foundation (NSF) and the U.S. Geological Survey (USGS) on March 1, 2010. I will describe some aspects of the SCEC4 planning process and how it relates to the meeting activities at the end of this report.

Table 1. Priority Science Objectives for SCEC3

1. Improve the unified structural representation and employ it to develop system-level models for earth-quake forecasting and ground motion prediction
2. Develop an extended earthquake rupture forecast to drive physics-based SHA
3. Define slip rate and earthquake history of southern San Andreas fault system for last 2000 years
4. Investigate implications of geodetic/geologic rate discrepancies
5. Develop a system-level deformation and stress-evolution model
6. Map seismicity and source parameters in relation to known faults
7. Develop a geodetic network processing system that will detect anomalous strain transients
8. Test of scientific prediction hypotheses against reference models to understand the physical basis of earthquake predictability
9. Determine the origin and evolution of on- and off-fault damage as a function of depth
10. Test hypotheses for dynamic fault weakening
11. Assess predictability of rupture extent and direction on major faults
12. Describe heterogeneities in the stress, strain, geometry, and material properties of fault zones and understand their origin and interactions by modeling ruptures and rupture sequences
13. Predict broadband ground motions for a comprehensive set of large scenario earthquakes
14. Develop kinematic rupture representations consistent with dynamic rupture models
15. Investigate bounds on the upper limit of ground motion
16. Develop high-frequency simulation methods and investigate the upper frequency limit of deterministic ground motion predictions
17. Validate earthquake simulations and verify simulation methodologies
18. Collaborate with earthquake engineers to develop rupture-to-rafters simulation capability for physics-based risk analysis
19. Prepare for post-earthquake response.

Highlights of SCEC Achievements

Greg and the PC have put together an impressive report (included in the meeting volume) on the research projects supported by SCEC in 2009. It demonstrates substantial progress towards the SCEC3 objectives listed in Table 1. Greg will highlight the research results in his plenary address on Monday morning. The poster presentations at the Annual Meeting will provide a forum for more detailed discussions and interchange of ideas. In this section, I'll mention just a few of the many accomplishments achieved by the SCEC special projects.

Under two large grants from NSF's Earth Sciences Division and Office of Cyberinfrastructure, the Community Modeling Environment (CME) collaboration, comprising computer scientists as well as geoscientists, has been developing a petascale cyberfacility for seismic hazard analysis, dubbed PetaSHA. The PetaSHA computational platforms, managed by Phil Maechling, the SCEC Associate Director for Information Technology, are rapidly evolving towards petascale capability. During this past year, the CME was allocated over 30 million service units on NSF and DOE supercomputers, and it delivered major advances in earthquake system science (Figure 2). A broadband simulation of a M7.8 earthquake on the San Andreas fault, computed by Rob Graves and colleagues on the TeraShake platform, provided the scenario for the Great Southern California ShakeOut in November, 2008, the largest earthquake disaster drill in U.S. history. A series of dynamic rupture simulations computed by SDSU and SDSC scientists further elucidated the ground motions expected from San Andreas earthquakes of this type, as well as their variability. Kinematic and dynamic rupture simulations are underway for a number of other interesting earthquake scenarios in Southern California as part of CME's "Big Ten" project. Capabilities for full-3D tomography, first demonstrated by the USC group in 2006, are now being applied to the inversion of regional waveform data on the Tera3D platform. Physics-based probabilistic seismic hazard analysis has been implemented on the CyberShake platform, and the first physics-based hazard maps, completed this summer, are showing how source directivity, rupture complexity, and basin effects control strong ground motions throughout the Los Angeles region.

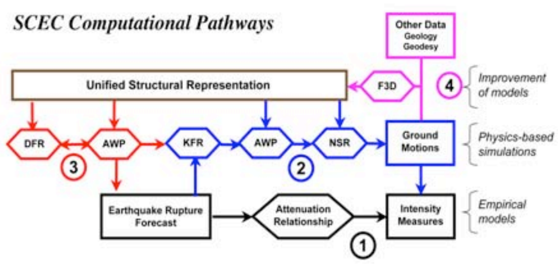
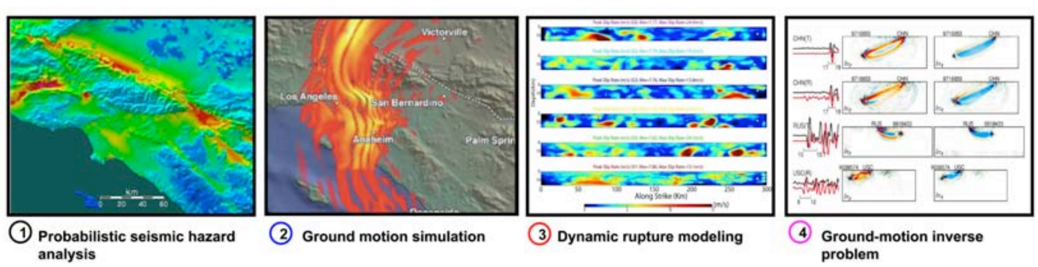


Figure 2. A wiring diagram for the SCEC computational pathways in seismic hazard analysis (left) and large-scale calculations exemplifying each of the pathways (below). (1) High-resolution seismic hazard map for the Los Angeles region using the UCERF2 model (Field et al., 2008). (2) Simulation of a M7.8 earthquake on the southern San Andreas fault for the 2008 ShakeOut exercise (Graves et al., 2008). (3) Dynamic rupture models for a M7.8 earthquake on the southern San Andreas fault used in the ShakeOut-D simulations (Olsen et al., 2009). (4) Fréchet kernels used in full 3D waveform tomography to improve seismic velocity models in Southern California (Chen et al., 2007).



The first time-dependent, uniform California earthquake rupture forecast (UCERF2), released in April, 2008, was developed on, and is being delivered to end-users via, the OpenSHA computational platform. OpenSHA, created by Ned Field and colleagues, is rapidly becoming the software of choice for seismic hazard calculations worldwide, including the Global Earthquake Model (GEM) now being constructed by a large international consortium. Ned chaired the 2007 Working Group on California Earthquake Probabilities that produced UCERF2; this very successful partnership among SCEC, the USGS, and the California Geological Survey

(CGS) was co-sponsored by the California Earthquake Authority (CEA). In June, the CEA Governing Board approved major funding for UCERF3, which will incorporate short-term as well as long-term forecasting techniques. The new WGCEP—again a USGS-CGS-SCEC partnership chaired by Ned—will be formally launched in January, 2010. Several informal discussions at the Annual Meeting will focus on the scientific challenges of the new UCERF3 project.

The Collaboratory for the Study of Earthquake Predictability (CSEP), which became operational in September, 2007, has expanded into an international cyberinfrastructure for conducting and evaluating earthquake forecasting models. Through the efforts of Danijel Schorlemmer and his colleagues, testing centers have been established at USC (Los Angeles), GNS (Wellington), ERI (Tokyo), and ETH (Zürich). CSEP is now running earthquake forecasting experiments in California, New Zealand, Japan, the western Pacific, and (as of August 1) Italy.

The results from these large collaborations and several others, including the Southern San Andreas Fault Evaluation (SoSAFE) and Extreme Ground Motions projects will be presented at the meeting.

Table 2. SCEC Institutions (September 1, 2009)

Core Institutions (16)	Participation Institutions (53)
California Institute of Technology Columbia University Harvard University Massachusetts Institute of Technology San Diego State University Stanford University U.S. Geological Survey, Golden U.S. Geological Survey, Menlo Park U.S. Geological Survey, Pasadena University of California, Los Angeles University of California, Riverside University of California, San Diego University of California, Santa Barbara University of California, Santa Cruz University of Nevada, Reno University of Southern California (lead)	Appalachian State University; Arizona State University; Berkeley Geochron Center; Boston University; Brown University; Cal-Poly, Pomona; Cal-State, Long Beach; Cal-State, Fullerton; Cal-State, Northridge; Cal-State, San Bernardino; California Geological Survey; Carnegie Mellon University; Case Western Reserve University; CICESE (Mexico); Cornell University; Disaster Prevention Research Institute, Kyoto University (Japan); ETH (Switzerland); Georgia Tech; Institute of Earth Sciences of Academia Sinica (Taiwan); Earthquake Research Institute, University of Tokyo (Japan); Indiana University; Institute of Geological and Nuclear Sciences (New Zealand); Jet Propulsion Laboratory; Los Alamos National Laboratory; Lawrence Livermore National Laboratory; National Taiwan University (Taiwan); National Central University (Taiwan); Ohio State University; Oregon State University; Pennsylvania State University; Princeton University; Purdue University; Texas A&M University; University of Arizona; UC, Berkeley; UC, Davis; UC, Irvine; University of British Columbia (Canada); University of Cincinnati; University of Colorado; University of Massachusetts; University of Miami; University of Missouri-Columbia; University of Oklahoma; University of Oregon; University of Texas-El Paso; University of Utah; University of Western Ontario (Canada); University of Wisconsin; University of Wyoming; URS Corporation; Utah State University; Woods Hole Oceanographic Institution

Organization and Leadership

SCEC is an institution-based center, governed by a Board of Directors, who represent its members. The membership currently stands at 16 core institutions and 53 participating institutions (Table 2). SCEC currently involves more than 650 scientists and other experts in active SCEC projects. A key measure of the size of the SCEC community—registrants at our Annual Meetings—is shown for the entire history of the Center in Figure 1.

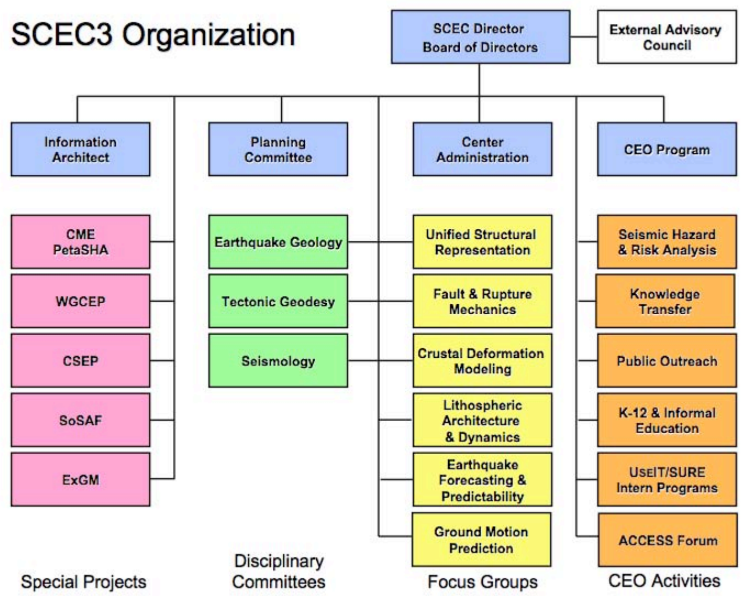


Figure 3. The SCEC3 organization chart, showing the disciplinary committees (green), focus groups (yellow), special projects (pink), CEO activities (orange), management offices (blue), and the external advisory council (white).

Board of Directors. Under the SCEC3 by-laws, each core institution appoints one member to the Board of Directors, and two at-large members are elected by the Board from the participating institutions. The Board is chaired by the Center Director, who also serves as the USC representative; the Vice-Chair is Lisa Grant Ludwig. During the past year, Tom Brocher replaced Bill Ellsworth as the Board member from USGS Menlo Park, and Ken Hudnut replaced Sue Hough as the Board member from USGS Pasadena. The complete Board of Directors is listed on page ii of the meeting volume.

Advisory Council. The Center's external Advisory Council (AC), chaired by Dr. Mary Lou Zoback, is charged with developing an overview of SCEC operations and advising the Director and the Board. Since the inception of SCEC in 1991, the AC has played a major role in maintaining the vitality of the organization and helping its leadership chart new directions. A verbatim copy of the AC's 2008 report follows my report in the meeting volume.

We thank Dr. Jack Moehle, who is rotating off the AC this year, and we welcome Drs. Jim Goltz and Steve Mahin as new AC members.

Working Groups. The SCEC organization comprises a number of disciplinary committees, focus groups, and special project teams (Figure 3). These working groups have been the engines of its success. The discussions organized by the working-group leaders at the Annual Meeting have provided critical input to the SCEC planning process.

The Center supports disciplinary science through three standing committees in Seismology, Tec-tonic Geodesy, and Earthquake Geology (green boxes of Figure 3). They are responsible for disciplinary activities relevant to the SCEC Science Plan, and they make recommendations to the Planning Committee regarding the support of disciplinary research and infrastructure.

SCEC coordinates earthquake system science through five interdisciplinary focus groups (yellow boxes): Unified Structural Representation (USR), Fault & Rupture Mechanics (FARM), Crustal Deformation Modeling (CDM), Lithospheric Architecture & Dynamics (LAD), Earthquake Forecasting & Predictability (EFP), and Ground Motion Prediction (GMP).

A sixth interdisciplinary focus group on Seismic Hazard & Risk Analysis (SHRA) manages the "implementation interface" as part of SCEC Communication, Education & Outreach (CEO) program (orange box). In particular, SHRA coordinates research partnerships with earthquake engineering organizations in end-to-end simulation and other aspects of risk analysis and mitigation.

Planning Committee. The SCEC Planning Committee (PC) is chaired by the SCEC Deputy Director, Greg Beroza, and comprises the leaders of the SCEC science working groups—disciplinary committees, focus groups, and special project groups—who together with their co-leaders guide SCEC's research program (Table 3). According to our by-laws, this mid-point of SCEC3 is the time to rotate the PC membership, and we are fortunate that some of our emerging new leaders have agreed to join. At this Annual Meeting, we will welcome Elizabeth Cochran as Seismology co-leader, Kim Olsen as USR co-leader, Kaj Johnson as CDM co-leader, Thorsten Becker as LAD co-leader, Jeanne Hardebeck as EFP co-leader, Brad Aagaard as GMP leader, Kate Scharer as SoSAFE co-leader, and Tom Rockwell as SoSAFE leader. We will also take the opportunity to thank those exceptional scientists they will replace, all of whom have led so well: Jamie Steidl, Jeroen Tromp, Tom Parsons, Gene Humphreys, Bernard Minster, Steve Day, and Ken Hudnut.

The PC has the responsibility for formulating the Center's science plan, conducting proposal reviews, and recommending projects to the Board for SCEC support. Its members will play key roles in formulating the SCEC4 proposal. Therefore, I urge you to use the opportunity of the Annual Meeting to communicate your thoughts about future research plans to them.

Table 3. SCEC3 Working Group Leadership

Disciplinary Committees	
Geology	Mike Oskin*
	James Dolan
Seismology	Egill Hauksson*
	Elizabeth Cochran
Geodesy	Jessica Murray-Moraleda*
	Rowena Lohman
Focus Groups	
Structural Representation	John Shaw*
	Kim Olsen
Fault & Rupture Mechanics	Judi Chester*
	Ruth Harris
Crustal Deformation Modeling	Liz Hearn*
	Kaj Johnson
Lithospheric Architecture & Dynamics	Paul Davis*
	Thorsten Becker
Earthquake Forecasting & Predictability	Terry Tullis*
	Jeanne Hardebeck
Ground Motion Prediction	Brad Aagaard*
	Rob Graves
Seismic Hazard & Risk Analysis	Paul Somerville*
	Nico Luco
Special Project Groups	
Community Modeling Environment	Phil Maechling*
WG on Calif. Earthquake Probabilities	Ned Field*
Collaboratory for Study of Equake Predictability	Tom Jordan
	Danijel Schorlemmer*
Southern San Andreas Fault Project	Tom Rockwell*
	Kate Scharer
Extreme Ground Motion	Tom Hanks*

* *Planning Committee members*

Center Budget and Project Funding

In April, 2009, SCEC received an $800K supplement to its NSF budget, which increased its NSF base funding to $3,500K. Combined with $1,100K from the U.S. Geological Survey, the total base funding now stands at $4,600K. In addition, the Center received $240K from the USGS Multi-Hazards Demonstration Project for SoSAFE, $90K from Pacific Gas & Electric Company for the broadband platform, and $37K rolled over from the 2008 Director's reserve. Exclusive CME, CSEP, ExGM, and CEO special projects, SCEC's total core funding was $4,967K.

The base budget approved by the Board of Directors for this year allocated $3,490K for science activities managed by the SCEC Planning Committee; $475K (including $25K for intern programs) for communication, education, and outreach activities, managed by the CEO Associate Director, Mark Benthien; $215K for information technology, managed by Associate Director for Information Technology, Phil Maechling; $332K for administration and $225K for meetings, managed by the Associate Director for Administration, John McRaney; and $130K for the Director's reserve account. As directed by NSF, $100K of the supplemental funding for this year is being expended for an external review of the CEO program.

Structuring of the SCEC program for 2009 began with the working-group discussions at our last Annual Meeting in September, 2008. An RFP was issued in October, 2008, and 176 proposals (including collaborative proposals) requesting a total of $5,632K were submitted in November, 2008. All proposals were independently reviewed by the Director and Deputy Director. Each proposal was also independently reviewed by the leaders and/or co-leaders of three relevant focus groups or disciplinary committees. (Reviewers were required to recuse themselves when they had a conflict of interest.) The Planning Committee met on January 22-23, 2009, and spent two days discussing every proposal. The objective was to formulate a coherent, budget-balanced science program consistent with SCEC's basic mission, short-term objectives, long-term goals, and institutional composition. Proposals were evaluated according to the following criteria:

a. Scientific merit of the proposed research.
b. Competence and performance of the investigators, especially in regard to past SCEC-sponsored research.
c. Priority of the proposed project for short-term SCEC objectives.
d. Promise of the proposed project for contributing to long-term SCEC goals.
e. Commitment of the P.I. and institution to the SCEC mission.
f. Value of the proposed research relative to its cost.
g. The need to achieve a balanced budget while maintaining a reasonable level of scientific continuity given the very limited Center funding.

The recommendations of the PC were reviewed by the SCEC Board of Directors at a meeting on February 8-9, 2009. The Board voted unanimously to accept the PC's recommendations, pending a final review of the program by the Center Director, which was completed in April, 2009 following notification of the supplemental funding from NSF.

Communication, Education, and Outreach

Through its CEO Program, SCEC offers a wide range of student research experiences, web-based education tools, classroom curricula, museum displays, public information brochures, online newsletters, workshops, and technical publications. Highlights of CEO activities for the past year are reported in the meeting volume by the Associate Director for CEO, Mark Benthien, who will present an oral summary on Monday morning.

SCEC has led the development of the Earthquake Country Alliance (ECA), an umbrella organization that includes earthquake scientists and engineers, preparedness experts, response and recovery officials, news media representatives, community leaders, and education specialists. The ECA has become our primary framework for developing partnerships, products, and services for the general public. SCEC maintains the ECA web portal (*www.earthquakecountry.info*.), which provides multimedia information about living in earthquake country, answers to frequently asked questions, and descriptions of other resources and services provided by ECA members.

A major focus of the ECA and the SCEC/CEO programs during the past year has been the organization of, and follow-up to, the Great Southern California ShakeOut, which was held in mid-November, 2008. As you know, ShakeOut was a tremendous success, thanks to the able leadership of Lucy Jones and the resources provided USGS Multi-Hazard Demonstration Project. ShakeOut has really changed the way organizations are approaching the problems of earthquake preparedness, not just here in the U.S., but worldwide (check out the "New Zealand Great West Coast Shakeout" at *www.shakeout.org.nz*). The SCEC staff, led by Mark Benthien, really put a huge effort into supporting ShakeOut, and the Annual Meeting will be an appropriate time to thank them for contributing to its success.

Owing to increased cooperation across California fostered by ShakeOut, the 1906 San Francisco Earthquake Centennial, and other events aimed at increasing community resiliency to earthquakes, the ECA has been broadened into a statewide organization with a number of regional chapters (see Mark's report for a more complete description). We look forward to working with our partners around the state in future preparedness activities, including a statewide ShakeOut exercise on October 15, 2009, and annually thereafter. I would like to encourage California members of the SCEC community to register for the ShakeOut (at *www.shakeout.org*) and to encourage their institutions to join USC and others that are already registered.

SCEC CEO staff continues to work with museums and other informal education venues to develop content and programs for earthquake education and to distribute SCEC resources, such as the extensive set of publications that has grown out of *Putting Down Roots in Earthquake Country*. In 2008, SCEC organized a group of museums and other locations interested in earthquake education into a network of *Earthquake Education and Public Information Centers* (Earthquake EPIcenters), which now involves 27 venues distributed around Southern California and the Bay Area.

SCEC is very active in the earth science education community, participating in organizations such as the National Association of Geoscience Teachers, The Coalition for Earth System Education, and local and national science educator organizations (e.g. NSTA). An example of a successful project was a partnership with EarthScope in hosting a San Andreas fault workshop for park and museum interpreters in April, 2009.

Bob de Groot is now skillfully leading SCEC's Office for Experiential Learning and Career Development. His office manages three SCEC intern programs: Summer Undergraduate Research Experiences (SURE), Undergraduate Studies in Earthquake Information Technology (USEIT), and Advancement of Cyberinfrastructure Careers through Earthquake System Science (ACCESS). The ELCA office promotes diversity in the scientific workforce and the professional development of early-career scientists (Figure 4). As someone very involved in these intern programs, I really enjoy seeing the students grapple with the tough but engaging problems of cutting-edge earthquake science. For example, the "grand challenge" for this year's USEIT program was *to deliver SCEC-VDO images and animations of faults and earthquake sequences to SCEC, the Earthquake Country Alliance, and other virtual organizations via a content management system that captures the metadata and guides the user*. Many of the summer interns will be presenting their work at this meeting, and I hope you'll have the opportunity to check out their posters and demos.

Figure 4. This "Brady Bunch" picture shows the students from around the country who participated in the 2009 USEIT summer program at USC. It includes 4 ACCESS-U interns and one SURE intern who worked with the 18 UseIT interns on this year's "grand challenge" project. Many will be attending the Annual Meeting to present posters, demos, and animations, as well as a film about the 2009 USEIT program.

SCEC4 Planning Process

The Center operates under cooperative agreements with NSF and the USGS. The current agreement (SCEC3) expires on January 31, 2012. We will apply for a new five-year agreement by submitting a proposal to these agencies on March 1, 2010. The proposal will be peer reviewed, and a special panel will be convened for a site review on June 22-24, 2010. If all goes according to plan, NSF and the USGS will inform us of their decision in the Fall of 2010, perhaps by the time of the next SCEC Annual Meeting (September 12-15, 2010).

The SCEC Board of Directors and Planning Committee will be very active in proposal process. The PC will summarize the SCEC3 accomplishments, with emphasis on our progress toward the objectives in Table 1, and they will work with the BoD to lay out the SCEC4 science plan. I have appointed a special BoD Committee on Fundamental Problems in Earthquake Science, chaired by Nadia Lapusta, to think broadly about our future research objectives, including the basic scientific hypotheses that will be proposed for testing in the proposed science plan.

I am hoping that all members of the SCEC community will contribute to this process. At this meeting, we have organized special discussion sessions around six key questions related to future SCEC research:

- What field and laboratory observations are most crucial for validating models of stress evolution and rupture dynamics?

- What data are most needed to understand the processes of active faulting, and which are the most promising for discovering new earthquake phenomena?
- How can progress best be made in understanding the predictability of earthquake ruptures?
- What innovations in theoretical and numerical modeling are needed to understand fault-system dynamics, forecast earthquake occurrence, and predict earthquake effects?
- How can earthquake scientists most effectively work with earthquake engineers to reduce earthquake risk?
- How should SCEC participate in national and international partnerships to promote earthquake system science?

I encourage you to participate vigorously in these discussions and other aspects of the SCEC4 planning process. The SCEC leadership is keen to get your input, and Greg and I would welcome personal communications, written or oral, about any suggestions regarding the SCEC4 proposal.

The SCEC/CEO program is an important—and very successful—component of the Center's activities, distinguished by its national leadership in earthquake preparedness, its exceptional student intern curriculum, and its close coordination of technology transfer with the SCEC research program. As part of the SCEC4 proposal process, an external panel will conduct a review of the CEO program in Palm Springs, immediately following the Annual Meeting. As input to this review process, an extensive report documenting CEO activities has been prepared by a team of outside consultants with experience in education and outreach. The review panel's assessment will be transmitted to the SCEC Advisory Council for comment in December. If you would like to provide your own input to this process, please contact Mary Lou Zoback, the AC chair, or another AC member during or after the meeting.

As SCEC Director, I want to express my thanks to all of you for your attendance at the Annual Meeting and your sustained commitment to the collaboration. And I'd especially like to thank Tran Huynh, the SCEC Special Projects and Events Coordinator, for her hard work and exceptional skill in organizing this meeting and arranging its many moving parts. Please do not hesitate to contact me, Tran, or other members of the SCEC staff if you have questions or comments about our meeting activities or future plans. Now please enjoy Palm Springs!

VI. 2009 SCEC Advisory Council Report

Note: As of the submission of the 2009 progress report to NSF and USGS, the Advisory Council had not yet submitted its final annual report to SCEC. The delay is due to the AC chair also being involved in the external review of the CEO program. The report of the CEO review takes a higher priority for completion. We are submitting the PowerPoint presentation made by the AC chair, Mary Lou Zoback, at the conclusion of the 2009 annual meeting. The slides that follow represent the key issues and recommendations that the AC will address in its report. The chair plans to submit the report by the end of 2009 and it will be forwarded to NSF and USGS at that time.

SCEC Advisory Council Report

Mary Lou Zoback, Advisory Council Chair
Risk Management Solutions

2007 SCEC Annual Meeting
Palm Springs, California
12 September 2007

SCEC Advisory Council Membership

Mary Lou Zoback, Risk Management Solutions RMS

Gail Atkinson, University of Western Ontario

Lloyd S. Cluff, Pacific Gas and Electric Company

John Filson, USGS (Emeritus)

Jeffrey T. Freymueller, University of Alaska

Jim Goltz*, CA Emergency Management Agency

Patti Guatteri, Swiss Re Capital Markets

Anne Meltzer, Lehigh University

Dennis Mileti, University of Colorado, Boulder (Emeritus)

Kate C. Miller, Texas A&M University

Steve Mahin*, Pacific Earthquake Engineering Research Center (PEER)

John Rudnicki, Northwestern University

*** New Members*

AC Issues from the SCEC Director

- Communication, Education, and Outreach (CEO) Program evaluation
- Input on Collaboratory for the Study of Earthquake Predictability (CSEP)
- Advice on initiatives in earthquake simulation and ground motion prediction
- Input on SCEC4 planning process
- Leadership development /succession planning within SCEC
- Science planning discussions at annual meeting

Additional Issues

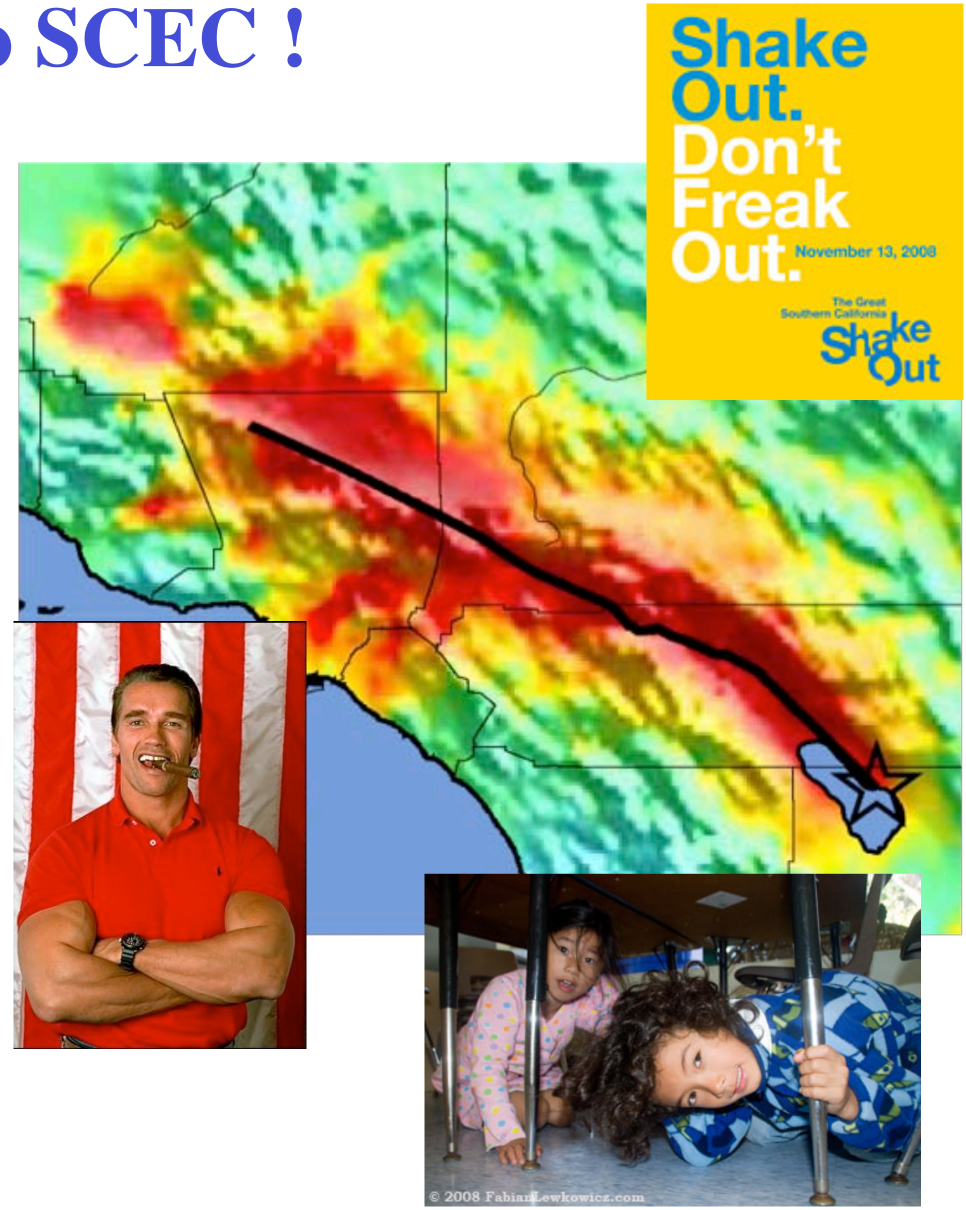
- Documenting and leveraging SCEC3 earthquake system science accomplishments
- Risk and crisis communication training
- Visibility and vital role of workshops within SCEC
- High risk/high return research opportunities

General Observations

- The AC lauds the selfless community spirit with which all SCEC members continue to collaborate to develop models and representations that are advancing the goal of earthquake system science.
- Annual Meeting once again a tremendous success!
    - infused with energy and enthusiasm—particularly students and interns
    - 121 registrants attending their first SCEC meeting (460+ total)
    - Ample time for viewing and lively interactions at posters and for individual and small group discussions
    - Outstanding plenary talks by young scientists who exemplify the new generation of SCEC leaders.

Kudos to SCEC !

- Nov. 2008 – ShakeOut exercise was a phenomenal success , Mark Benthien's superb leadership
- Remarkable on-going commitment to involving undergrads in SCEC research, Bob de Groot doing an outstanding job
- Funding of special projects
  - UCERF3 - $2M/ 32 months
  - PetaSHA3 - $1.7M/ 24 months
- Special thanks to SCEC staff for a wonderful annual meeting and wonderful weather!



To be mindful of

- Maintaining focus and avoid getting spread too thin (especially going into new funding cycle)
- Continue to seek creative funding opportunities and ways of engaging new core funding sponsors

Evaluation of CEO Program

- Phase I - Retrospective CEO Review to evaluate impact

  The Advisory Committee will respond to the phase I retrospective CEO evaluation within the January 2010 timeframe.

- Phase II – Forward-looking CEO Planning – *Utilize an external panel informed by a range of disciplines (e.g., marketing and psychology) to explore new CEO activities & directions*

  The Advisory Committee will update last year's recommendation regarding a phase II planning effort following it's evaluation of the phase I review.

CEO Evaluation -- ShakeOut and the Earthquake Country Alliance

- *ShakeOut 2008 an unparalleled success*
  - *5.5 million participants, broad-based appeal to many constituencies to prepare for a large earthquake*
- *Taking the Earthquake Country Alliance, the coalition of preparedness organizations organized by SCEC CEO, state-wide following ShakeOut is a very positive step.*
  - *SCEC key in getting statewide eq drill established-continue to pursue CA EMA for funding*
- *AC recommends that SCEC CEO continue to identify appropriate post-Shake Out activities & spin-offs to continue to foster similar efforts statewide*

CEO Evaluation -- Leverage CEO Activities

- *Explore FEMA as a potential source of funding for CEO activities. Many FEMA programs emphasize preparedness, mitigation and public education.*

- *Consider engaging other departments (e.g. sociology, psychology, economics and public health) at USC and other SCEC institutions in CEO activities and as possible grant writers for CEO*

Risk communication

- *Recommend that SCEC provide training in risk and crisis communication, particularly for those speaking publicly for SCEC on matters of earthquake occurrence and risk*

Feedback on CSEP (1)

- *Applaud SCEC for its continued progress in developing CSEP and in promoting test centers in other countries*
- *Recommend soliciting input from private industry on which products and timeframes would be of most interest and exploring private industry funding for CSEP (consortium of stakeholders?) -*
- *Explore public-sector partnerships (NASA, FEMA, state agencies) to expand the awareness, scope and support of CSEP activities*

Feedback on CSEP (2)

- *Focus of CSEP should continue to be the testing and evaluation of forecasting models*
- *CSEP should work with public agencies who have direct responsibilities for operational forecasting to define its role in this area*
- *UCERF3 – establish a process for exchange of results between UCERF3 and CSEP*
- *Formal training in risk communication and its effective use is particularly important for success of CSEP*

Advice on initiatives in earthquake simulation and ground motion prediction

- *Work with the engineering community to define engineering needs as well as metrics for testing/validation of simulations (e.g., reasonable means and standard deviations)*
- *Recommend SCEC explore a robust code validation effort, similar to CSEP, conducted jointly with leaders in the eq engineering community (perhaps in partnership with engineering centers?)*
    - *Critical in establishing user acceptance for practical applications.*
    - *Engineers need to know sensitivity of simulated ground motions to input parameters (and their uncertainty).*

Leadership development

- *Planning Committee under Greg Beroza's leadership is functionally exceptionally well*
- *AC extremely impressed with the diversity and youth within the SCEC community and particularly in the new leadership within the Planning Committee*
- *Rotation within this leadership group is healthy, and provides more opportunities for young scientists. We encourage SCEC senior leadership to continue to remain diligent to the need for mentoring and leadership development.*

Leadership / succession/ sustainability planning

- *Gratefully acknowledge USC's long-term generous support of SCEC, and strongly endorse keeping SCEC at USC*
- *Recommend putting a process in place ASAP (for implementation after SCEC4 proposal) to recruit new Director*
- *Develop a clear cut plan for succession with specific timelines*
- *Cultivate a pool of potential candidates by engaging them in SCEC, e.g. Advisory Council, meetings, workshops*
- *Consider alternate leadership structures for the future, such as allowing for separate Directors of Special Projects – this may be key to allowing future growth*

Visibility and vital role of workshops within SCEC

- *SCEC is filling a tremendous community need by facilitating easy to convene topical workshops*
- *AC noted that while many SCEC members were aware of recent workshops, they did not know much about the workshop outcomes.*
- *AC recommends:*
  - *Continued SCEC-wide promotion of workshop opportunities*
  - *Posting of a brief workshop summary on SCEC website within 30 days of the meeting*

Science plan discussions at annual meeting

- *AC very impressed with the format of this year's meeting – collaboration amongst disciplines was fostered by a single plenary session (more seating needed?)*
- *Plenary speakers were outstanding, in terms of content, timeliness and accessibility for the entire audience– we all learned something from them, even Dennis!*
- *Preparation/recasting of science plan into a few provocative questions was an effective strategy for promoting discussions*
- *We encourage discussion leaders to make a special effort to engage all SCEC members to participate in the science planning discussions*

Disseminating SCEC3 Accomplishments

- *Recommend that SCEC seize the opportunity to highlight their role in creating an extremely effective model for interdisciplinary collaboration and system-level approach*
  - *SCEC is a national model for interdisciplinary research*
  - *Highlight in a national forum- Perspective article for Science?, well-timed moving towards SCEC4;*
- *Again strongly endorse an integrated (but not exhaustive) accomplishment synthesis (monograph) that focuses on the progress made towards the 3 or 4 main goals of SCEC3*
- *(Continue to) recommend that a speakers program to broadly disseminate the results of all aspects of SCEC work.*

SCEC4 Planning

Have SCEC's scientific accomplishments made the impact on practitioners (engineers, planners, public officials) that a 20-year investment would warrant? How could this be improved in SCEC4?

- *Elucidate a clear and unifying vision, based on a few overarching goals (<< 19); show how the work of the individual focus and disciplinary groups feeds directly into these overarching goals*
- *Consider expanded partnerships to increase SCEC's impact and potential funding sources*
  - *FEMA - preparedness and mitigation*
  - *NASA – eq predictability*
  - *Private sector affiliates for special projects*
  - *NIST – engineering practice*

SCEC4 Planning: other issues

- *Investigate the roles for high performance computing in other SCEC disciplines and focus areas*
- *Create tools to make SCEC databases and community models more accessible and user-friendly (including non-SCEC users)*
- *Elucidate the role for international collaborations in SCEC4 (eg. CSEP)*
- *Manage growth in SCEC program due to success in bringing in special projects; re-evaluate staffing needs*

High risk/high return research opportunities

- *Identify and recognize potential high return opportunities*
- *Consider mechanisms to create a pool of funding for such projects*
- *Need process to leverage results of high-risk projects*

Final Comments

- *It is the current sense of the AC that the researchers and senior leadership of SCEC are doing an outstanding job*
- *The many individuals now leading committees and focus groups constitute a broadly diverse, extremely able, and committed group*
- *We look forward to working with SCEC leadership to help ensure that the products and progress of the Center in the SCEC3 era are commensurate with agency and community investment*
- *We continue to encourage comments, criticisms, and advice from inside and outside the SCEC membership, both at this meeting and throughout the year.*

VII. Financial Report

Table VII.1 gives the breakdown of the SCEC 2008 budget by major categories. The list of individual projects supported by SCEC in 2009 was sent to the NSF and USGS program officers in the spring of 2009.

Table VII.1 2009 Budget Breakdown by Major Categories

Total Funding (NSF and USGS):	$4,600,000
Management	315,000
CEO Program	450,000
Annual, AC, Board, and PC Meetings	225,000
Information Technology	215,000
Director's Reserve Fund	130,000
SCEC Summer Intern Program	25,000
CEO Review	100,000
Budgets for Disciplinary and Focus Group Activities: (including workshops)	$ 3,140,000
SoSAFE Supplement (from USGS)	240,000

VIII. Report on Subawards and Monitoring

The process to determine funding for 2009 began with discussions at the SCEC annual meeting in Palm Springs in September, 2008. An RFP was issued in October, 2008 and 182 proposals (including collaborations) were submitted in November, 2008. Proposals were then sorted and sent out for review in mid-December, 2008. Each proposal was independently reviewed by the Center Director Tom Jordan, the then Deputy Director Greg Beroza, by the chair and co-chair of the relevant focus group, and by the chair and co-chair of the relevant disciplinary committee. Reviewers had to recuse themselves where conflicts of interest existed. Every proposal had from 4 to 6 reviews. Reviews were sent to John McRaney, SCEC Associate Director for Administration, who collated and tabulated them. The SCEC Planning Committee (chaired by Archuleta) met on January 22-23, 2009 and spent 25+ hours over two days discussing every proposal. The PC assigned a rating from 1-5 (1 being highest) to each proposal and recommended a funding level. Proposals were rated based on quality of science and the proposed research plan, their relevance to the SCEC 2009 science goals, and the amount of money available for the overall program.

The recommendations of the PC were reviewed by the SCEC board at a meeting on February 8-9, 2009. The board voted 18-0 to accept the recommendations of the PC, pending a final review of the program by the Center Director. The director did not make any changes in the proposed plan approved by the board. The board was given two days to comment on the final plan of Jordan.

SCEC funding for 2009 was $4,600M. The board approved $315K for administration; $450K for the communications, education, and outreach program; $225K for workshops and meetings; and $215K for the information technology program. $100,000 was allocated for an independent review of the CEO program. We also received $25K from NSF for the summer undergraduate intern program and $240K from the USGS for the SoSAFE project.

The Center Director did not give specific targets for funding by infrastructure and science groups. Final funding for each category is shown in Table VII.I. Most research in SCEC involves aspects of several focus groups. The funding is shown by primary review group at the Planning Committee meeting.

The Center Director also was given a small ($130,000) fund for supporting projects at his discretion. This funding was used to provide additional workshop support, publication costs, SoSAFE studies, and CEO activities.

Following this action, individual PI's were notified of the decision on their proposals. Successful applicants submit formal requests for funding to SCEC. After all PI's at a core or participating institution submit their individual proposals, the proposals are scanned and the institution's request is submitted electronically to NSF/USGS for approval to issue a subcontract. Once that approval is received, the formal subcontract is issued to each institution to fund the individual investigators and projects.

Scientific oversight of each project is the responsibility of the Center Director, Deputy Director, and focus/disciplinary group leaders. Fiscal oversight of each project is the responsibility of the Associate Director for Administration. Regular oversight reports go to the SCEC Board. Any unusual problems are brought to the attention of agency personnel.

Subcontracts issued in 2009 are shown in the table below for both the USGS and NSF components of SCEC funding.

Table VIII.1 SCEC Subcontracts for 2009

USGS Funds

Appalachian State University	$17,000
Arizona State University	$61,000
Cal State, Long Beach	$15,000
Cal State, Northridge	$25,000
Cal State, San Bernardino	$30,000
California Institute of Technology	$245,000
Invisible Software	$36,000
MMI Engineering	$10,000
Pennsylvania State University	$10,000
San Diego State University	$56,207
University of British Columbia	$18,000
University of California, Davis	$65,000
University of California, Irvine	$70,975
University of Cincinnati	$20,000
University of Colorado	$24,000
University of Nevada, Reno	$158,914
University of Oregon	$23,000
Utah State University	$16,000
Total USGS	**$931,096**

NSF Funds

Arizona	$41,000
Arizona State	$20,000
Berkeley Geochron Center	$20,000
Brown	$75,000
California Institute of Technology	$59,000
Case Western	$45,000
Columbia	$76,000
Cornell	$21,000
Georgia Tech	$35,329
Harvard	$169,000
Indiana University	$40,000
Massachusetts	$20,000
Miami	$15,000
MIT	$55,000
Oregon	$25,000
Princeton	$27,000
San Diego State University	$95,499
Stanford	$212,858
Texas A&M	$21,000
UCB	$30,000
UCLA	$170,000
UCR	$158,624
UCSB	$235,000
UCSC	$89,000
UCSD	$157,000
URS	$162,000

UNR	$18,951
UTEP	$16,000
WHOI	$23,000
Wisconsin	$20,000
Total NSF	**$2,152,261**

Report on 2009 SCEC Cost Sharing

The University of Southern California contributes substantial cost sharing for the administration of SCEC. In 2009, USC provided $366,916 for SCEC administration and staff costs, waived $720,090 in overhead recovery on subcontracts, and provided nearly $110,000 in release time to the center director to work on SCEC. USC previously spent $7,500,000 in 2002-2003 renovating SCEC space.

SCEC Management Cost-Sharing Report for 2009

1. USC provided $520,277 in cost-sharing for SCEC management and staff (Direct Costs).

Institution	Amount	Purpose
USC	$292,508	Salary Support of Jordan, McRaney, Huynh
	$52,260	Salary Support for Education Director deGroot
	$103,850	Salary Support for IT Staff Member Patrick Small
	$10,000	Report Preparation and Publication Costs
	$10,000	Meeting Expenses
	$16,000	Office Supplies
	$12,000	Computers and Usage Fees
	$6,000	Administrative Travel Support for SCEC Officers
	$6,500	Postage
	$11,159	Telecommunications
	$520,277	Total

2. USC waives overhead on subcontracts. There are 54 subcontracts in 2009.

$1,143,000	Amount Subject to Overhead
0.63	USC Overhead Rate
$720,090	Savings Due to Overhead Waiver

3. SCEC Director receives a 50% release from teaching for administrative work.

$110,000	Cost Sharing for 2005-2006 Academic Year
$1,062,186	2007 USC Cost-Sharing to SCEC

In addition to USC support of SCEC management activities, each core institution of SCEC is required by the by-laws to spend at least $35,000 in direct costs on SCEC activities at the local institution. These funds are controlled by the institution's participants in SCEC, not centrally directed by SCEC management.

IX. Demographics of SCEC Participants

Center Database of SCEC Participants in 2008

	Administration/ Technical	Faculty Researcher	Graduate Student	Non-faculty Researcher	Undergraduate Student
Race					
Asian	5	8	20	10	0
Black	0	0	0	1	1
White	17	90	47	97	9
Native American	0	1	2	0	0
No Information	59	52	149	74	67
Ethnicity					
Latino	2	4	11	3	2
Not Latino	33	99	97	105	17
No information	45	43	98	66	57
Withheld	1	5	12	8	1
Gender					
Female	25	27	66	35	39
Male	55	123	147	144	37
Withheld/No Info	1	1	5	3	1
Citizenship					
US	37	94	64	95	22
Other	2	9	51	22	0
No information	39	36	89	51	54
Resident	2	12	10	13	1
Withheld	1	0	4	1	0
Disability Status					
None	11	74	46	85	10
No information	70	75	172	94	67
Hearing	0	1	0	0	0
Visual	0	0	0	2	0
Mobility	0	0	0	1	0
Other	0	1	0	0	0

X. Report on International Contacts and Visits

1. SCEC Advisory Council. We have one international member of our Advisory Council, Gail Atkinson of the University of Western Ontario.

2. ACES (APEC Cooperative for Earthquake Simulation). SCEC and JPL are the U.S. organizations participating in ACES. Information on ACES can be found at http://www.quakes.uq.edu.au/ACES/. Andrea Donnellan of SCEC/JPL is the U.S. delegate to the ACES International Science Board and John McRaney of SCEC is the secretary general. The ACES group held two special sessions at the Asia Oceanic Geological Society meeting in Singapore in August, 2009. A visit was also made to the Association of Pacific Rim Universities (APRU) HQ in Singapore and a presentation made to their science group. The next ACES workshop will be held in Japan in October, 2010.

3. ETH/Zurich. Stefan Wiemar, Jeremy Zechar and Martin Mai (also at KAUST) of ETH are participants in the SCEC/CSEP projects.

4. IGNS/New Zealand. Mark Stirling and David Rhoades of the Institute for Geological and Nuclear Sciences of New Zealand are involved in the RELM/CSEP program.

5. University of Western Ontario/Canada. Kristy Tiampo of the University of Western Ontario in London, Ontario is funded through the SCEC core program.

6. University of British Columbia/Canada. Elizabeth Klein of UBC is funded through the SCEC core program.

7. SCEC Annual Meeting. The SCEC annual meeting continues to attract international participants each year. There were participants in the 2009 annual meeting from China, Japan, India, Mexico, Canada, France, Switzerland, Germany, Russia, the Czech Republic, Taiwan, Turkey, and New Zealand.

8. International Participating Institutions. ETH/Zurich, CICESE/Mexico, University of Western Ontario, University of British Columbia, and Institute for Geological and Nuclear Sciences/New Zealand; and 4 institutions from Taiwan (Academia Sinica; National Central University; National Chung Cheng University; National Taiwan University) are participating institutions in SCEC.

9. International Travel by PI and SCEC Scientists. The PI and other SCEC scientists participated in many international meetings and workshops during the report year. They include: 1) UJNR Workshop in Seattle in November, 2008, 2) the IASPEI meeting in Capetown, South Africa in January, 2009, 3) a workshop on Earthquake Hazards of the Red River fault in Hanoi, Vietnam in March, 2009, 4) the 6th International Conference on Statistical Seismology at Lake Tahoe in April, 2009, 5) Global Earthquake Model (GEM) meetings in Australia in February, 2009, and Zurich in June, 2009, 6) meetings at ERI in Tokyo and DPRI in Kyoto, Japan in June, 2009; 7) the Iran-US joint workshop in Irvine in June, 2009, and 8) the International

Commission on Earthquake Forecasting for Civil Protection, Italy in Rome, Italy in May, August, and September, 2009.

XI. Publications

Note: Publication numbers listed here are continued from the SCEC list that was initiated in 1991. This list includes on research publications that had updates between October, 2009 and October, 2009.

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Computational Earthquake Science, Concurrency and Computation: Practice and Experience, Geoffrey Fox, submitted, 2008.
1227 Sammis, C. G., A. J. Rosakis, and H. S. Bhat, Effects of Off-Fault Damage on Earthquake Rupture Propagation: Experimental Studies, PAGEOPH, in review, 2008.
1228 Noda, H., E. M. Dunham, and J. R. Rice, Earthquake Ruptures with Thermal Weakening and the operation of Major Faults at Low Overall Stress Levels, Journal of Geophysical Research, published, 2008.
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XII. SCEC 2010 RFP and Research Goals

I. Introduction

On February 1, 2002, the Southern California Earthquake Center (SCEC) changed from an entity within the NSF/STC program to a freestanding center, funded by NSF/EAR and the U.S. Geological Survey. SCEC2 was funded for a five-year period, February 2002 to January 2007. SCEC was renewed for the period February 2007 through January 2012, referred to now as SCEC3. This document solicits proposals from individuals and groups to participate in the fourth year of the SCEC3 research program.

II. Guidelines for Proposal Submission

A. **Due Date.** Friday, November 6, 2009, 5:00 pm PST. Late proposals will not be accepted. Note the different deadline for submitting annual progress reports below.

B. **Delivery Instructions.** Proposals must be submitted as PDF documents via the SCEC Proposal web site at *http://www.scec.org/proposals*. Submission procedures, including requirements for how to name your PDF files, will be found at this web site.

C. **Formatting Instructions.**

- **Cover Page.** The cover page should be headed with the words "2010 SCEC Proposal" and include the project title, Principal Investigator(s), institutional affiliation, amount of request, and proposal categories (from types listed in Section IV). List in order of priority three science objectives (Section VII) that your proposal addresses, for example A3, A5 and A11. Indicate if the proposal should also be identified with one or more of the SCEC special projects (see Section VIII). Collaborative proposals involving multiple investigators and/or institutions should list all Principal Investigators. Proposals do not need to be formally signed by institutional representatives, and should be for one year, with a start date of February 1, 2010.
- **Technical Description.** Describe in up to five pages (including figures) the technical details of the project and how it relates to the short-term objectives outlined in the SCEC Science Objectives (Section VII). References are not included in the five-page limit.
- **Budget Page.** Budgets and budget explanations should be constructed using NSF categories. Under guidelines of the SCEC Cooperative Agreements and A-21 regulations, secretarial support and office supplies are not allowable as direct expenses.
- **Current Support.** Statements of current support, following NSF guidelines, should be included for each Principal Investigator.
- **2009 Annual Report.** Scientists funded by SCEC in 2009 must submit a report of their progress by 5:00 pm PST February 28, 2010. 2010 proposals approved by the PC will not be funded until all progress reports are submitted. Reports should be up to five pages of text and figures. Reports should include bibliographic references to any SCEC publication during the past year (including papers submitted and in review), including their SCEC contribution number. Publications

are assigned numbers when they are submitted to the SCEC publication database at *http://www.scec.org/signin*.

- **Special Note on Workshop Reports.** Reports on results and recommendations of workshops funded by SCEC in 2010 are to be submitted no later than 30 days following the completion of the workshop. The reports will be posted on the SCEC web site as soon as possible after review by the directors.
- **Labeling the Submitted PDF Proposal.** PI's must follow the proposal naming convention. Investigators must label their proposals with their last name followed by 2010, e.g., Archuleta2010.pdf. If there is more than one proposal, then the file would be labeled as: Archuleta2010_1.pdf (for the 1st proposal) and Archuleta2010_2.pdf (for the 2nd proposal).

D. **Principal Investigator Responsibilities.** PI's are expected to interact with other SCEC scientists on a regular basis (e.g., by attending workshops and working group meetings), and contribute data, analysis results, and/or models to the appropriate SCEC data center (e.g., Southern California Earthquake Data Center—SCEDC), database, or community model (e.g., Community Velocity Model—CVM). Publications resulting entirely or partially from SCEC funding must include a publication number available at *http://www.scec.org/signin*. By submitting a proposal, investigators are agreeing to these conditions.

E. **Eligibility.** Proposals can be submitted by eligible Principal Investigators from:

- U.S. Academic institutions
- U.S. Private corporations
- International Institutions (funding will mainly be for travel)

F. **Collaboration.** Collaborative proposals with investigators from the USGS are encouraged. USGS employees should submit their requests for support through USGS channels. Collaborative proposals involving multiple investigators and/or institutions are strongly encouraged; these can be submitted with the same text, but with different institutional budgets if more than one institution is involved.

G. **Budget Guidance.** Typical SCEC grants funded under this Science Plan in the past have fallen in the range of $10,000 to $35,000. This is not intended to limit SCEC to a fixed award amount, nor to a specified number of awards, rather it is intended to calibrate expectations for proposals written by first-time SCEC investigators.

H. **Award Procedures.** All awards will be funded by subcontract from the University of Southern California. The Southern California Earthquake Center is funded by the National Science Foundation and the U.S. Geological Survey.

III. SCEC Organization

A. **Mission and Science Goal.** SCEC is an interdisciplinary, regionally focused organization with a mission to:

- Gather data on earthquakes in Southern California and elsewhere
- Integrate information into a comprehensive, physics-based understanding of earthquake phenomena

- Communicate understanding to the world at large as useful knowledge for reducing earthquake risk

SCEC's primary science goal is to develop a comprehensive, physics-based understanding of earthquake phenomena in Southern California through integrative, multidisciplinary studies of plate-boundary tectonics, active fault systems, fault-zone processes, dynamics of fault ruptures, ground motions, and seismic hazard analysis. The long-term science goals are summarized in Appendix A.

B. **Disciplinary Activities.** The Center sustains disciplinary science through standing committees in seismology, geodesy, and geology. These committees will be responsible for planning and coordinating disciplinary activities relevant to the SCEC science plan, and they will make recommendations to the SCEC Planning Committee regarding support of disciplinary research and infrastructure. High-priority disciplinary activities are summarized in Section VII.A.

C. **Interdisciplinary Focus Areas.** Interdisciplinary research is organized within five science focus areas: 1) Unified Structural Representation (URS), 2) Fault and Rupture Mechanics (FARM), 3) Crustal Deformation Modeling (CDM), 4) Lithospheric Architecture and Dynamics (LAD), 5) Earthquake Forecasting and Predictability (EFP), 6) Ground Motion Prediction (GMP) and 7) Seismic Hazard and Risk Analysis (SHRA). High-priority activities are listed for each of these interdisciplinary focus areas in Section VII.B.

D. **Special Projects.** SCEC supports eight special projects that will advance designated research frontiers. Several of these initiatives encourage further development of an advanced IT infrastructure for system-level earthquake science in Southern California. High-priority initiatives are listed and described in Section VIII.

E. **Communication, Education, and Outreach.** SCEC maintains a strong Communication, Education, and Outreach (CEO) program with four principal goals: 1) coordinate productive interactions among SCEC scientists, and with partners in science, engineering, risk management, government, business, and education; 2) increase earthquake knowledge and science literacy at all educational levels; 3) improve earthquake hazard and risk assessments; and 4) promote earthquake preparedness, mitigation, and planning for response and recovery. Opportunities for participating in the CEO program are described in Section IX. Current activities are described online at *http://www.scec.org/ceo*.

IV. Proposal Categories

A. **Data Gathering and Products.** SCEC coordinates an interdisciplinary and multi-institutional study of earthquakes in Southern California, which requires data and derived products pertinent to the region. Proposals in this category should address the collection, archiving and distribution of data, including the production of SCEC community models that are on-line, maintained, and documented resources for making data and data products available to the scientific community.

B. **Integration and Theory.** SCEC supports and coordinates interpretive and theoretical investigations on earthquake problems related to the Center's mission. Proposals in this category should be for the integration of data or data products from Category A, or for general or theoretical studies. Proposals in Categories A and B should address one or more of the goals in Section VII, and may include a brief description (<200 words) as to how the proposed research and/or its results might be used in a special initiative (see Section VIII) or in an educational or outreach mode (see Section IX).

C. **Workshops.** SCEC participants who wish to host a workshop between February 2010 and January 2011 should submit a proposal for the workshop in response to this RFP. This includes workshops that might be organized around the SCEC annual meeting in September. Workshops in the following topics are particularly relevant:
   - Organizing collaborative research efforts for the five-year SCEC program (2007-2012). In particular, interactive workshops that engage more than one focus and/or disciplinary group are strongly encouraged.
   - Engaging earthquake engineers and other partner and user groups in SCEC-sponsored research.
   - Participating in national initiatives such as EarthScope, the Advanced National Seismic System (ANSS), and the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES).

D. **Communication, Education, and Outreach.** SCEC has developed a long-range CEO plan and opportunities for participation are listed in Section IX. Investigators who are interested in participating in this program should contact Mark Benthien (213-740-0323; benthien@usc.edu) before submitting a proposal.

E. **SCEC/SURE Intern Project.** If your proposal includes undergraduate funding, please note this on the cover page. Each year SCEC coordinates the SCEC Summer Undergraduate Research Experience (SCEC/SURE) program to support one-on-one student research with a SCEC scientist. See *http://www.scec.org/*internships for more information. SCEC will be recruiting mentors in November 2009, and will request descriptions of potential projects via email. In December, these descriptions will be published on the SCEC Internship web page to allow applicants to identify their preferred projects.

   Mentors will be required to provide at least $2500 of the $5000 intern stipend, and SCEC will pay the balance. Mentor contributions can come from any source, including SCEC-funded research projects. Therefore, interested SCEC scientists are encouraged to include at least $2500 for an undergraduate intern in their 2009 SCEC proposals, and then respond to the recruitment emails.

   Questions about the SCEC/SURE Intern Project should be referred to Robert de Groot, *degroot@usc.edu*.

F. **SCEC Annual Meeting participation.** Investigators who wish to only request funding to cover travel to the annual meeting can participate in a streamlined review process with an abbreviated proposal. Investigators who are already funded to study projects that would be of interest to the SCEC community, and investigators new to SCEC who would benefit from exposure to the annual meeting in order to fine-tune future proposals are encouraged to apply.

V. Evaluation Process and Criteria

A. Proposals should be responsive to the RFP. A primary consideration in evaluating proposals will be how directly the proposal addresses the main objectives of SCEC. Important criteria include (not necessarily in order of priority):
   - Scientific merit of the proposed research
   - Competence and performance of the investigators, especially in regard to past SCEC-sponsored research
   - Priority of the proposed project for short-term SCEC objectives as stated in the RFP
   - Promise of the proposed project for contributing to long-term SCEC goals as reflected in the SCEC science plan (see Appendix).
   - Commitment of the P.I. and institution to the SCEC mission
   - Value of the proposed research relative to its cost
   - Ability to leverage the cost of the proposed research through other funding sources
   - Involvement of students and junior investigators
   - Involvement of women and underrepresented groups
   - Innovative or "risky" ideas that have a reasonable chance of leading to new insights or advances in earthquake physics and/or seismic hazard analysis.

B. Proposals may be strengthened by describing:
   - Collaboration
     - Within a disciplinary or focus group
     - Between disciplinary and/or focus groups
     - In modeling and/or data gathering activities
     - With engineers, government agencies, and others. (See Section IX)
   - Leveraging additional resources
     - From other agencies
     - From your institution
     - By expanding collaborations
   - Development and delivery of products
     - Community research tools, models, and databases
     - Collaborative research reports
     - Papers in research journals
     - End-user tools and products
     - Workshop proceedings and CDs
     - Fact sheets, maps, posters, public awareness brochures, etc.
     - Educational curricula, resources, tools, etc.
   - Educational opportunities
     - Graduate student research assistantships
     - Undergraduate summer and year-round internships (funded by the project)
     - K-12 educator and student activities
     - Presentations to schools near research locations

- Participation in data collection

C. All research proposals will be evaluated by the appropriate disciplinary committees and focus groups, the Science Planning Committee, and the Center Director. CEO proposals will be evaluated by the CEO Planning Committee and the Center Director.
D. The Science Planning Committee is chaired by the Deputy Director and comprises the chairs of the disciplinary committees, focus groups, and special projects. It is responsible for recommending a balanced science budget to the Center Director.
E. The CEO Planning Committee is chaired by the Associate Director for CEO and comprises experts involved in SCEC and USGS implementation, education, and outreach. It is responsible for recommending a balanced CEO budget to the Center Director.
F. Recommendations of the planning committees will be combined into an annual spending plan and forwarded to the SCEC Board of Directors for approval.
G. Final selection of research projects will be made by the Center Director, in consultation with the Board of Directors.
H. The review process should be completed and applicants notified by the end of February 2010.

VI. Coordination of Research Between SCEC and USGS-EHRP

A. Earthquake research in Southern California is supported both by SCEC and by the USGS Earthquake Hazards Reduction Program (EHRP). EHRP's mission is to provide the scientific information and knowledge necessary to reduce deaths, injuries, and economic losses from earthquakes. Products of this program include timely notifications of earthquake locations, size, and potential damage, regional and national assessments of earthquakes hazards, and increased understanding of the cause of earthquakes and their effects. EHRP funds research via its External Research Program, as well as work by USGS staff in its Pasadena, Menlo Park, and Golden offices. The EHRP also supports SCEC directly with $1.1M per year.
B. SCEC and EHRP coordinate research activities through formal means, including USGS membership on the SCEC Board of Directors and a Joint Planning Committee, and through a variety of less formal means. Interested researchers are invited to contact Dr. Ken Hudnut, EHRP coordinator for Southern California, or other SCEC and EHRP staff to discuss opportunities for coordinated research.
C. The USGS EHRP supports a competitive, peer-reviewed, external program of research grants that enlists the talents and expertise of the academic community, State and local governments, and the private sector. The investigations and activities supported through the external program are coordinated with and complement the internal USGS program efforts. This program is divided into six geographical/topical 'regions', including one specifically aimed at Southern California earthquake research and others aimed at earthquake physics and effects and at probabilistic seismic hazard assessment (PSHA). The Program invites proposals that assist in achieving EHRP goals.
D. The EHRP web page, http://earthquake.usgs.gov/research/external/, describes program priorities, projects currently funded, results from past work, and instructions for submitting proposals. The EHRP external funding cycle is several months offset from

SCEC's, with the RFP due out in February and proposals due in May. Interested PI's are encouraged to contact the USGS regional or topical coordinators for Southern California, Earthquake Physics and Effects, and/or National (PSHA) research, as listed under the "Contact Us" tab.

E. USGS internal earthquake research is summarized by topic at *http://earthquake.usgs.gov/research/topics.php*

VII. SCEC3 Science Priority Objectives

The research objectives outlined below are priorities for SCEC3. They carry the expectation of substantial and measurable success during the coming year. In this context, success includes progress in building or maintaining a sustained effort to reach a long-term goal. How proposed projects address these priorities will be a major consideration in proposal evaluation, and they will set the programmatic milestones for the Center's internal assessments. In addition to the priorities outlined below, the Center will also entertain innovative and/or "risky" ideas that may lead to new insights or major advancements in earthquake physics and/or seismic hazard analysis.

There are four major research areas with the headings **A, B, C** and **D** with subheadings given by numbers. The front page of the proposal should specifically identify subheadings that will be addressed by the proposed research.

A. Develop an extended earthquake rupture forecast to drive physics-based SHA

A1. Define slip rates and earthquake history of southern San Andreas fault system for the last 2000 years

A2. Investigate implications of geodetic/geologic rate discrepancies

A3. Develop a system-level deformation and stress-evolution model

A4. Statistical analysis and mapping of seismicity and source parameters with an emphasis on their relation to known faults

A5. Develop a geodetic network processing system that will detect anomalous strain transients

A6. Test scientific prediction hypotheses against reference models to understand the physical basis of earthquake predictability

A7. Determine the origin, evolution and implications of on- and off-fault damage

A8. Test hypotheses for dynamic fault weakening

A9. Assess predictability of rupture extent and direction on major faults

A10. Develop statistical descriptions of heterogeneities (e.g., in stress, strain, geometry and material properties), and understand their origin and implications for seismic hazard by observing and modeling single earthquake ruptures and multiple earthquake cycles.

A11. Constrain absolute stress and understand the nature of interaction between the faulted upper crust, the ductile crust and mantle, and how geologic history helps to resolve the current physical properties of the system.

B. Predict broadband ground motions for a comprehensive set of large scenario earthquakes

B1. Develop kinematic and dynamic rupture representations consistent with seismic, geodetic, and geologic observations.

B2. Investigate bounds on the upper limit of ground motion

B3. Develop high-frequency simulation methods and investigate the upper frequency limit of deterministic ground-motion predictions

B4. Validate ground-motion simulations and verify simulation methodologies

B5. Improve our understanding of site effects and develop methodologies to include these effects in broadband ground-motion simulations.

B6. Collaborate with earthquake engineers to develop rupture-to-rafters simulation capability for physics-based risk analysis

C. **Improve and develop community products (data or descriptions) that can be used in system-level models for the forecasting of seismic hazard. Proposals for such activities should show how they would significantly contribute to one or more of the numbered goals in A or B.**

D. **Prepare post-earthquake response strategies**

Some of the most important earthquake data are gathered during and immediately after a major earthquake. Exposures of fault rupture are erased quickly by human activity, aftershocks decay rapidly within days and weeks, and post-seismic slip decays exponentially. SCEC solicits proposals for a workshop to plan post-earthquake science response. The goals of the workshop would be to: 1) develop a post-earthquake science plan that would be a living document such as a wiki; 2) identify permanent SCEC and other science facilities that are needed to ensure success of the science plan; 3) identify other resources available in the community and innovative ways of using technology for coordination and rapid data processing that will allow for rapid determination of source parameters, maps, and other characteristics of the source and ground motion patterns; 4) develop plans for use of simulations in post-earthquake response for evaluation of short-term earthquake behavior and seismic hazards; and 5) develop mechanisms for regular updates of the SCEC post-earthquake response plan

VII-A. Disciplinary Activities

The Center will sustain disciplinary science through standing committees in seismology, geodesy, and geology. These committees will be responsible for planning and coordinating disciplinary activities relevant to the SCEC science plan, and they will make recommendations to the SCEC Planning Committee regarding the support of disciplinary infrastructure. High-priority disciplinary objectives include the following tasks:

1. Seismology

A. **Objectives.** The objectives of the Seismology group are to gather data on the range of seismic phenomena observed in southern California and to integrate these data into physics-based models of fault slip. Of particular interest are proposals that foster innovations in network deployments, data collection, real-time research tools, and data processing. Proposals that provide community products that support one or more of the numbered goals in **A, B, C** or **D** or those that include collaboration with network operators in Southern California are especially encouraged. Proposers should consider the

SCEC resources available including the Southern California Earthquake Data Center (SCEDC) that provides extensive data on Southern California earthquakes as well as crustal and fault structure, the network of SCEC funded borehole instruments that record high quality reference ground motions, and the pool of portable instruments that is operated in support of targeted deployments or aftershock response.

B. **Research Strategies.** Examples of research strategies that support the objectives above include:

- Enhancement and continued operation of the SCEDC and other existing SCEC facilities particularly the near-real-time availability of earthquake data from SCEDC and automated access.
- Real-time processing of network data such as improving the estimation of source parameters in relation to known and unknown faults (A3, A4, A10), especially evaluation of the short term evolution of earthquake sequences and real-time stress perturbations on nearby major fault segments (D).
- Enhance or add new capabilities to existing earthquake early warning (EEW) systems or provide new EEW algorithms. Develop real-time finite source models constrained by incoming seismic and GPS data to estimate evolution of the slip function and potentially damaging ground shaking (D).
- Advance innovative and practical strategies for densification of seismic instrumentation, including borehole instrumentation, in Southern California and develop innovative algorithms to utilize data from these networks. Develop metadata, archival and distribution models for these semi-mobile networks.
- Develop innovative new methods to search for unusual signals using combined seismic, GPS, and borehole strainmeter data (A5, A6); collaborations with EarthScope or other network operators are encouraged.
- Investigate near-fault crustal properties, evaluate fault structural complexity, and develop constraints on crustal structure and state of stress, and (A7, A10, C).
- Collaborations, for instance with the ANSS and NEES projects, that would augment existing and planned network stations with downhole and surface instrumentation to assess site response, nonlinear effects, and the ground coupling of built structures (B4, B6).
- Preliminary design and data collection to seed future passive and active experiments such as dense array measurements of basin structure and large earthquake properties, OBS deployments, and deep basement borehole studies.

C. **Priorities for Seismology in 2010:**

- **Earthquake early warning research.** In the next few years, earthquake early warning (EEW) systems will be installed in California. The seismology group seeks proposals that will provide new algorithms, enhance or add new capabilities to existing EEW algorithms. The development of Bayesian probabilities that would take advantage of the extensive knowledge developed by SCEC about fault structures and spatial and temporal seismicity patterns are needed to make EEW algorithms more robust. Similarly, high-sample rate GPS 1 second solutions are being made available real-time for EEW development. Using these new data to develop new EEW algorithms for finite sources is a new area of research for

SCEC scientists. For instance, we seek proposals that will provide algorithms for real-time finite source models constrained by incoming real-time seismic and GPS data to predict spatial and temporal development of the slip function, as well as the resulting potentially damaging ground shaking.

- **Low-cost dense sensor networks.** Several low cost seismic sensors networks are being developed in California. We seek proposals that would address development of seismological algorithms to utilize data from these networks in innovative ways. We also seek proposals that would develop metadata and archiving models for these new semi-mobile networks, as well as archive and serve these data to the SCEC user community.
- **Near Real-time earthquake sequence source processes.** Two recent earthquake sequences (in Italy and near Bombay Beach in the Salton Sea area of southern California) highlight the need for rapid evaluation of earthquake probabilities and to identify the onset of significant events within evolving earthquake sequences. We seek proposals that would address the earthquake statistics aspects of earthquake sequences, and quantifying source processes that may have value for predicting short-term evolution of earthquake sequences. In addition, small sequences may perturb the state of stress on nearby major fault segments. We seek proposals that would provide quantitative evaluation of such processes, and possibly provide near real-time estimates of changes in earthquake probabilities for these major fault segments.

2. Tectonic Geodesy

A. **Objectives.** The broad objective of SCEC's Tectonic Geodesy disciplinary activities is to foster the availability of the variety of geodetic data collected in Southern California and the innovative and integrated use of these observations, in conjunction with other relevant data (e.g., seismic or geologic information), to address the spectrum of deformation processes affecting this region. Topics of interest include, but are not limited to, rapid earthquake response, transient deformation, anthropogenic or nontectonic effects, and the quantification and interpretation of strain accumulation and release, with one goal being the increased use of insights from geodesy in seismic hazard assessment. Proposed work may overlap with one or more focus areas, such as Crustal Deformation Modeling (CDM).

B. **Research Strategies.** The following are research strategies aimed at meeting the broad objective:

- Develop reliable means for detecting, assessing, and interpreting transient deformation signals and for using this information in monitoring and response activities. (A5).
  - Develop detection algorithms. Work that extends the demonstrated capability of such algorithms to real data, that utilizes other data types in addition to or instead of GPS, or that explores means for incorporating such algorithms into monitoring systems is encouraged, as is participation in the ongoing Transient Detection Blind Test Exercise.
  - Generate sets of real or synthetic GPS or other types of data for the Transient Detection Blind Test Exercise.

- Investigate processes underlying detected signals and/or their seismic hazard implications.

- Extend methods for estimating crustal motion and refine such estimates for southern California (A1, A2, A3, B1, C, D). In all cases, work should include assessment of the sources of uncertainty in the analysis and quantification of uncertainties in results (especially those relating to model uncertainty). Proposals for the development of new data products or collection of new data must explicitly motivate the need for such efforts and state how the resulting data or products will be used. Data collected with SCEC funding must be made publically available in an online archive within two years of its collection, although PIs may choose to share data on a case-by-case basis earlier than the two-year deadline.
  - Collaborate on the generation and maintenance of an up-to-date consensus velocity field for southern California.
  - Improve vertical velocity estimates, for example by refining or extending data processing and analysis strategies or approaches for the combined use of multiple data types.
  - Identify possible trade-offs in regional slip rate models, conduct quantitative comparison of such models, and/or develop new models.
  - Develop methods for combining data types (e.g., GPS, InSAR, strainmeter, and/or other data) that have differing spatial and temporal apertures, sampling frequencies, and sensitivities, and assess the utility of such combinations for interpreting tectonic or nontectonic signals.
  - Develop tools for using high-rate and real-time GPS positions and demonstrate application of these data to address topics such as rapid earthquake response, postseismic analysis, or the combined use of GPS and seismic data.

3. Earthquake Geology

A. **Objectives.** The Earthquake Geology group promotes studies of the geologic record of the Southern California natural laboratory that advance SCEC science. Geologic observations can provide important contributions to nearly all SCEC objectives in seismic hazard analysis (A1-A3, A6-A11) and ground motion prediction (B2-B5). Studies are encouraged to test outcomes of earthquake simulations and crustal deformation modeling. Earthquake Geology also fosters data-gathering activities that will contribute demonstrably significant geologic information to (C) community data sets such as the Unified Structural Representation. The primary focus of the Earthquake Geology is on the Late Quaternary record of faulting and ground motion in southern California. Collaborative proposals that cut across disciplinary boundaries are especially competitive.

B. **Research Strategies.** Examples of research strategies that support the objectives above include:

- Paleoseismic documentation of earthquake ages and displacements, including a coordinated effort to develop slip rates and earthquake history of southern San Andreas fault system (A1).
- Evaluating the potential for 'wall-to-wall' rupture or a brief cluster of major earthquakes on the San Andreas fault system (A1, A9).

- Investigating the likelihood of multi-segment and multi-fault ruptures on major southern California faults (A1, A9).
- Testing models for geologic signatures of preferred rupture direction (A9).
- Development of slip rate and slip-per-event data sets, taking advantage of newly collected GeoEarthScope LiDAR data, and with a particular emphasis on documenting patterns of seismic strain release in time and space (A1-A3, A5, A6, A9).
- Development of methods to evaluate multi-site paleoseismic data sets and standardize error analysis (A1, A9).
- Characterization of fault-zone geology, material properties, and their relationship to earthquake rupture processes, including studies that relate earthquake clustering to fault loading in the lower crust (A7, A8, A10).
- Quantitative analysis of the role of distributed deformation in accommodating block motions, dissipating elastic strain, and modifying rheology (A2, A3, A7, A10, A11).
- Development of constraints on the magnitude and recurrence of strong ground motions from precarious rocks and slip-per-event data (B2-B5).

C. **Geochronology Infrastructure.** The shared geochronology infrastructure supports C-14, optically stimulated luminescence (OSL), and cosmogenic dating for SCEC-sponsored research. The purpose of shared geochronology infrastructure is to allow flexibility in the number and type of dates applied to each SCEC-funded project as investigations proceed. Investigators requesting geochronology support must estimate the number and type of dates needed in their proposal. For C-14 specify if sample preparation will take place at a location other than the designated laboratory. For cosmogenic dating, investigators are required to arrange for sample preparation. These costs must be included in the proposal budget unless preparation has been pre-arranged with one of the laboratories listed. Investigators are strongly encouraged to contact the investigators at the collaborating laboratories prior to proposal submission. Currently, SCEC geochronology has established relationships with the following laboratories:

  - C-14: University of California at Irvine (John Southon, *jsouthon@uci.edu*) and Lawrence Livermore National Laboratory (Tom Guilderson, *tguilderson@llnl.gov*).
  - OSL: University of Cincinnati (Lewis Owen, *lewis.owen@uc.edu*) and Utah State University (Tammy Rittenour, *tammy.rittenour@usu.edu*)
  - Cosmogenic: Lawrence Livermore National Laboratory (Tom Guilderson, *tguilderson@llnl.gov*).

  Investigators at collaborating laboratories are requested to submit a proposal that states the cost per sample analysis and estimates of the minimum and maximum numbers of analyses feasible for the upcoming year. These investigators are also strongly encouraged to request for funds to support travel to the SCEC annual meeting. New proposals from laboratories not listed above will be considered, though preference will be given to strengthening existing collaborations.

  Investigators may alternatively request support for geochronology outside of the infrastructure proposal for methods not listed here or if justified on a cost-basis. These outside requests must be included in the individual proposal budget. Please direct questions regarding geochronology infrastructure to the Earthquake Geology group leader, Mike Oskin (*meoskin@ucdavis.edu*).

VII-B. Interdisciplinary Focus Areas

Interdisciplinary research will be organized into seven science focus areas: 1) Unified Structural Representation (USR), 2) Fault and Rupture Mechanics (FARM), 3) Crustal Deformation Modeling (CDM), 4) Lithospheric Architecture and Dynamics (LAD), 5) Earthquake Forecasting and Predictability (EFP), 6) Ground Motion Prediction (GMP) and 7) Seismic Hazard and Risk Analysis (SHRA). High-priority objectives are listed below for each of the seven interdisciplinary focus areas. Collaboration within and across focus areas is strongly encouraged.

1. Unified Structural Representation (USR)

The Structural Representation group develops unified, three-dimensional representations of active faults and earth structure (velocity, density, etc.) for use in fault-system analysis, ground motion prediction, and hazard assessment. This year's efforts will focus on making improvements to existing community models (CVM-H, CFM) that will facilitate their uses in SCEC science, education, and post-earthquake response planning.

A. **Community Velocity Model (CVM).** Improve the current SCEC CVM-H model, with emphasis on more accurate representations of Vp, Vs, density structure, and basin shapes, and derive models for attenuation. Generate improved mantle Vp and Vs models, as well as more accurate descriptions of near-surface property structure that can be incorporated into a revised geotechnical layer. Evaluate the existing models with data (e.g., waveforms, gravity) to distinguish alternative representations and quantify model uncertainties. Establish an evaluation procedure and benchmarks for testing how future improvements in the models impact ground motion studies. Special emphasis will be placed on developing and implementing 3D waveform tomographic methods for evaluating and improving the CVM-H.

B. **Community Fault Model (CFM).** Improve and evaluate the CFM, placing emphasis on defining the geometry of major faults that are incompletely, or inaccurately, represented in the current model. Evaluate the CFM with data (e.g., seismicity, seismic reflection profiles, geodetic displacement fields) to distinguish alternative fault models. Integrate northern and Southern California models into a statewide fault framework, and update the CFM-R (rectilinear fault model) to reflect improvements in the CFM.

C. **Unified Structural Representation (USR).** Develop better IT mechanisms for delivering the USR, particularly the CVM parameters and information about the model's structural components, to the user community for use in generating and/or parameterizing computational grids and meshes. An example of such IT mechanism is a web-based system that allows plot and download of profiles and cross sections of the CVMs and related data (i.e., Vs30) at desired locations. Generate maps of geologic surfaces compatible with the CFM that may serve as strain markers in crustal deformation modeling and/or property boundaries in future iterations of the USR.

2. Fault and Rupture Mechanics (FARM)

The primary mission of the Fault and Rupture Mechanics focus group in SCEC3 is to develop physics-based models of the nucleation, propagation, and arrest of dynamic earthquake rupture. We specifically solicit proposals that address this mission through field, laboratory, and modeling efforts directed at characterizing and understanding the influence of material properties, geometric irregularities, and heterogeneities in stress and strain over multiple length and time scales (A7-A10, B1, B4), and that will contribute to our understanding of earthquakes in the Southern California fault system.

We invite proposals to:

A. Investigate the relative importance of different dynamic weakening and fault healing mechanisms, and the slip and time scales over which these mechanisms operate (A7-A10).

B. Determine the properties of fault cores and damage zones and characterize their variability with depth and along strike to constrain theoretical and laboratory studies, including width and particle composition of actively shearing zones, signatures of temperature variations, extent, origin and significance of on- and off-fault damage, healing, and poromechanical behavior (A7-A11).

C. Determine the relative contribution of on- and off-fault damage to the total earthquake energy budget, and the absolute levels of local and average stress (A7-A11).

D. Develop realistic descriptions of heterogeneity in fault geometry, properties, stresses, and strains, and tractable ways to incorporate heterogeneity in numerical models of single dynamic rupture events and multiple earthquake cycles (A10-11, B1, B4).

E. Understand the significance of fault zone characteristics and processes on fault dynamics and formulate constitutive laws for use in dynamic rupture models (A7-11, B1, B4).

F. Assess the predictability of rupture direction and directivity of seismic radiation by collecting and analyzing field and laboratory data, and conducting theoretical investigations to understand implications for strong ground motion (A7-A10, B1).

G. Evaluate the relative importance of fault structure, material properties, interseismic healing, and prior seismic and aseismic slip to earthquake dynamics, in particular, to rupture initiation, propagation, and arrest, and the resulting ground motions (A7-A10, B1).

H. Characterize earthquake rupture, fault loading, degree of localization, and constitutive behavior at the base of and below the seismogenic zone. Understand implications of slow events and non-volcanic tremors for constitutive properties of faults and overall seismic behavior. Use these data to evaluate seismic moment-rupture area relationships (A3, A11).

3. Crustal Deformation Modeling (CDM)

We seek proposals aimed at resolving the kinematics and dynamics of southern California faults over time scales ranging from hours to thousands of years. Our long-term goal is to contribute to the SCEC objective of developing a physics-based probabilistic seismic hazard analysis for southern California by developing and applying system-wide deformation models of processes at time-scales of the earthquake cycle. Our immediate goals include assessing the level of detail necessary in deformation models to achieve the broader SCEC objectives. Collaborations with geologists and researchers in other SCEC groups are strongly encouraged.

System-Wide Deformation Models:

A. Develop kinematic models of interseismic deformation or the earthquake cycle to estimate slip rates on primary southern CA faults, fault geometries at depth, and spatial distribution slip or moment deficits on faults. Compare with or refine SCEC CFM and assess discrepancies of the kinematic models with geodetic, geologic, and seismic data (A1, A3).

B. Develop a system-wide model of southern California faults, incorporating the SCEC CFM, properties derived from the SCEC CVM, and realistic inferred rheologies, to model interseismic deformation, including transfer of stress across the fault system (A3).

C. Develop simpler models to compare with the system-wide deformation model above for benchmarking purposes and to assess the degree of detail needed to adequately represent interseismic deformation and stress transfer. Various modeling approaches are requested and might include boundary element methods, 2D simplifications, and analytical or semi-analytical methodology (A10, A3).

D. Assess whether stress transfer implicitly assumed in earthquake simulator models is similar to stress transfer estimated from either category of deformation model mentioned above (A11).

More Focused Deformation Models:

A. Determine the extent to which rheological heterogeneity (including damage) influences deformation and stress transfer at various spatial and temporal scales. What level of detail will be required for the system-wide model (A7, A10, A11, A3)?

B. Evaluate spin-up effects for viscoelastic models and methods to accelerate this process. How much does deep viscoelastic relaxation influence interseismic deformation and stress transfer? Can it be neglected or "worked around" in a southern-California-wide stress transfer model (A11, A3)?

C. Evaluate whether nonlinear rheologies be represented with heterogeneous distributions of linearly viscoelastic material (A11, A3).

D. Investigate causes of discrepancies between geologic and geodetic slip rate estimates (A2).

E. Investigate possible causes and effects of transient slip and earthquake clustering (A1, A11).

4. Lithospheric Architecture and Dynamics (LAD)

The lithospheric architecture and dynamics group (LAD) seeks proposals that will contribute to our understanding of the structure, geologic provenance and physical state of the major southern California lithospheric units, and how these relate to absolute stress in the crust and the evolution of the lithospheric system (A3, A11).

The principal objective of this group is to understand the physics of the southern California system, the boundary conditions and internal physical properties. Special attention is given to constraining the average absolute stress on southern California faults. Our general approach is to use 3D geodynamic models to relate the various forces loading the lithosphere to observable fields such as geodetic and geologic strain, seismic anisotropy and gravity. Of particular importance are: how flow in the sub-seismogenic zone and the asthenosphere accommodates plate motion, constraints on density structure and rheology of the southern California lithosphere, and how the system loads faults.

Physics models will be developed that use the paleo-history of the 3D geology to infer how present physical conditions were created, such as depths of Moho, the seismogenic layer, base of the lithosphere, topography and basin depths, rock type, temperature, water content, rheology and how these relate to mantle flow, velocity, anisotropy and density.

The LAD work will interface with the geology group to better understand crustal structure and North America mantle lithosphere. Of particular interest are the distribution of the underplated schist and the fate of Farallon microplate fragments and their relation to inferred mantle drips. We will interact with FARM to obtain constraints on rheology and stress (absolute and dynamic), with the USR and seismology groups on 3D structure, and CDM on current stress and strain rates.

In this context, proposals are sought that contribute to our understanding of geologic inheritance and its relation to the three-dimensional structure and physical properties of the crust and lithosphere. Proposals should indicate how the work relates to stress evolution (A2, A3, A11) as well as the current geological structure (C). A primary goal is to generate systems-level models that describe southern California dynamics against which hypotheses can be tested regarding the earthquake mechanism, fault friction, seismic efficiency, the heat flow paradox and the expected evolution of stress and strain transients (A5).

The LAD group will be involved in the USGS-NSF Margins/EarthScope Salton Trough Seismic Project and will interface to the southern California offshore seismic (OBS) experiment, and will consider proposals that piggyback these experiments and integrate the results into LAD goals.

5. Earthquake Forecasting and Predictability (EFP)

In general we seek proposals that will increase our understanding of how earthquakes might be forecast and whether or not earthquakes are predictable (A6). Proposals of any type that can assist in this goal will be considered. We are especially interested in proposals that will utilize the Collaboratory for the Study of Earthquake Predictability (CSEP). In order to increase the number of earthquakes in the data sets, and so decrease the time required to learn about predictability, proposals are welcome that deal with global data sets and/or include international collaborations.

For research strategies that plan to utilize CSEP, see the description of CSEP under Special Projects to learn of its capabilities. Successful investigators proposing to utilize CSEP would be funded via core SCEC funds to adapt their prediction methodologies to the CSEP framework, to transfer codes to the externally accessible CSEP computers, and to be sure they function there as intended (A6). Subsequently, the codes would be moved to the identical externally inaccessible CSEP computers by CSEP staff who will conduct tests against a variety of data as outlined in the CSEP description. In general, methodologies will be considered successful only if they do better than null hypotheses that include both time-independent and time-dependent probabilities. Proposals aimed toward developing useful measurement/testing methodology that could be incorporated in the CSEP evaluations are welcomed, including those that address how to deal with observational errors in data sets.

Proposals are also welcome that assist in attaining the goals of these two Special Projects: WGCEP (the Working Group on California Earthquake Probabilities) and SoSAFE (the Southern San Andreas Evaluation), especially if the proposals focus on understanding some physical basis for connections between earthquakes. Proposals to utilize and/or evaluate the significance of earthquake simulator results are encouraged. Investigation of what is an appropriate magnitude-area relationship, including the maximum depth of slip during large earthquakes, is encouraged. Studies of how to properly characterize the relationship between earthquake frequency and magnitude for use in testing prediction algorithms are also encouraged.

Proposals that can lead to understanding whether or not there exists a physical basis for earthquake predictability (A6) are welcome, even if they are not aimed toward, or are not ready for, tests in CSEP, or are not aimed toward assisting WGCEP or SoSAFE. For example, proposals could include ones that connect to objectives A1, A2, A3, A5, A9, A10 and A11, as well as ones focused on understanding patterns of seismicity in time and space, as long as they are aimed toward understanding the physical basis of some aspect of extended earthquake predictability (A6). Development of methods for testing prediction algorithms that are not yet in use by CSEP is encouraged.

Proposals for workshops are welcome. Specific workshops of interest include one on earthquake simulators and one on setting standards that could be used by CSEP for testing and evaluation, data, and products.

6. Ground Motion Prediction (GMP)

The primary goal of the Ground Motion Prediction focus group is to develop and implement physics-based simulation methodologies that can predict earthquake strong motion waveforms over the frequency range 0-10 Hz. Source characterization plays a vital role in ground motion prediction. At frequencies less than 1 Hz, the methodologies should deterministically predict the amplitude, phase and waveform of earthquake ground motions using fully three-dimensional representations of the ground structure, as well as dynamic or dynamically-compatible kinematic representations of fault rupture. At higher frequencies (1-10 Hz), the methodologies should predict the main character of the amplitude, phase and waveform of the motions using a combination of deterministic and stochastic representations of fault rupture and wave propagation.

Research topics within the Ground Motion Prediction program include:

A. Developing and/or refining physics-based simulation methodologies, with particular emphasis on high frequency (1-10 Hz) approaches (B3)

B. Incorporation of non-linear models of soil response (B2, B4, B5);

C. Development of more realistic implementations of dynamic or kinematic representations of fault rupture. In collaboration with FARM, this research could also include the examination of current source-inversion strategies and development of robust methods that allow imaging of kinematic and/or dynamic rupture parameters reliably and stably, along with a rigorous uncertainty assessment. (B1, B2).

D. Verification (comparison against theoretical predictions) and validation (comparison against observations) of the simulation methodologies with the objective of being to develop robust and transparent simulation capabilities that incorporate consistent and accurate representations of the earthquake source and three-dimensional velocity structure (B4, C).

It is expected that the products of the Ground Motion Prediction group will have direct application to seismic hazard analysis, both in terms of characterizing expected ground motion levels in future earthquakes, and in terms of directly interfacing with earthquake engineers in the analysis of built structures (B6). Activities within the Ground Motion Prediction group will be closely tied to several special projects, with particular emphasis on addressing ground motion issues related to seismic hazard and risk. These special projects include the Extreme Ground Motion Project and the Tall Buildings Initiative (see SHRA below).

7. Seismic Hazard and Risk Analysis (SHRA)

The purpose of the SHRA Focus Group is to apply SCEC knowledge to the development of information and techniques for quantifying earthquake hazard and risk, and in the process to provide feedback on SCEC research. Projects in this focus group will in some cases be linked to the Ground Motion Prediction Focus Group, to SCEC special projects such as the Extreme Ground Motion Project, and to Pacific Earthquake Engineering Research Center (PEER) special projects such as the Tall Buildings Initiative (TBI) and Reference Buildings and Bridges Project. Projects that involve interactions between SCEC scientists and members of the community involved in earthquake engineering research and practice are especially encouraged. Examples of work relevant to the SHRA Focus Group follow:

Improved Hazard Representation

A. Develop improved hazard models that consider simulation-based earthquake source and wave propagation effects that are not already well reflected in observed data. These could include improved methods for incorporating rupture directivity effects, basin effects, and site effects in the USGS ground motion maps, for example. The improved models should be incorporated into OpenSHA.

B. Use broadband strong motion simulations, possibly in conjunction with recorded ground motions, to develop ground motion prediction models (or attenuation relations). Broadband simulation methods must be verified (by comparison with simple test case results) and validated (against recorded strong ground motions) before use in model development. The verification, validation, and application of simulation methods must be done on the SCEC Broadband Simulation Platform. Such developments will contribute to the future NGA-H Project.

C. Develop ground motion parameters (or intensity measures), whether scalars or vectors, that enhance the prediction of structural response and risk.

D. Investigate bounds on the variability of ground motions for a given earthquake scenario.

Ground Motion Time History Simulation

A. Develop acceptance criteria for simulated ground motion time histories to be used in structural response analyses for building code applications or risk analysis.

B. Assess the advantages and disadvantages of using simulated time histories in place of recorded time histories as they relate to the selection, scaling and/or modification of ground motions for building code applications or risk analysis.

C. Develop and validate modules for the broadband simulation of ground motion time histories close to large earthquakes, and for earthquakes in the central and eastern United States, for incorporation in the Broadband Platform.

Collaboration in Building Response Analysis

A. Tall Buildings. Enhance the reliability of simulations of long period ground motions in the Los Angeles region using refinements in source characterization and seismic velocity models, and evaluate the impacts of these ground motions on tall buildings. Such projects could potentially build on work done in the TBI Project.

B. End-to-End Simulation. Interactively identify the sensitivity of building response to ground motion parameters and structural parameters through end-to-end simulation. Buildings of particular interest include non-ductile concrete frame buildings.

C. Reference Buildings and Bridges. Participate with PEER investigators in the analysis of reference buildings and bridges using simulated broadband ground motion time histories. The ground motions of large, rare earthquakes, which are poorly represented in the NGA strong motion database, are of special interest. Coordination with PEER can be done through Yousef Bozorgnia, yousef@berkeley.edu.

D. Earthquake Scenarios. Perform detailed assessments of the results of scenarios such as the ShakeOut exercise, and the scenarios for which ground motions were generated for the Tall Buildings Initiative (including events on the Puente Hills, Southern San Andreas, Northern San Andreas and Hayward faults) as they relate to the relationship between ground motion characteristics and building response and damage.

Ground Deformation

A. Investigate the relationship between input ground motion characteristics and local soil nonlinear response, liquefaction, lateral spreading, local soil failure, and landslides. Investigate hazards due to surface faulting and to surface deformation due to subsurface faulting and folding.

Risk Analysis

A. Develop improved site/facility-specific and portfolio/regional risk analysis (or loss estimation) techniques and tools, and incorporate them into the OpenRisk software.

B. Use risk analysis software to identify earthquake source and ground motion characteristics that control damage estimates.

Other Topics

A. Proposals for other innovative projects that would further implement SCEC information and techniques in seismic hazard and risk analysis, and ultimately loss mitigation, are encouraged.

VIII. Special Projects and Initiatives

The following are SCEC special projects with which proposals in above categories can be identified:

1. Southern San Andreas Fault Evaluation (SoSAFE)

The SCEC Southern San Andreas Fault Evaluation (SoSAFE) Project will continue to increase our knowledge of slip rates, paleo-event chronology, and slip distributions of past earthquakes, for the past two thousand years on the southern San Andreas fault system. From Parkfield to Bombay Beach, and including the San Jacinto fault, the objective is to obtain new data to clarify and refine relative hazard assessments for each potential source of a future 'Big One.'

Past SoSAFE workshops have led to a focused research plan that responds to the needs and opportunities identified across existing research projects. We strongly welcome proposals that will help to improve correlation of ruptures over the past 2000 years. This includes short-term (3-5 earthquake) and slip-per-event data from paleoseismic sites, but can include longer-term rates (60,000 years) in some cases. Use of novel methods for estimating slip rates from geodetic data would also potentially be supported within the upcoming year. Lengthening existing paleoearthquake chronologies or starting new sites in key locations along the fault system is encouraged. It is expected that much support will go towards improved dating (e.g., radiocarbon and OSL) of earthquakes within the past 2000 yrs., so that event correlations and coefficient of variation in recurrence intervals may be further refined. We welcome requests for infrastructure resources, for example geochronology support. That is, an investigator may ask for dating support (e.g., to date 12 radiocarbon samples). Requests for dating shall be coordinated with Earthquake Geology and a portion of SoSAFE funds will be contributed towards joint support for dating. However, we also welcome proposals, which seek to add other data (such as climate variations) to earthquake chronologies, which may be used to improve age control or site-to-site correlation of events.

We also welcome proposals that investigate methodologies for integrating paleoseismic and geologic data into rupture histories. For example, ongoing interaction between SoSAFE and the scenario rupture modeling activities of SCEC will continue beyond the ShakeOut, as we continue to develop constraints such as dating or slip data that can be used to eliminate the scenario of a “wall-to-wall” rupture (from Parkfield to Bombay Beach). SoSAFE will also work to constrain scenario models by providing the best possible measurements of actual slip distributions from past earthquakes on these same fault segments as input, thereby enabling a more realistic level of scenario modeling. Research will address significant portions of the fault system, and all investigators will agree to collaboratively review one another’s progress. Research by single or multi-investigator teams will be supported to rapidly advance SCEC research towards meeting priority scientific objectives related to the mission of the SoSAFE special project. SoSAFE objectives also foster common longer-term research interests and engage in facilitating future collaborations in the broader context of a decade-long series of interdisciplinary, integrated and complementary studies on the southern San Andreas fault system.

The fourth year of SoSAFE may again be funded at $240K by USGS, depending on 1) the report on progress in the first three years, 2) effective leveraging of USGS funds with funds from other sources, 3) level of available funding from USGS for the year, and 4) competing demands for the USGS Multi-Hazards Demonstration Project funding.

2. Working Group on California Earthquake Probabilities (WGCEP)

Following the 2008 release of the Uniform California Earthquake Rupture Forecast version 2 (UCERF2), the WGCEP is now working on adding some major enhancements in a forthcoming UCERF3. Our primary goals are to relax segmentation, add multi-fault ruptures, and include spatial-temporal clustering (earthquake triggering). As the latter will require robust interoperability with real-time seismicity information, UCERF3 will bring us into the realm of operational earthquake forecasting. This model is being developed jointly by SCEC, the USGS, and CGS, with tight coordinated with the USGS National Seismic Hazard Mapping Program. The following are examples of SCEC activities that could make direct contributions to WGCEP goals:

A. Reevaluate fault models in terms of the overall inventory, and specify more precisely fault endpoints in relationship to neighboring faults (important for multi-fault rupture possibilities)

B. Reevaluate fault slip rates, especially using more sophisticated modeling approaches (e.g., that include GPS data, generate kinematically consistent results, and perhaps provide off-fault deformation rates as well).

C. Help determine the average along-strike slip distribution of large earthquakes, especially where multiple faults are involved (e.g., is there reduced slip at fault connections?)

D. Help determine the average down-dip slip distribution of large earthquakes (the ultimate source of existing discrepancies in magnitude-area relationships).

E. Contribute to the compilation and interpretation of mean recurrence-interval constraints from paleoseismic data.

F. Develop earthquake rate models that relax segmentation and include multi-fault ruptures.

G. Develop ways to constrain the spatial distribution of maximum magnitude for background seismicity (for earthquakes occurring off of the explicitly modeled faults).

H. Answer the question of whether every small volume of space exhibits a Gutenberg Richter distribution of nucleations?

I. Develop methods for quantifying elastic-rebound based probabilities in un-segmented fault models.

J. Help quantify the amount of slip in the previous event (including variations along strike) on any major faults in California.

K. Develop models for fault-to-fault rupture probabilities, especially give uncertainties in fault endpoints.

L. Determine the proper explanation for the apparent post-1906 seismicity-rate reduction (which appears to be a statewide phenomenon)?

M. Develop applicable methods for adding spatial and temporal clustering to the model.

N. Develop easily computable hazard or loss metrics that can be used to evaluate and perhaps trim logic-tree branch weights.

O. Develop techniques for down-sampling event sets to enable more efficient hazard and loss calculations.

Further suggestions and details can be found at *http://www.WGCEP.org*, or by speaking with the project leader (Ned Field: *field@usgs.gov*; (626) 644-6435).

3. Next Generation Attenuation Project, Hybrid Phase (NGA-H)

The NGA-H Project is currently on hold, but it is hoped that it will go forward at some point in the future in conjunction with PEER. It will involve the use of broadband strong motion simulation to generate ground motion time histories for use, in conjunction with recorded ground motions, in the development of ground motion attenuation relations for hard rock that are based on improved sampling of magnitude and distance, especially large magnitudes and close distances, and improved understanding of the relationship between earthquake source and strong ground motion characteristics. Broadband simulation methods are verified (by comparison of simple test case results with other methods) and validated (against recorded strong ground motions) before being used to generate broadband ground motions for use in model development. These simulation activities for verification, validation, and application are done on the SCEC Broadband Simulation Platform. The main SCEC focus groups that are related to this project are Ground Motion Prediction and Seismic Hazard and Risk Analysis.

4. End-to-End Simulation

The purpose of this project is to foster interaction between earthquake scientists and earthquake engineers through the collaborative modeling of the whole process involved in earthquake fault rupture, seismic wave propagation, site response, soil-structure interaction, and building response. Recent sponsors of this project have been NSF (tall buildings) and CEA (wood frame buildings), and new sponsors are being sought. The main SCEC discipline and focus groups working on this project are Geology, especially fault models; Unified Structural Representation; Faulting and the Mechanics of Earthquakes; Ground Motion Prediction; Seismic Hazard and Risk Analysis; and PetaSHA – TeraShake and CyberShake.

5. Collaboratory for the Study of Earthquake Predictability (CSEP)

CSEP is developing a virtual, distributed laboratory—a collaboratory—that supports a wide range of scientific prediction experiments in multiple regional or global natural laboratories. This earthquake system science approach seeks to provide answers to the questions: (1) How should scientific prediction experiments be conducted and evaluated? and (2) What is the intrinsic predictability of the earthquake rupture process? Contributions may include:

A. Establishing rigorous procedures in controlled environments (testing centers) for registering prediction procedures, which include the delivery and maintenance of versioned, documented code for making and evaluating predictions including intercomparisons to evaluate prediction skills;
B. Constructing community-endorsed standards for testing and evaluating probability-based and alarm-based predictions;
C. Developing hardware facilities and software support to allow individual researchers and groups to participate in prediction experiments;
D. Providing prediction experiments with access to data sets and monitoring products, authorized by the agencies that produce them, for use in calibrating and testing algorithms;
E. Intensifying the collaboration between the US and Japan through international projects, and initiating joint efforts with China;

F. Developing experiments to test basic physical principles of earthquake generation (e.g., models for estimating the largest possible earthquake on a given fault are important to earthquake scenarios like ShakeOut and to earthquake hazard models. We seek proposals to develop quantitative tests of such models); and

G. Conducting workshops to facilitate international collaboratories.

A major focus of CSEP is to develop international collaborations between the regional testing centers and to accommodate a wide-ranging set of prediction experiments involving geographically distributed fault systems in different tectonic environments.

6. National Partnerships through EarthScope

The NSF EarthScope project provides unique opportunities to learn about the structure and dynamics of North America. SCEC encourages proposals to the NSF EarthScope program that will address the goals of the SCEC Science Plan.

7. Extreme Ground Motion Project (ExGM)

Extreme ground motions are the very large amplitudes of earthquake ground motions that can arise at very low probabilities of exceedance, as was the case for the 1998 PSHA for Yucca Mountain when extended to 10**-8/yr. This project investigates the credibility of such ground motions through studies of physical limits to earthquake ground motions, unexceeded ground motions, and frequency of occurrence of very large ground motions or of earthquake source parameters (such as stress drop and faulting displacement) that cause them. Of particular interest to ExGM (and more generally to ground-motion prediction and SHRA) is why crustal earthquake stress drops are so independent of earthquake size (amidst considerable scatter) and so much less than the frictional strength of rocks at mid-crustal depths.

Since the summer of 2005, the DOE-funded Extreme Ground Motion (ExGM) program has supported research at SCEC, both institutionally and individually. ExGM funding has been dramatically cut in the current year, and prospects for the future are uncertain. Available funds will be directed to ground-motion simulations in accord with the original ExGM prospectus and schedule. While the status of ExGM as a separately funded, Special Project is thus uncertain, the research imperatives of ExGM remain significant to several of the SCEC focus and disciplinary groups, including, Geology – especially fault zone geology; Faulting and Mechanics of Earthquakes, Ground-Motion Prediction, and Seismic Hazard and Risk Analysis. This project is also discussed above within SHRA.

8. Petascale Cyberfacility for Physics-Based Seismic Hazard Analysis (PetaSHA)

SCEC's special project titled "A Petascale Cyberfacility for Physics-based Seismic Hazard Analysis" (PetaSHA) aims to develop and apply physics-based predictive models to improve the practice of seismic hazard analysis. This project will utilize numerical modeling techniques and high performance computing to implement a computation-based approach to SHA. Three scientific initiative areas have been identified for this project to help to guide the scientific research. The PetaSHA initiative areas are: (1) development of techniques to support higher frequencies waveform simulations including deterministic and stochastic approaches; (2) development of dynamic rupture simulations that include additional complexity including nonplanar faults, a variety of friction-based behaviors, and higher inner /outer scale ratios (e.g.

(fault plane mesh dimension) / (simulation volume dimension)); and (3) physics-based probabilistic seismic hazard analysis including probabilistic seismic hazard curves using 3D waveform modeling. All of these modeling efforts must be accompanied by verification and validation efforts. Development of new techniques that support the verification and validation of SCEC PetaSHA modeling efforts are encouraged.

The SCEC PetaSHA modeling efforts address several of the SCEC3 objectives. Development of new verification and validation techniques (B4) are common to each of the PetaSHA initiative areas. Research activities related to the improved understanding and modeling of rupture complexity (A8, B1) support the PetaSHA initiatives. In addition, research into the upper frequency bounds on deterministic ground motion predictions (B2, B3) are SCEC3 science objectives that are important work areas in the PetaSHA Project.

IX. SCEC Communication, Education, and Outreach

SCEC maintains a Communication, Education, and Outreach (CEO) program with four long-term goals:

- Coordinate productive interactions among a diverse community of SCEC scientists and with partners in science, engineering, risk management, government, business, and education.
- Increase earthquake knowledge and science literacy at all educational levels, including students and the general public.
- Improve earthquake hazard and risk assessments
- Promote earthquake preparedness, mitigation, and planning for response and recovery.

Short-term objectives are outlined below. These objectives present opportunities for members of the SCEC community to become involved in CEO activities, which are for the most part coordinated by CEO staff. As project support is very limited, budgets for proposed projects should be on the order of $2,000 to $5,000. Hence proposals that include additional sources of support (cost-sharing, funding from other organizations, etc.) are highly recommended. Smaller activities can be supported directly from the CEO budget and do NOT need a full proposal. Those interested in submitting a CEO proposal should first contact Mark Benthien, associate SCEC director for CEO, at 213-740-0323 or *benthien@usc.edu*. There may be other sources of funding that can be identified together.

CEO Focus Area Objectives

1. **SCEC Community Development and Resources** (activities and resources for SCEC scientists and students)

   SC1 Increase diversity of SCEC leadership, scientists, and students

   SC2 Facilitate communication within the SCEC Community

   SC3 Increase utilization of products from individual research projects

2. **Education** (programs and resources for students, educators, and learners of all ages)

   E1 Develop innovative earth-science education resources

   E2 Interest, involve and retain students in earthquake science

   E3 Offer effective professional development for K-12 educators

3. **Public Outreach** (activities and products for media reporters and writers, civic groups and the general public)

   P1 Provide useful general earthquake information

   P2 Develop information for the Spanish-speaking community

   P3 Facilitate effective media relations

   P4 Promote SCEC activities

4. **Knowledge transfer** (activities to engage other scientists and engineers, practicing engineers and geotechnical professionals, risk managers, government officials, utilities, and other users of technical information)

   I1 Communicate SCEC results to the broader scientific community

   I2 Develop useful products and activities for practicing professionals

   I3 Support improved hazard and risk assessment by local government and industry

   I4 Promote effective mitigation techniques and seismic policies

Appendix: SCEC3 Long-Term Research Goals

This section outlines the SCEC science priorities for the five-year period from February 1, 2007, to January 31, 2012. Additional material on the science and management plans for the Center can be found in the SCEC proposal to the NSF and USGS (*http://www.scec.org/aboutscec/documents/*).

Basic Research Problems

SCEC is, first and foremost, a basic research center. We therefore articulate our work plan in terms of four basic science problems: (1) earthquake source physics, (2) fault system dynamics, (3) earthquake forecasting and predictability, and (4) ground motion prediction. These topics organize the most pressing issues of basic research and, taken together, provide an effective structure for stating the SCEC3 goals and objectives. In each area, we outline the problem, the principle five-year goal, and some specific objectives. We then assess the research activities and the new capabilities needed to attain our objectives.

1. Earthquake Source Physics

Problem Statement. Earthquakes obey the laws of physics, but we don't yet know how. In particular, we understand only poorly the highly nonlinear physics of earthquake nucleation, propagation, and arrest, because we lack knowledge about how energy and matter interact in the extreme conditions of fault failure. A complete description would require the evolution of stress, displacement, and material properties throughout the seismic cycle across all relevant scales, from microns and milliseconds to hundreds of kilometers and many years. A more focused aspect of this problem is the physical basis for connecting the behavior of large ruptures at spatial resolutions of hundreds of meters and fracture energies of megajoules per square meter with laboratory observations of friction at centimeter scales and fracture energies of kilo-joules per square meter. Two further aspects are the problem of stress heterogeneity—the factors that create and maintain it over many earthquake cycles—and the related problem of defining the concept of strength in the context of stress and rheological heterogeneity.

Goal and Objectives. The goal for SCEC3 will be to discover the physics of fault failure and dynamic rupture that will improve predictions of strong ground motions and the understanding of earthquake predictability. This goal is directly aligned with our mission to develop physics-based seismic hazard analysis. Specific objectives include:

A. Conduct laboratory experiments on frictional resistance relevant to high-speed coseismic slip on geometrically complex faults, including the effects of fluids and changes in normal stress, and incorporate the data into theoretical formulations of fault-zone rheology.

B. Develop a full 3D model of fault-zone structure that includes the depth dependence of shear localization and damage zones, hydrologic and poroelastic properties, and the geometric complexities at fault branches, step-overs, and other along-strike and down-dip variations.

C. Combine the laboratory, field-based, and theoretical results into fault constitutive models for the numerical simulation of earthquake rupture, test them against seismological data, and extend the simulation methods to include fault complexities such as bends, step-overs, fault branches, and small-scale roughness.

D. Develop statistical descriptions of stress and strength that account for slip heterogeneity during rupture, and investigate dynamic models that can maintain heterogeneity throughout many earthquake cycles.

2. Fault System Dynamics

Problem Statement. In principle, the Southern California fault system can be modeled as a dynamic system with a state vector **S** and an evolution law d**S**/dt = **F**(**S**). The state vector represents the stress, displacement, and rheology/property fields of the seismogenic layer as well as its boundary conditions. Its evolution equation describes the forward problem of fault dynamics. Many of the most difficult (and interesting) research issues concern two inference or *inverse problems*: (1) model building—from our knowledge of fault physics, what are the best representations of **S** and **F**?—and (2) data assimilation—how are the parameters of these representations constrained by the data *D* on the system's present state S_0 as well as its history?

The SCEC approach is not to proceed by trying to write down general forms of **S** and its rate-of-change **F**. Rather, we use judicious approximations to separate the system evolution into a series of numerical simulations representing the interseismic, preseismic, coseismic, and postseismic behaviors. In particular, the natural time-scale separation between inertial and non-inertial dynamics usually allows us to decouple the long-term evolution of the state vector from its short-term, coseismic behavior. Therefore, in describing many interseismic and postseismic processes, we can treat the fault system quasi-statically, with discontinuous jumps in **S** at the times of earthquakes. On the other hand, the dynamics of earthquake rupture is clearly important to the basic physics of fault system evolution. In the modeling of stress heterogeneity, for example, the coupling of inertial and non-inertial dynamics must be addressed by integrating across this scale gap.

Goal and Objectives. The principal SCEC3 goal for fault system dynamics is *to develop representations of the postseismic and interseismic evolution of stress, strain, and rheology that can predict fault system behaviors within the Southern California Natural Laboratory*. The SCEC3 objectives are six fold:

A. Use the community modeling tools and components developed in SCEC2 to build a 3D dynamic model that is faithful to the existing data on the Southern California fault system, and test the model by collecting new data and by predicting its future behavior.

B. Develop and apply models of coseismic fault slip and seismicity in fault systems to simulate the evolution of stress, deformation, fault slip, and earthquake interactions in Southern California.

C. Gather and synthesize geologic data on the temporal and spatial character and evolution of the Southern California fault system in terms of both seismogenic fault structure and behavior at geologic time scales.

D. Constrain the evolving architecture of the seismogenic zone and its boundary conditions by understanding the architecture and dynamics of the lithosphere involved in the plate boundary deformation.

E. Broaden the understanding of fault systems in general by comparing SCEC results with integrative studies of other fault systems around the world.

F. Apply the fault system models to the problems of earthquake forecasting and predictability.

3. Earthquake Forecasting and Predictability

Problem Statement. The problems considered by SCEC3 in this important area of research will primarily concern the physical basis for earthquake predictability. Forecasting earthquakes in the long term at low probability rates and densities—the most difficult scientific problem in seismic hazard analysis—is closely related to the more controversial problem of high-likelihood predictions on short (hours to weeks) and intermediate (months to years) time scales. Both require a probabilistic characterization in terms of space, time, and magnitude; both depend on the state of the fault system (conditional on its history) at the time of the forecast/prediction; and, to put them on a proper science footing, both need to be based in earthquake physics.

Goal and Objectives. The SCEC3 goal is *to improve earthquake forecasts by understanding the physical basis for earthquake predictability*. Specific objectives are to:

A. Conduct paleoseismic research on the southern San Andreas and other major faults with emphasis on reconstructing the slip distributions of prehistoric earthquakes, and explore the implications of these data for behavior of the earthquake cycle and time-dependent earthquake forecasting.

B. Investigate stress-mediated fault interactions and earthquake triggering and incorporate the findings into time-dependent forecasts for Southern California.

C. Establish a controlled environment for the rigorous registration and evaluation of earthquake predictability experiments that includes intercomparisons to evaluate prediction skill.

D. Conduct prediction experiments to gain a physical understanding of earthquake predictability on time scales relevant to seismic hazards.

4. Ground Motion Prediction

Problem Statement. Given the gross parameters of an earthquake source, such as its magnitude, location, mechanism, rupture direction, and finite extent along a fault, we seek to predict the ground motions at all regional sites and for all frequencies of interest. The use of 3D velocity models in low-frequency (< 0.5 Hz) ground motion prediction was pioneered in SCEC1 (§II.A), and this type of simulation, based on direct numerical solution of the wave equation, has been taken to new levels in SCEC2 (§II.B.6). The unsolved basic research problems fall into four classes: (a) the ground motion inverse problem at frequencies up to 1 Hz; (b) the stochastic extension of ground motion simulation to high frequencies (1-10 Hz); (c) simulation of ground motions using realistic sources; and (d) nonlinear wave effects, including nonlinear site response. In addition, there remain scientific and computational challenges in the practical prediction of ground motions near the source and within complex structures such as sedimentary basins, as well as in the characterization of the prediction uncertainties.

Goal and Objectives. The principal SCEC3 goal is *to predict the ground motions using realistic earthquake simulations at frequencies up to 10 Hz for all sites in Southern California*. The SCEC3 objectives are:

A. Combine high-frequency stochastic methods and low-frequency deterministic methods with realistic rupture models to attain a broadband (0-10 Hz) simulation capability, and verify this capability by testing it against ground motions recorded at a variety of sites for a variety of earthquake types.

B. Use observed ground motions to enhance the Unified Structural Representation (USR) by refining its 3D wavespeed structure and the parameters that account for the attenuation and scattering of broadband seismic energy.
C. Apply the ground-motion simulations to improve SHA attenuation models, to create realistic scenarios for potentially damaging earthquakes in Southern California, and to explain the geologic indicators of maximum shaking intensity and orientation.
D. Investigate the geotechnical aspects of how built structures respond to strong ground motions, including nonlinear coupling effects, and achieve an end-to-end simulation capability for seismic risk analysis.