Southern California Earthquake Center

Annual Technical Report for 2008
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 second year (2008) of SCEC3. The report is organized into the following sections:

I. Introduction
II. Planning, Organization, and Management of the Center
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IV. Communication, Education, and Outreach Activities
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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.

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.

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, Irivine
Ralph Archuleta	University of California, Santa Barbara
Peter Bird	University of California, Los Angeles
David Bowman (At-Large)	California State-Fullerton
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
Bill Ellsworth	USGS-Menlo Park
Yuri Fialko	University of California, San Diego
Thomas A. Herring	Massachusetts Institute of Technology
Susan Hough*	USGS-Pasadena
Nadia Lapusta	California Institute of Technology
James Rice*	Harvard University
Paul Segall	Stanford University
Bruce Shaw	Columbia University
Robert Wesson	USGS-Golden

Ex-Officio Members

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

* Executive Committee members

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 is reproduced in Section VI. New AC members this year include Anne Meltzer, John Filson, and Jim Goltz.

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)* Jamie Steidl (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)* Jeroen Tromp (co-leader)
Fault and Rupture Mechanics:	Judi Chester (leader)* Ruth Harris (co-leader)
Crustal Deformation Modeling:	Liz Hearn (leader)* Tom Parsons (co-leader)
Lithospheric Architecture and Dynamics:	Paul Davis (leader)* Gene Humphreys (co-leader)
Earthquake Forecasting and Predictability:	Terry Tullis (leader)* Bernard Minster (co-leader)
Ground Motion Prediction:	Rob Graves (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:	Ken Hudnut (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)*

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 2008 began with the working-group discussions at the annual meeting in September, 2007. An RFP was issued in October, 2007, and 209 proposals (165 projects, including collaborations) requesting a total of $6,320+ were submitted in November, 2007.

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 14-15, 2008, 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 3-4, 2008. 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 first-year CEO activities is given in Section IV.

III. Research Accomplishments

This section summaries the main research accomplishments and research-related activities during 2007-08. While the presentation is organized sequentially by disciplinary committees, focus groups, and special project working groups, it's important to note that most SCEC activities are cross-cutting 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

Eight projects were particularly relevant to the Seismology Infrastructure focus group. Three of these were strictly infrastructure: the Southern California Earthquake Data Center, the Borehole Seismometer Network, and the Portable Broadband Instrument Center. Also included in this category are: the post-earthquake planning workshop as well as the Caltech/UCSD collaboration assembling earthquake catalogs and measuring earthquake properties and structure.

a. Southern California Earthquake Data Center (SCEDC)

Major 2007 Accomplishments:

1. The SCEDC continued 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 10,820 local events and 361 teleseismic earthquakes (Figure 1).
2. The SCEDC has migrated all read-only applications to its Oracle 10g database cluster system (Oracle RAC). This transfer has allowed significant performance improvements to the users of catalog search applications and STP, especially in continuous waveform searches.
3. Developed and implemented new waveform storage with a single server managing several RAID units. This architecture will save on initial purchase price and administration overhead. The new pair of servers and RAID storage with > 20 TB of capacity were installed and populated the binary waveform archive. In 2007 SCEDC migrated the bulk of its legacy archives to this new mirrored RAID storage.
4. The SCEDC has completed integrating station response information from the Station Information System (SIS) with the Southern California Seismic Network (SCSN). The goal of this project was to develop a simplified database-driven system that interacted with a single database source to enter, update and retrieve station metadata easily and efficiently. Station field work are entered by field technicians in SIS through a GUI, 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; by design these changes are distributed to the Real Time system manually. The result is a system that

is more streamline and easier to QC. All updates made by a field technician in the SIS are now available to users of SCEDC within 24 hours.

The SCEDC has worked extensively to populate the SIS with historic station information to provide users with access to complete and accurate station metadata. They also continued development of the system and have worked with the Station Fieldwork group to modify the interface so that it is more appropriate for their needs. This interface now has more reporting capabilities and provides the queries that are tailored to the information that is of interest to the field personnel and real time administrators.

5. The SCEDC implemented searchable online distribution of station metadata. The new interface at *http://www.data.scec.org/stations/meta/* allows users to easily search for stations, to retrieve multiple dataless SEED volumes in one download, and to save their results for later.

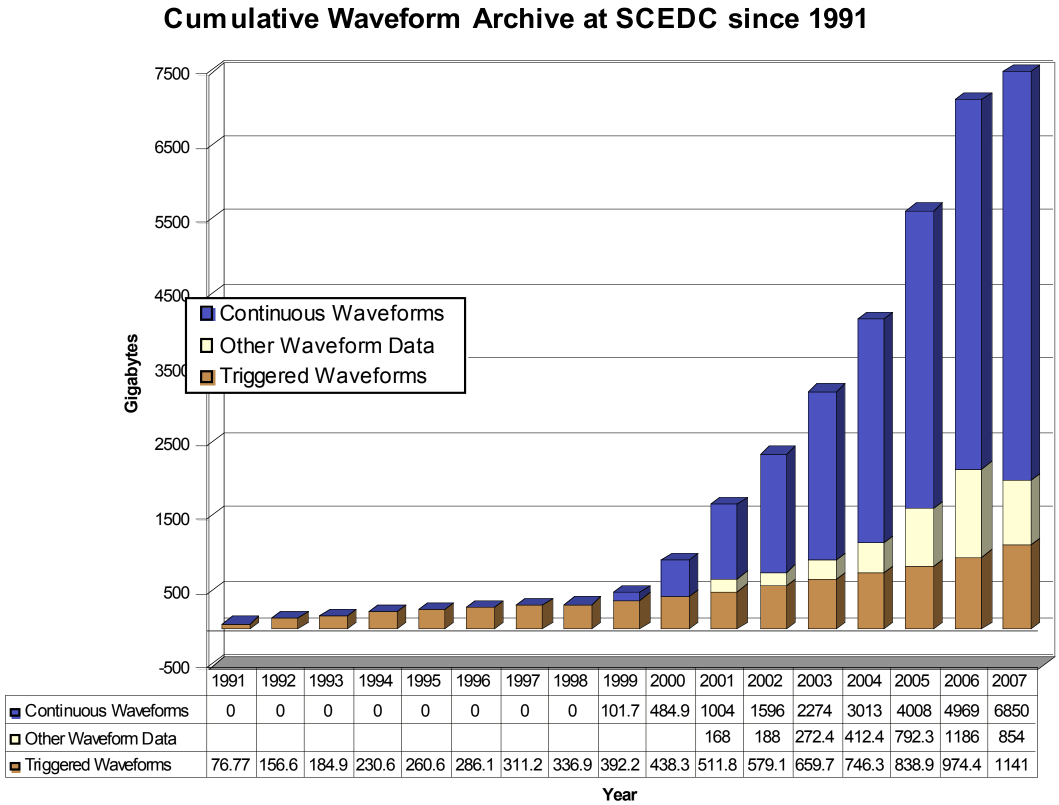
6. The SCEDC expanded the ANSS XML strawman and developed a schema for distributing seismic station metadata. The SCEDC has been a leader in XML formats, having previously developed an event and parametric information schema for the distribution of catalog data. The SCEDC released version 1.0 of the 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 the other schemas are available at *http://www.data.scec.org/xml/station/* and *http://www.data.scec.org/xml/*.

7. The Data Center organized a town-hall meeting of the SCEDC users at the 2007 SCEC Annual Meeting in Palm Springs, CA to gather feedback and identify the needs of the SCEC research community. User recommendations addressed SCEDC priorities including science, data-management, operations, data-products and funding.

8. In response to user recommendations at the SCEDC town-hall meeting, the SCEDC began continuous archiving of all EH_, HH_, and SH_ channels as of Jan 1, 2008.

9. The SCEDC archived and processed real-time data from two SCEC portable stations deployed by the SCEC Portable Instrumentation Center, near Superstition Mountain.

10. The SCEDC has made the latest relocated catalog from *Lin et al.* 2007b available to users via the SCEDC searchable web pages.



	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Continuous Waveforms	0	0	0	0	0	0	0	0	101.7	484.9	1004	1596	2274	3013	4008	4969	6850
Other Waveform Data											168	188	272.4	412.4	792.3	1186	854
Triggered Waveforms	76.77	156.6	184.9	230.6	260.6	286.1	311.2	336.9	392.2	438.3	511.8	579.1	659.7	746.3	838.9	974.4	1141

Figure 1. The archive at the SCEDC currently has the following holdings: The Caltech/USGS catalog of over 573,350 earthquakes spanning 1932-present.

- 6.07 terabytes of continuous and triggered waveforms.
- 13.2 million phase picks.
- 61.7 million triggered waveform segments.
- Nearly 7 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).
- 25.1 million amplitudes available for electronic distribution.
- Triggered data for more than 20,370 significant teleseismic events.

b. 2007 SCEC Borehole Instrumentation Program Activity

Major 2007 Accomplishments:

1. The SCEC borehole instrumentation program continued to maintain existing sites and work with other collaborating agencies to facilitate the data acquisition, archival, and dissemination of data from the sites. The primary partner agencies include Caltech/USGS, CGS, the NSF EarthScope/PBO, and NSF NEES programs. A total of 18 borehole sites that used SCEC funds are now operating. In addition, another 10 stations have are operating in the Southern California region through funds from other

agencies for a total of 28 sites (Figure 2), of which 23 of these come back in real-time to UCSB and to CISN.

Southern California Borehole Instrumentation

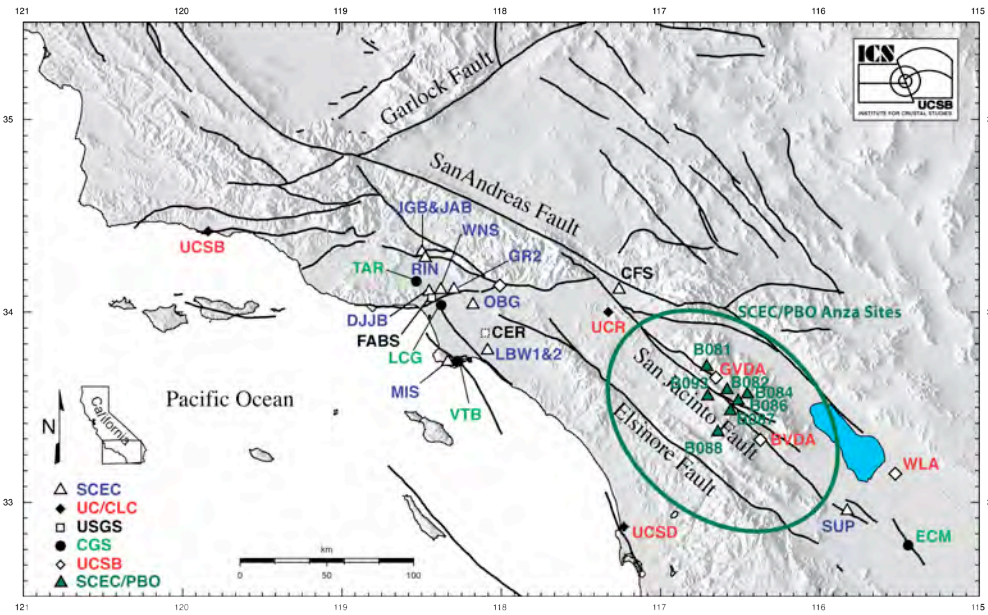


Figure 2. The Borehole instrumentation network in the Southern California region.

2. The SCEC/CISN operated site (WNS-Figure 2) in the mountains above downtown Los Angeles, at Wonderland School in Laurel Canyon, had been taken out of service as the school underwent major construction. In the spring of 2007, the borehole and surface instruments were re-installed, now located directly under the new school, accessed through the parking garage. This site is once again providing extremely quiet recordings of small earthquakes at this hard rock site condition, and ready to capture future motions up to +/- 2g.

3. The SCEC/CISN operated site in downtown San Bernardino (CFS-Figure 2), located at the Central Fire Station was re-installed in January of 2008. After a complete reconstruction of the site infrastructure by the USGS team, the instrument was re-deployed and connected to a new Q330 datalogger. While the data quality of this refurbished downhole sensor is not as good as the WNS station, the larger earthquakes produce data with plenty of signal-to-noise. In the future, we may remove the sensor for more testing at the manufacturer to examine what's causing the noise at the very low end of its sensitivity.

4. As in the previous year, the EarthScope/PBO collaboration was an important component of the SCEC Borehole program. With the data from the SCEC/PBO Anza sites streaming in real-time to UCSB, we are able to examine the quality of data. The weak motion sensors are providing high quality data for the small earthquakes, and have improved the CISN detection threshold in the region. The strong motion sensors extend the range of ground motion observations out to +/- 3.5g with MEMS

accelerometers. These sensors have proved to be a good compliment to the weak motion sensors in this regard, but have not performed as well as we had hoped in the low amplitude range. We are not able to examine the small earthquakes at high frequencies with these sensors, as they are just not sensitive enough. The community should recommend to the EarthScope/PBO program that the weak-motion channels be recorded at 200 sps, like the strong motion channels are, at least for the sites where the bandwidth is available. Currently, the weak-motion channels are recorded at 100 samples per second.

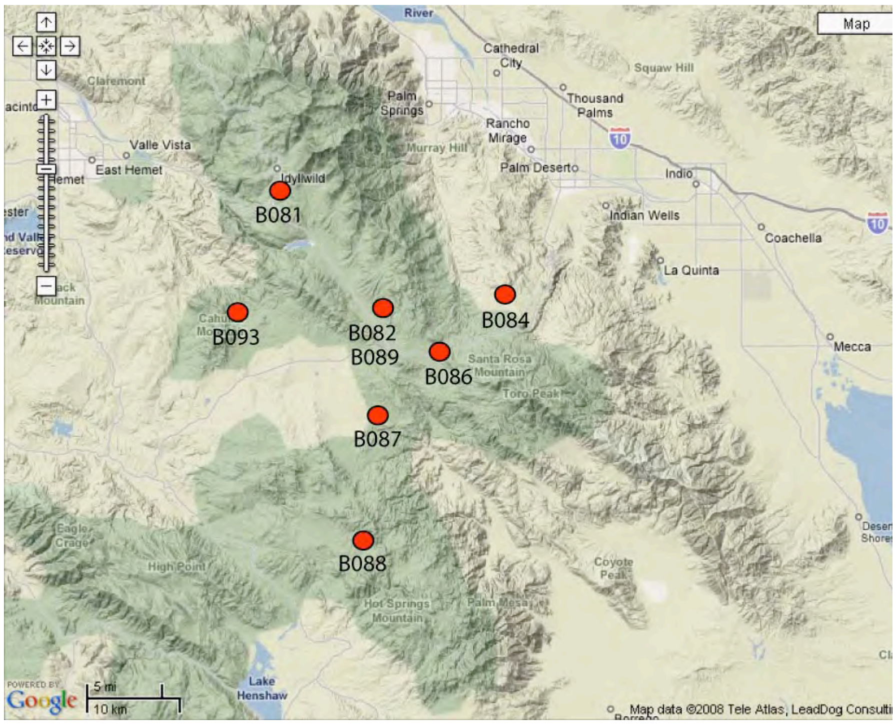


Figure 3. The SCEC/PBO Anza borehole stations.

5. The SCEC borehole program continues to leverage the software, data processing, and analysis developments and upgrades being made possible through the NEES instrumented field sites program. Upgrades to the Antelope real-time software each year are provided through this collaboration. In addition, new processing and analysis tools for automated calculation of spectral parameters are currently under development. In the near future, we plan to include web access to station state-of-health, web access for data dissemination and earthquake source parameters.

c. 2007 SCEC Portable Broadband Instrument Center Activities

Major 2007 Accomplishments:

1. Updates to the PBIC web page were made to provide potential users with quicker access to the PBIC equipment inventory database. This was in response to feedback

that the information was not easy to find. The link is not prominent on the PBIC home page.

2. GPS and Solar were installed on the roof of the PBIC lab space on campus at UCSB. We also installed a GPS repeater in the PBIC instrumentation lab, so we can now operate stations on a 24/7 basis in test mode, as if they were deployed on an experiment. This has been very useful in troubleshooting problems with the older DAS's and disks.
3. Two new students, junior geophysics and geology majors at UCSB, started working for the PBIC in 2007. They handle most of the general maintenance for the equipment on a week-to-week basis. The students are now continuously swapping the equipment in the lab into 24/7 continuous use to determine which of the stations are the most reliable. In addition, they are learning how to open up the DAS's and troubleshoot problems at the board level.
4. A new compact flash to SCSI interface was purchased and is being evaluated in the PBIC lab. This data recording system is lower power than the older SCEC hard drives, and can operate in more extreme temperature environments. While the interface hardware components are not cheap, the compact flash media is very inexpensive, and makes swapping data media in the field quite easy. Field-testing of this new system will take place in 2008.
5. Support for the Superstition Hills experiment continued throughout 2007. This involved both field support and data processing support. The GPS firmware updates provided by RefTek had the unfortunate "feature" of adding time jumps to the data of exactly 1 week, both backwards and forwards. Software was developed to detect these jumps, and correct the time in every data block. Once the data was corrected, it was then provided via external drive to Elizabeth Cochran, the experiment PI.
6. The data from two PBIC stations deployed along the superstition hills fault zone are integrated directly into the network processing at Caltech/USGS in Pasadena and are used for locating earthquakes and constructing shake maps. These are the only two stations in the PBIC pool that are capable of real-time network integration. The hardware was purchased as a pilot test, for a potential future upgrade of the PBIC equipment. As an example of this real-time integration of the PBIC equipment we show a M1.6 event located in the region as seen by CISN display software in Figure 4.

   The corresponding waveforms used by the analysts to locate this event can be seen by clicking the waveform products page on CISN display. Figure 5 shows the waveforms, of these two real-time PBIC stations along with other stations in the region.

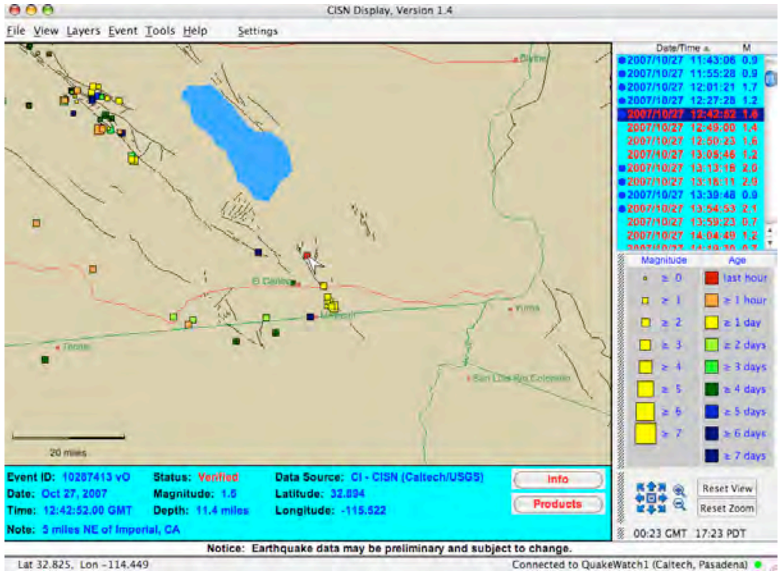


Figure 4. M 1.6 event ~17 km SE of the SCEC PBIC portable stations deployed at Superstition Hills.

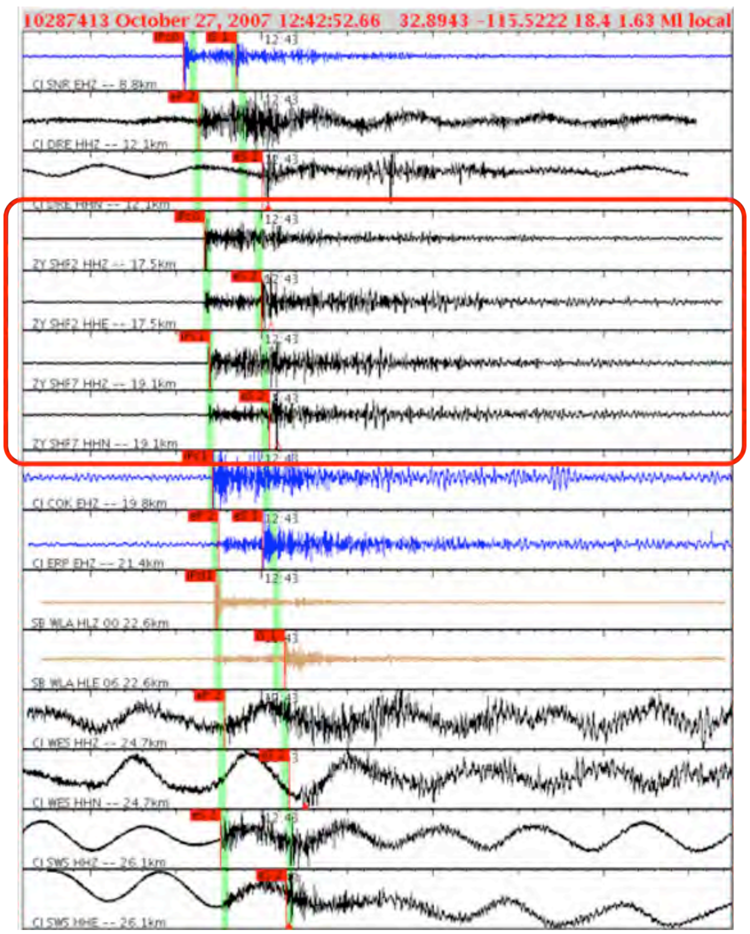


Figure 5. Waveform products from CISN and SCEDC including data from the PBIC networked stations.

d. Post-Earthquake Planning for SCEC Science, Workshop

How should SCEC respond when the next major earthquake strikes California? During 2007 several conference calls were held to prepare for the workshop on “post-earthquake response planning for SCEC science”. The workshop was held at the 2007 annual meeting. This workshop attempted to answer this question and to lay the groundwork for future science and infrastructure planning. Formulating SCEC post-earthquake science goals was the major focus of the workshop. These goals ranged from collection of data in the field to ensure that no opportunities are lost, to peta-scale computer modeling of earthquake sources, ground motions and stress transfer in support of rapid post-earthquake response. The workshop also addressed, what infrastructure is required for the next generation post-earthquake science. The SCEC post-earthquake response workshop included updates on plans of other science responders such as USGS, CGS, and UNAVCO.

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

A New 3-D Crustal Velocity Model. Motivated by a desire to improve the absolute location accuracy of southern California earthquakes, Lin and others computed a new 3-D seismic velocity model derived from P and S arrival times from local earthquakes and explosions (Figure 6). To reduce the volume of data and ensure a more uniform source distribution, they computed “composite event” picks for 2597 distributed master events that include pick information for other events within spheres of 2 km radius. The approach reduces random picking error and maximizes the number of S-wave picks. The composite events consist of 110,913 composite P picks and 54,303 composite S picks, while the number of total contributing P picks is 2,293,728 and S picks is 575,769. In other words, 0.6% of the total events—the 2,597 composite events—preserve most of the information of 38% of the original picks (7.75 million picks). To constrain absolute event locations and shallow velocity structure, they also used times from controlled sources, including both refraction shots and quarries. They implemented the SIMULPS tomography algorithm (Thurber, 1983, 1993; Eberhart-Phillips, 1993; Evans et al., 1994) to obtain 3-D Vp and Vs structure and hypocenter locations of the composite events.

Waveform Cross-Correlation Event Location. Waveform cross-correlation is an increasingly important tool for characterizing event similarity, improving earthquake locations, and studying source properties (Figure 7). However, it is not yet used routinely for network data owing to its greater computational requirements compared to standard processing based on phase picks. For example, even relatively small clusters (thousands of events) require that millions of cross-correlation functions be computed and that large parts of the waveform archive be available online. However, with modern computers these requirements are increasingly tractable and larger and larger problems may be addressed. A key benefit of waveform cross-correlation is more precise timing of P and S arrivals, which makes possible relative location accuracy of tens of meters or less within individual similar event clusters, permitting detailed imaging of small-scale fault structure.

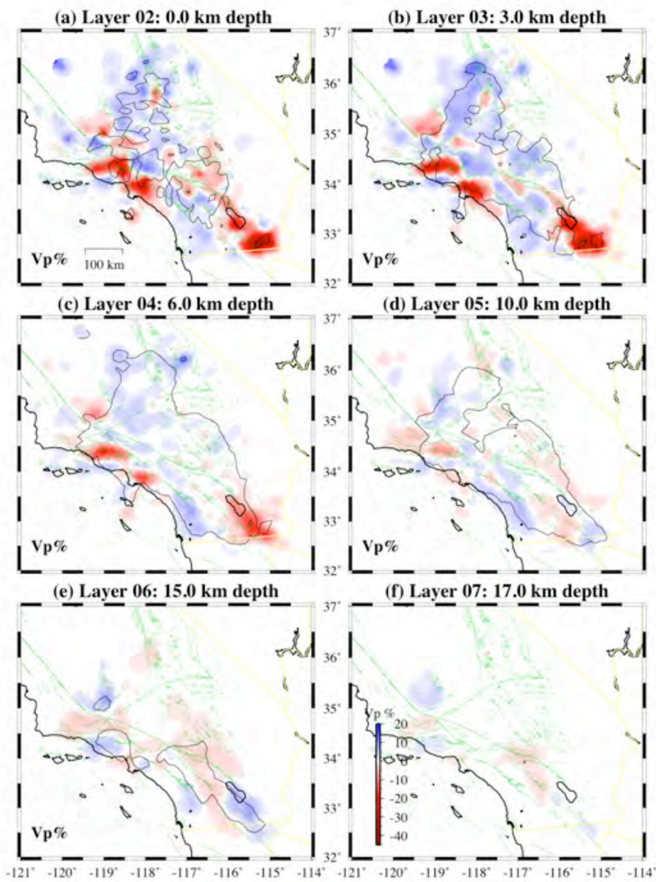


Figure 6. *P* velocity perturbations in the new 3-D crustal velocity model (Lin et al., 2007). The black contour lines enclose the well-resolved parts of the model. The best resolution is between about 3 and 10 km depth where ray coverage is best.

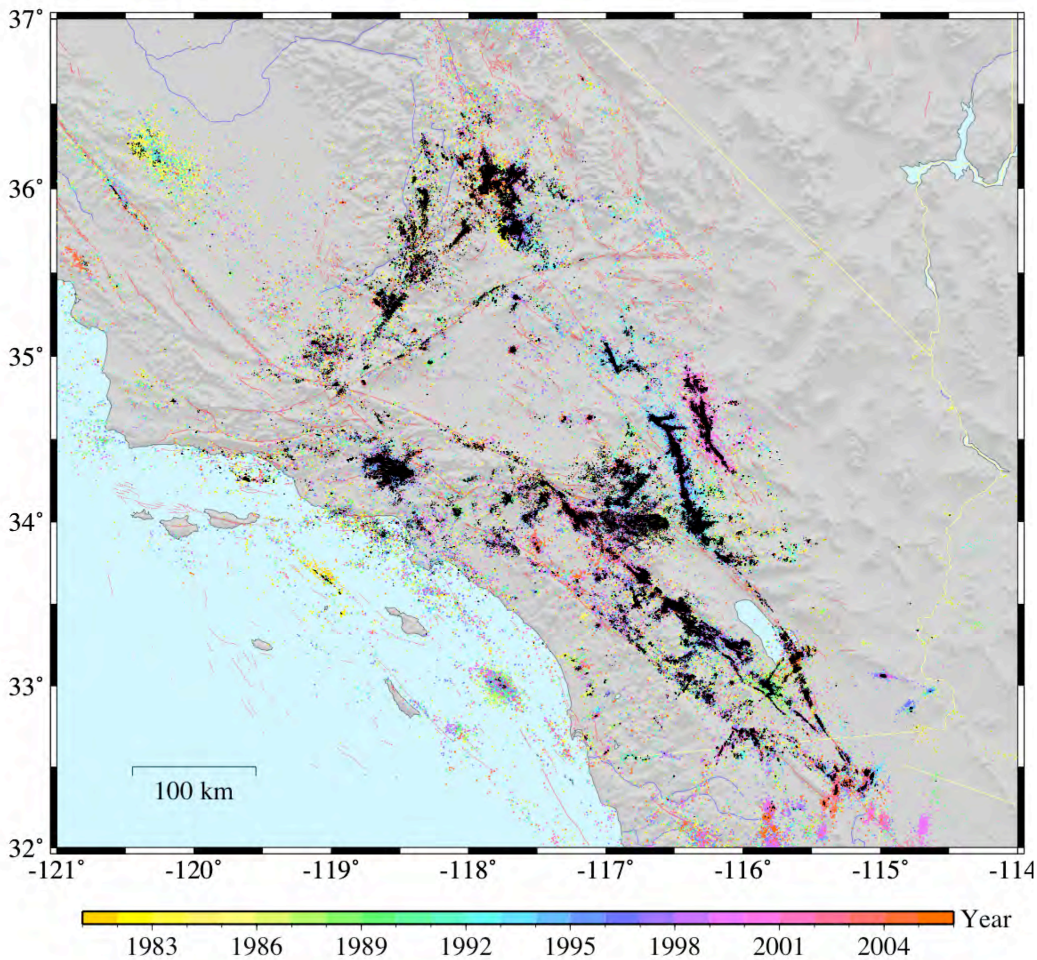


Figure 7. Relocated seismicity in the 2007 catalog (Lin et al., 2007b). Black dots show similar event clusters relocated using cross-correlation data. About 25% of events do not correlate and are plotted in color by year.

Lin, Shearer, and Hauksson computed high-precision earthquake locations using southern California pick and waveform data from 1981 to 2005. Their latest results are significantly improved compared to the previous catalogs (Hauksson and Shearer, 2005; Shearer et al., 2005) by the following: (1) They located events with respect to the new crustal P and S velocity model using 3-D ray tracing, (2) They examined 6 more years of waveform data and computed cross-correlation results for many more pairs than previously, (3) They computed locations within similar event clusters using a new method that applies robust fitting to obtain the best locations satisfying all the differential time constraints from the waveform cross-correlation. These results build on the relocated catalogs of Hauksson and Shearer (2005) and Shearer et al. (2005) and provide additional insight regarding the fine-scale seismicity structure in southern California. In particular, they obtain spectacular results for active faults in southern California, with previously diffuse seismicity in many regions now being resolved into narrow seismicity streaks.

f. Towards an Improved Understanding of Deep Tremor in Central California and its Implications for the Cholame Segment of the San Andreas Fault

Under this grant Beroza et al. have searched for low frequency earthquakes (LFEs) during episodes of tremor in the vicinity of the San Andreas Fault at Cholame (Figure 8). During the project period, *Gomberg et al.* [2008] reported the discovery of tremor in this region that was triggered by the 2002 Denali, Alaska earthquake. Because this triggered tremor was both time-localized and strong, they made it the focus of the initial efforts.

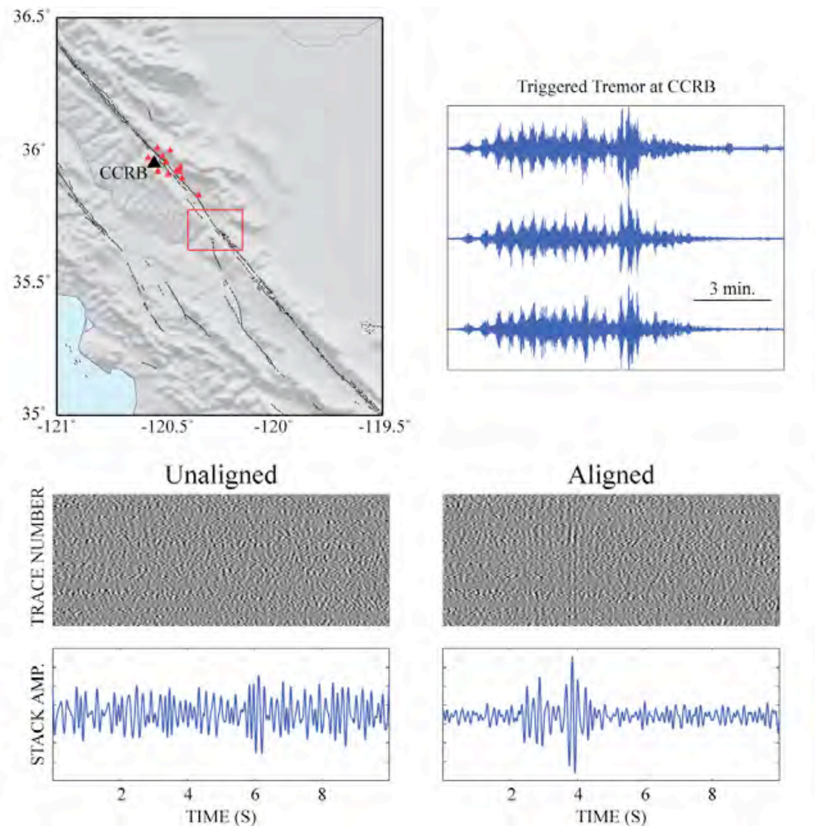


Figure 8. Study area is shown in map view. Red box marks the approximate location of tremor found by *Nadeau and Dolenc* [2005]. Faults are marked with solid black lines. Red triangles represent borehole seismic stations of the Parkfield high-resolution seismic network (HRSN). The records on the top right correspond to the triggered tremor activity by the Denali earthquake in 2002 (Rubinstein et al., 2007) as observed by station CCRB. Bottom figures show correlation of 75 candidate LFE detected at station CCRB (channel DP1) within the tremor using all HRSN stations. The candidate LFEs are realigned and both P and S waves appear to be visible.

Beroza and others analyzed 20 sps data continuous data from the High Resolution Seismic Network (HRSN) and applied a running network autocorrelation method developed by *Brown et al.* [2008] to search for LFEs within tremor. They appear to have found LFEs during the triggered tremor sequence. This should allow us to bring the power of waveform cross-correlation to the tremor problem, which proved a key to understanding the origin of deep, non-volcanic tremor in Japan [*Shelly et al.,* 2006, 2007]. The results should be applicable, not just to the San Andreas fault in this region, but also to other places such as Anza, where triggered tremor is observed.

g. Seismic Characterization of Fault Damage and Healing over Multiple Length and Time Scales on the San Andreas Fault, Parkfield and the Calico Fault in the Eastern California Shear Zone

Highly damaged rocks within the San Andreas fault zone at Parkfield form a low-velocity waveguide for seismic waves. Prominent fault-guided waves have been observed on the San Andreas Fault Observatory at Depth (SAFOD) seismographs, including a surface array placed across the fault-zone and a borehole unit placed in the SAFOD main hole at a depth of ~2.7 km below ground (Figure 9).

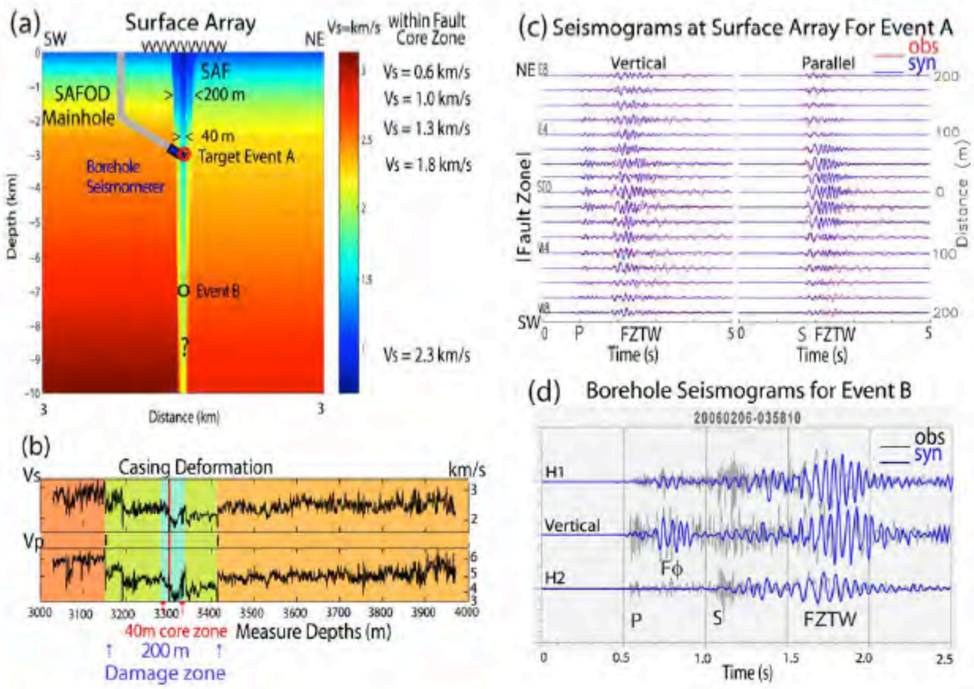


Figure 9. (a) Cross section near the SAFOD site showing the *S*-wave velocity model used in this study to compute synthetic fault-zone trapped waves (FZTWs) for the surface and borehole observations recorded in 2003 and 2005. Earthquakes A and B illustrate this type of fault guided waves used in this study. (b) Seismic velocities from SAFOD well logs showing the 40-m fault core and 200 m jacket low velocity damage zones. The red line indicates the location where fault creep is deforming the borehole casing. (c) Observed (red) and computed (blue) vertical- and parallel-component seismograms at the surface array for event A. The seismograms were low-pass filtered below 8 Hz and are plotted using a single global scale. (d) Observed and computed 3-component borehole seismograms recorded for event B. The synthetic seismograms have been low pass filtered below 12 Hz. The large signal between the P- and S- waves labeled "Fφ" has been recently identified as a fault guided P-wave [*Malin et al.*, 2006; *Ellsworth and Malin*, 2006].

Li and others modeled the resulting observations by using 3-D finite-difference methods. To fit the amplitude, frequency, and travel-time characteristics of the data, the models require a downward tapering, 30-40-m wide fault-core embedded in a 100-200-m wide jacket. Compared with intact wall rocks, the core velocities are reduced by ~40% and jacket velocities by ~25%. Based on the depths of earthquakes generating guided-waves with long-duration wavetrains after the S-waves, they estimate that the low-velocity waveguide along the fault at the SAFOD site extends at least to depths of ~7 km. Thus it appears that significant damage zone exists at even twice the depths previously reported.

The damage zone at seismogenic depths may be caused by intense fracturing during earthquakes, including brecciation. Alternatively, given the fluid leakages currently taking place into the SAFOD well, the cause might relate to liquid-saturation and high pore-fluid pressure nears the fault. However, pore fluids arising from depth appear to hold a complex relationship with this damage zone, with its outer portions appearing to be more permeable than its core [Lockner et al., 2000]. Moreover, the damage zone may actually form more of a fluid barrier which fluids are simply pounded against. The damage zone is also asymmetric, apparently broader on the southwest side of the main fault trace. The asymmetry may imply that the fault has a moving damage zone or that when it ruptures it may preferentially damage the already weakened rocks [Chester et al., 1993]. Alternately, greater damage may be inflicted in the extensional quadrant than the compressional quadrant near the propagating crack tip [Andrews, 2005]. Although the structural model accounts for the FZTWs and Fφ observations and its parameters at ~3 km depth are confirmed by logging data, it is likely to represent a gross average of the actual fault-zone structure. The true structure in 3-D will certainly be more complicated, and the damage magnitude and extent will vary along the fault strike and depth due to rupture distributions and stress variations over multiple length and time scales.

h. Modeling Short-Period Seismograms

Helmberger and others present results aimed at the use of a recently developed technique, CAPloc, in recovering source parameters from a few stations. They conducted a detailed test of a recently developed technique, CAPloc, in recovering source parameters from a few stations against results from a large broadband network. 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 earthquake 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 hard-rock sites. This simplification allows the source inversion for both mechanism and location to be easily obtained by grid search. They test one-station mechanisms for 160 recent events against the array for both PAS and GSC which have data since 1960. While individual solutions work well (about 90%), joint solutions produce more reliable and defensible results.

Inverting for both mechanism and location also works well except for difficult paths across deep basins and along mountain fronts. Traditional methods, using body waves for hypocenter location and their phase polarities for the focal mechanism, require dense coverage of short-period seismometers. In contrast, the recently-developed technique "CAPloc" (Tan et al., 2006) makes use of 3-component broadband seismograms and enables reliable source estimates from a relatively small number of stations for events with magnitudes down to ~3.5. For events of smaller size, high frequency P-waves (2s to 2Hz) can be calibrated for site effects and inverted for accurate focal mechanisms (Tan and Helmberger, 2007).

The essence of "CAPloc" is to model the entire record with the differential travel times between major phase groups (the P and surface waves) adjusted from known calibration information. These travel time adjustments, either from a well-determined tomographic map (Liu et al., 2004) or a calibration study are made to correct for deviations of the real crustal structure from the model (Figure 10). They are the prerequisites for accurate epicentral location. Compared to the traditional method of using impulsive P- waves, “CAPloc” greatly enhances sampling of the focal sphere by using the whole seismograms, so reliable source estimates can be achieved with sparse data set.

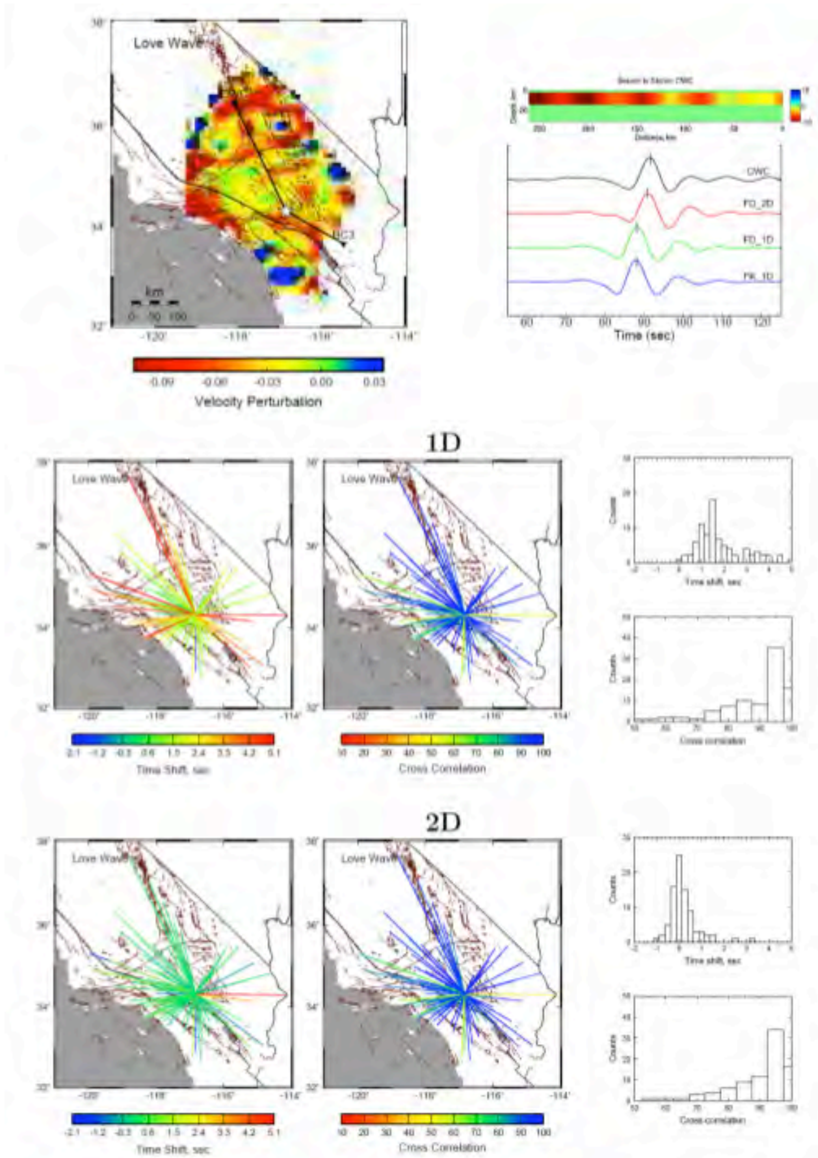


Figure 10. Top panel shows Love wave phase velocity perturbation with selected source (star)-receiver (triangle) path, along which the 2D cross section is shown. Synthetics are compared against the data on right. Lower panel summarizes the comparison between 1D and 2D synthetics against the observed Love waves for a Big Bear event.

i. References

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2. Tectonic Geodesy

In 2007, geodetic activities fell under two major categories – improving data products volume and quality, and broadening the range of stress modeling applied to geodetic data. Priorities include the characterization and interpretation of strain accumulation and release, increased use of Plate Boundary Observatory (PBO) data (including high-rate GPS and InSAR), the development of tools for detecting transient deformation, and improvement in modeling and inversion methods that utilize multiple data types. Jessica Murray and Rowena Lohman assumed new roles as chair and co-chair of the Tectonic Geodesy disciplinary committee.

The PBO Global Positioning System (GPS) network has vastly improved the spatial coverage of GPS in the western U.S.; however, several regional networks of continuously operating GPS predated PBO, and PBO was planned in the context of these other networks. Some of the stations in pre-existing networks were folded into PBO through the NUCLEUS program, while others remained part of their original networks. With PBO nearly completed the challenge to the geodesy community is how to use the data from this and other networks to its fullest.

Herring and King made a significant contribution to this effort by developing and implementing tools for automatically merging results from PBO and PBO NUCLEUS GPS processing (carried out by the PBO data processing centers) with results from the 160 non-NUCLEUS SCIGN stations processed by the USGS in Pasadena. They have shown that the quality of the positions in the merged solutions, as quantified by WRMS scatter, are as good for sites processed by the USGS as for those done by the PBO processing centers. The merged data products will continue to improve as gaps in the USGS-processed time series are filled. This work not only supports comprehensive and consistent GPS position and velocity products for southern California, but also lays the groundwork for the integration into PBO solutions of data from non-NUCLEUS continuous GPS sites in other geographic regions.

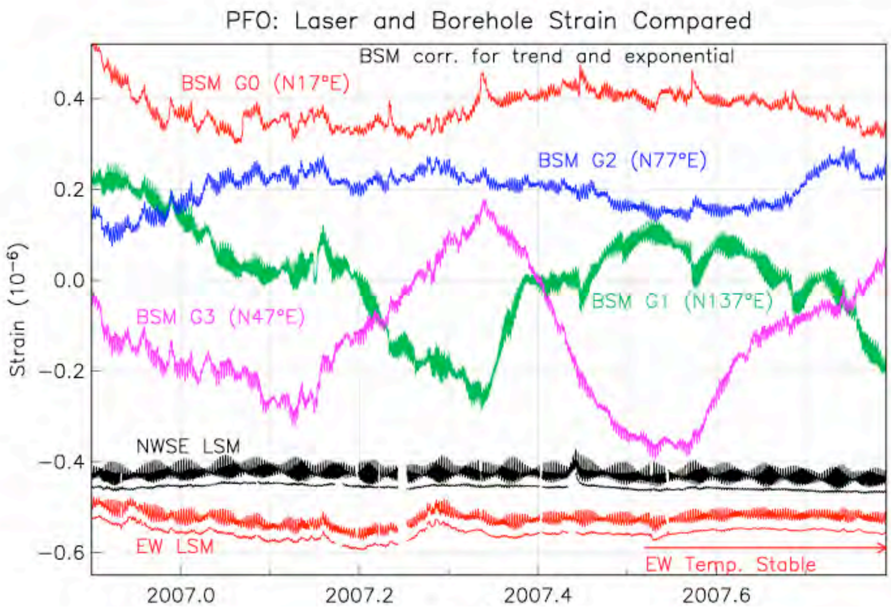

Figure 11. Comparison of PFO laser strainmeter (bottom two curves) with nearby PBO borehole strainmeters, illustrating the high stability of the laser strainmeters at timescales longer than a few days.

Wyatt and Agnew continue to maintain the Piñon Flat Observatory (PFO). Located between the San Andreas and San Jacinto faults, this facility consists of three laser strainmeters and two longbase tiltmeters that provide continuous measurements of crustal strain at periods of seconds to years, bridging the gap between seismology and other geodetic methods. Data from PFO have been used to study time-varying permeability. Data from PFO provide a detailed record of aseismic strain, including postseismic effects from Landers, Hector Mine, and most recently the 2005 M. 5.2 Anza earthquake. The authors also present a comparison of the strain measurements from the PFO strainmeters to more recently installed PBO borehole strainmeters in the Anza area. The PFO strainmeters provide much less noisy data for periods longer than a few days, and thus are well-suited to tracking aseismic slip events (Figure 11). Award funds were used to maintain the facility to ensure uninterrupted operations. Major components of this were the building and testing new data loggers for the PFO strainmeters, which will allow better remote access, and the installation of a new temperature-control system for one of the strainmeters. Progress is also being made toward archiving PFO data at the NCEDC in parallel with, and using the same format as, PBO data, which will greatly facilitate the use of this data.

Another focus area for Tectonic Geodesy involves better understanding of the origins of geodetic/geologic slip rate discrepancies. One such discrepancy exists in the San Bernardino section of the San Andreas Fault. In newly funded work for 2007 Bennett's research group has collaborated with McGill to reoccupy campaign GPS sites in the San Bernardino Mountains region as well as add new sites. The planned 2007 field work was curtailed due to forest fires, but it is anticipated that the intended sites will be occupied in the 2008 field season. Bennett's group has established and occupied other regional campaign GPS networks and has processed data from those sites to produce a densified GPS velocity field for southern California (Figure 12).

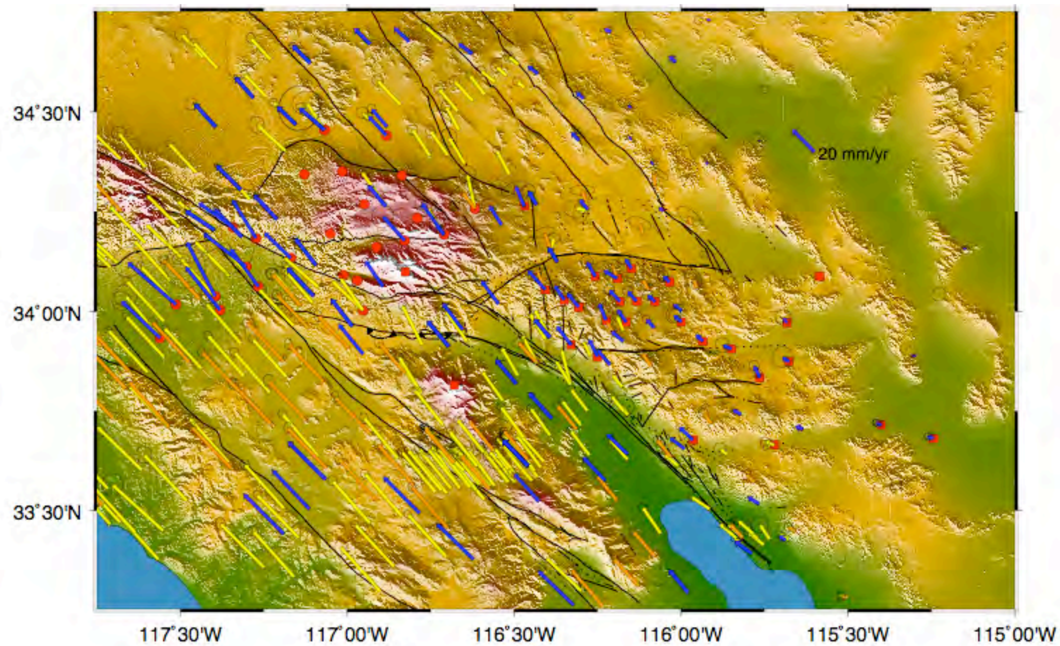

Figure 12. The southern California crustal velocity field relative to the Stable North America Reference Frame, with U. Arizona solution (blue), and SCEC CMM v.3 velocities from trilateration (orange) and GPS (yellow).

In particular, the data from their Joshua Tree National Park network has produced well-resolved velocity estimates in a span of only 2.5 years of tri-annual occupations. Addition of data from the San Bernardino Mountains will make significant improvements in the southern California velocity product.

The integration of crustal motion estimates from GPS with those from InSAR is an area that the SCEC Tectonic Geodesy community has identified as being a priority. Sandwell and colleagues have made significant progress this year in providing tools that allow the community as a whole to utilize new types of SAR data, and in interpreting InSAR time series within actively-deforming regions n Southern California. Because work on the original topic of his proposal was postponed due to other funding and personnel constraints, Sandwell instead used his SCEC 2007 funds to develop infrastructure needed for SCEC scientists to take advantage of the new ALOS PALSAR data. The ALOS L-band signal suffers less from decorrelation than C-band or X-band InSAR, and is a valuable new tool for extending the areas that may be studied using InSAR.

Sandwell collaborated with Mellors to produce preprocessing software for ALOS data (freely available on the WInSAR website), assessed the accuracy and resolution of these data in southern California, and began investigating aseismic slip on the Superstition Hills fault. Sandwell and coauthors found that the ALOS data provide good spatial resolution (38 m in range and 30 m in azimuth), better line-of-site precision than expected (3.3 mm), and good temporal coherence within areas of interest in Southern California. Using InSAR data (from ERS-1, ERS-2, and ENVISAT) Sandwell estimates that creep on the Superstition Hills fault is confined to the upper 2-3 km, with the majority of slip in the upper 500 m. They infer that the October, 2006 creep event along the Superstition Hills fault involved ~10 mm of slip on the upper 1 km of the fault over a distance of 20 km (Figure 13). Other InSAR-time-series analysis includes work done by Fialko and colleagues on how to optimize the use of SAR interferometric pairs in generating stacks spanning many years worth of data.

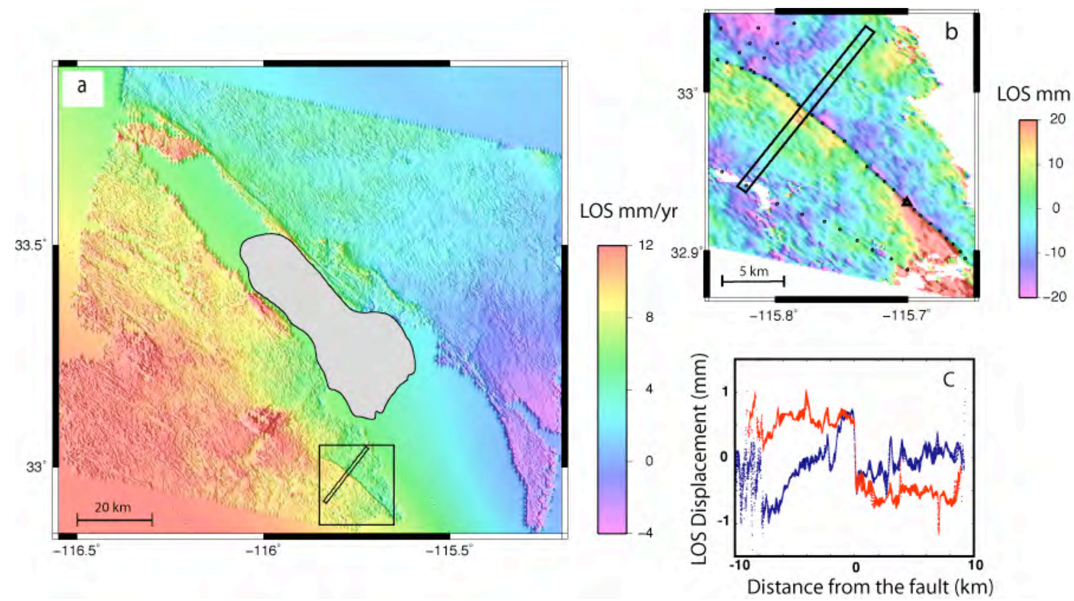

Figure 13. (a) Stacked interferogram of 10 years ERS1/2 data. The square box is the area of the Superstition Hills Fault. (b) Stacked interferogram of Envisat data spanning the 2006 creep event. Black dots are the SH, Elmore Ranch and Superstition Mountain faults. (c) Satellite line-of-sight displacement profile in mm, for the creep event (blue) and a 10-year interferogram (red).

In addition to the kinematic modeling performed by Sandwell and colleagues, SCEC also supported work by Hearn on the effects on stress transfer within the crust by elastic heterogeneities. They evaluated both the effects of large-scale, permanent structures that occur when terranes of different lithologies are juxtaposed against one another, as well as the effects of damage-induced elastic heterogeneity along faults.

Hearn and colleagues use finite element modeling of damage zones along faults to conclude that tectonic strain is concentrated along the highly-damaged cores of fault zones. They find the largest damage along "flower-structure" zones (Figure 14) that heal inter-seismically at greater depths - consistent with geologic and seismic observations. However, these zones are very small relative to the seismogenic zone, so they do not appear to influence regional-scale stress transfer or coseismic slip inversions for large earthquakes such as Landers and Hector Mine.

A key element missing from current efforts involves the detection and characterization of strain transients within the rich datasets now being developed. To address that need, we are holding a workshop in early August, 2008, to identify the best direction forward for SCEC in this field, and will report our findings at the annual meeting.

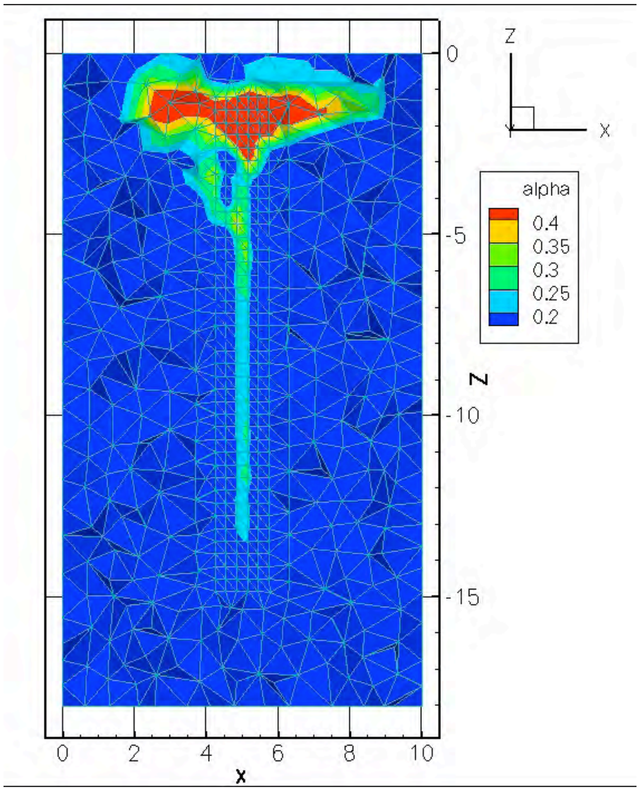

Figure 14: Modeled damage across a strike-slip fault segment. Hearn et al are continuing evaluation of features that control compliant zone width, including the effects of grid resolution.

SCEC researchers continue to advance our ability to incorporate data types with distinct strengths and challenges (such as GPS, InSAR and strainmeter data) into models of fault slip and crustal deformation over the seismic cycle. Finite element modeling efforts have improved and can address the need for spatially varying elastic structure and damage characteristics, which is now allowing researchers to look at the effects of more realistic crustal models on inversions.

3. Earthquake Geology

Many of the projects in the category of earthquake geology over the past year focused on defining spatial and temporal patterns of strain release on the major fault systems of southern California, with a particular emphasis on developing a better understanding of possible discrepancies between long-term geologic and short-term geodetic data. These studies include development of deep-time records of paleo-earthquakes on the San Andreas fault, development of better understanding of the relationships between geomorphic processes and surficial dating, fault slip rates at several new sites over Holocene and latest Pleistocene time-scales, and tying slip-rate data to earthquake clustering. Many of these activities dovetail with the objectives of the Southern San Andreas fault Evaluation (SoSAFE) project, and several projects were jointly funded. In addition to these goals, earthquake geology also supports data gathering to improve structural representation in southern California, observational tests of fault-zone mechanics, and development of geomorphic indicators of past strong-ground motions. Further information on these studies may be found in reports of their associated focus groups.

SCEC3 sparked a new emphasis on understanding the earthquake behavior of the southern part of the San Andreas fault system, including the San Jacinto fault. With the addition of support from the USGS multihazards demonstration project through the SoSAFE program, SCEC3 has been able to make significant strides toward this goal. One of the premier results of this work has been the development of a new paleoseismic site on the San Andreas fault at Frazier Park by a group led by Kate Scharer together with Ray Weldon (U. Oregon) and Tom Fumal. Development of a deep paleoseismic record at this site was recognized by the community as critical to linking paleoseismic records from the Mojave segment to the Carrizo plain and, from this, testing recurrence models for great earthquakes. For example, is the 1857 earthquake, which ruptured both segments, typical of the San Andreas fault? Or do smaller events such as 1812 typify strain release? Figure 15 shows evidence for the last five earthquakes from the new trenching efforts. Overall, evidence for at least nine earthquakes has been recovered thus far. Through the SCEC3 pooled geochronology program the earthquake geology group has been able to rapidly approve additional dating of these paleoearthquakes. In addition to the development of the Frazier Mountain site, SCEC3 also supported paleoseismic investigations along the San Andreas fault system in the Coachella Valley, the Imperial fault, and the San Jacinto fault.

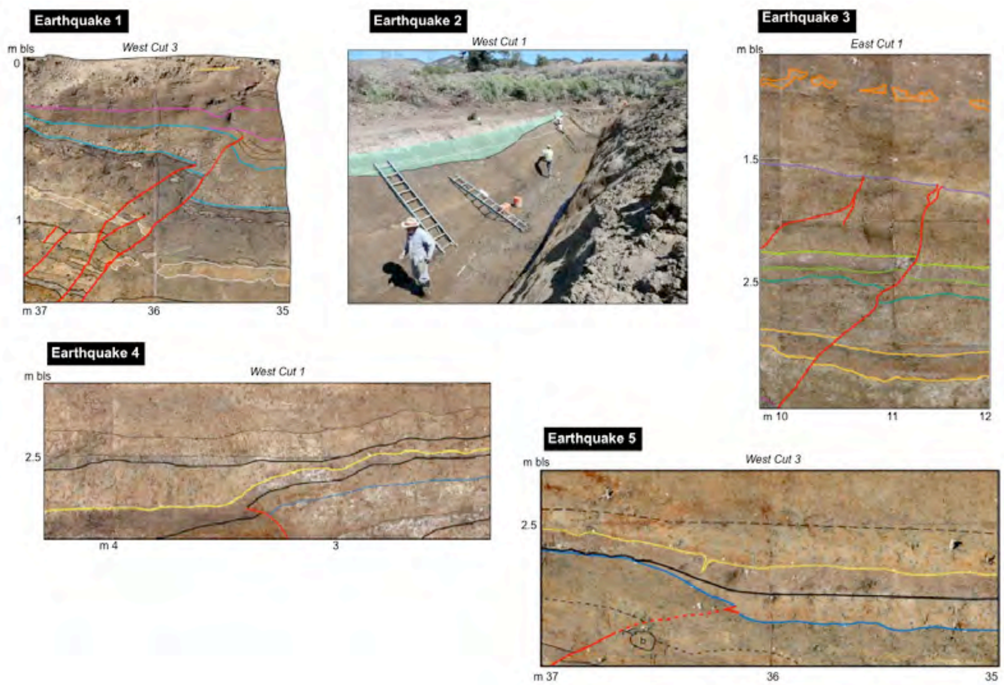

Figure 15. Annotated trench-wall photography showing evidence for most recent five major earthquakes on the San Andreas fault at Frazier Mountain.

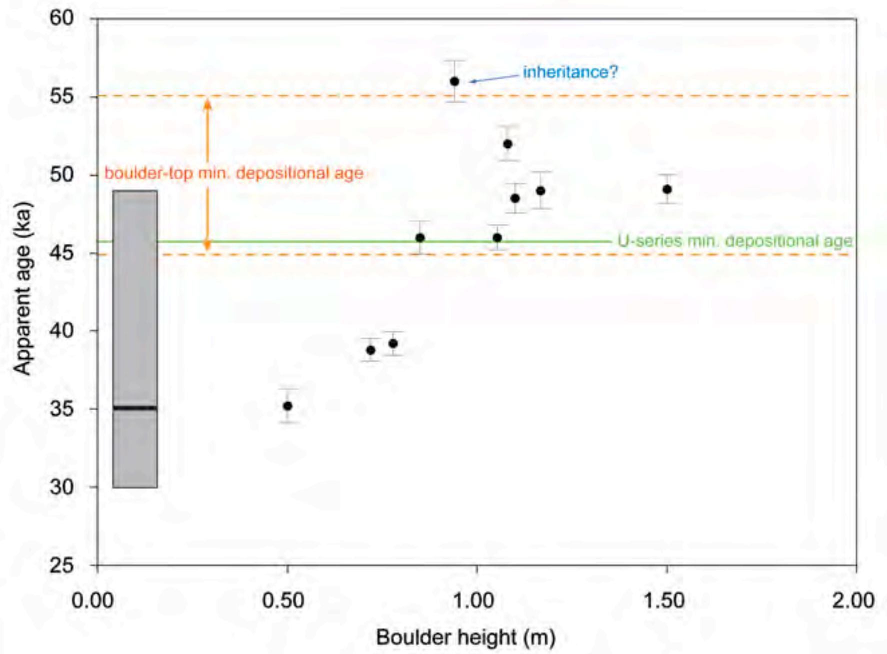

Figure 16. Apparent age of boulder-top samples (error bars are 2-sigma) plotted against boulder height relative to the current fan surface. Grey rectangle represents the range of ages from cobble-sized clasts from van der Woerd et al. (2006). Black line is their mean cobble age of 35.5 ka. Green line shows the minimum depositional age from U-series on pedogenic carbonate from Fletcher et al. (2008). Boulders less than ~ 1.0 m appear to scale with height, whereas those greater than ~ 1.0 m cluster at around 50 +/- 5 ka. This suggests that the T2 fan has undergone incremental surface lowering since its deposition. A simple calculation in which we prescribe a depositional age between 45 and 55 ka and an amount of surface lowering of 0.8-1.2 m allows us to predict the concentration of Be-10 radionuclides in the boulder and cobble-sized clasts based on their height below the original fan surface. This model provides a reasonable explanation for the scatter in the boulder and cobble sample ages and suggests 1) that boulders (where present) will provide a closer approximation of the depositional age of an alluvial fan than cobble-sized clasts and 2) that boulders may be used as a full cosmogenic depth profile that extrapolates to the original surface of an alluvial fan, thus preserving its entire post-depositional history.

Fault slip rates are fundamental to quantifying seismic hazard and, as the precision of these rates increases, for defining patterns of temporally irregular strain accumulation across the southern California fault system. Precise dating of landforms is key to defining fault slip-rates over time scales longer than those accessible from paleoseismology. In 2007, SCEC3 supported a multi-investigator effort, led by Ph.D. student Whitney Behr and John Platt, to precisely date the Biskra Palms alluvial fan where it has been offset by the San Andreas fault in the Coachella Valley. This study, in collaboration with Dylan Rood, Warren Sharp, and Tom Hanks, compares multiple approaches in cosmogenic exposure age-dating and U-series dating of soil carbonate. By comparing cosmogenic ^{10}Be concentrations of boulder tops, the fan surface, and at depth (Figure 16), these investigators reconcile cosmogenic and U-series ages by modeling ~1 m erosion of the fan surface. In addition to providing a much better-defined slip rate of the San

Andreas fault in the Coachella Valley, this study pioneers multi-technique approaches for dating landforms.

Another SCEC3-supported slip-rate study from the southern San Andreas fault system is providing new insights into what part of the lithosphere controls unsteady strain accumulation and release over millennial time scales. In a study of two parallel strands of the San Jacinto fault zone, Ph.D. student Kim Le and Mike Oskin have uncovered an intriguing pattern of irregular strain release. The Clark and Coyote Creek strands of the San Jacinto fault zone are independent faults separated by >5 km in the brittle crust and well-defined from micro-earthquakes to the base of seismicity. Using the newly available 'B4' LiDAR data set, Le mapped the fault zone in detail and identified new slip-rate sites on both strands (e.g., Figure 17). Surprisingly, the new slip-rate results from both of these faults show a coherent pattern of irregular strain release. Slip rates averaged over the past ~4 kyr are about double longer-term average slip-rates since ~31 ka. These results support the notion that irregular strain accumulation and release over these time scales is controlled by variability in the strength of the ductile portion of the San Jacinto fault zone. This study is but one of four SCEC3-supported geological studies of the San Jacinto fault zone designed to elucidate its earthquake behavior. Other studies include a slip-rate and exploratory paleoseismic investigation of the northern San Jacinto fault zone by Nathan Onderdonk, a study of distributed deformation in the Salton Trough by Susanne Janecke, and completion of a deep paleoseismic record from the central portion of the fault at Hog Lake by Rockwell and Seitz. Altogether, we anticipate significant new insights from the concentration of SCEC3 efforts on the San Jacinto fault.

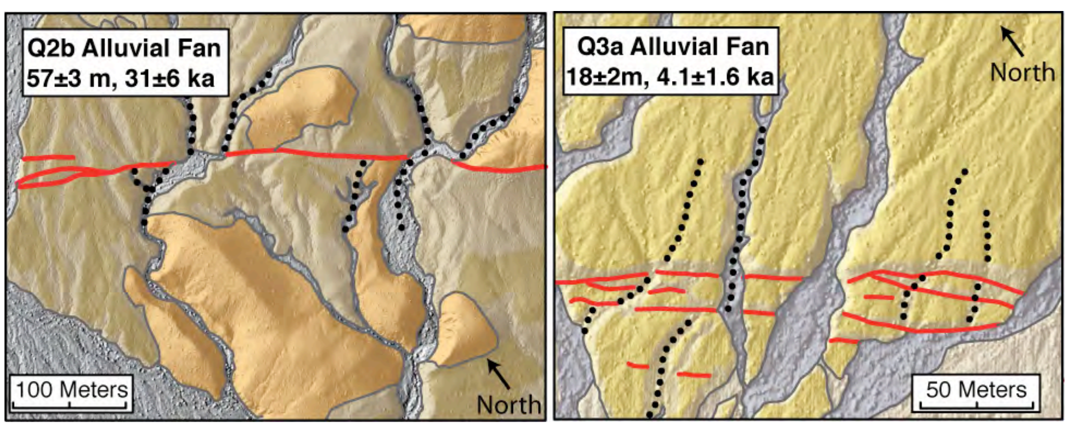

Figure 17. Slip rate sites from the Clark fault documented in 2007 show ~2x increase in average rate since 4 ka. A similar increase in rate was found for the Coyote Creek fault.

Ultimately, if unsteady strain release proves common across the southern California fault system, it is important to link these observations to earthquake production. One of the central issues is whether periods of more rapid fault slip are characterized by more frequent or larger earthquakes. One way to explore this question is to improve our understanding of fault system behavior by generating deep-time series of earthquake records from the fast-slipping faults, as already described for both the southern San Andreas fault and the San Jacinto fault. Another approach is to examine clustering of earthquakes across portions of the fault system. Paleoseismic investigations of the eastern California shear zone under SCEC1 showed that strain release is temporally clustered across this system of faults. Emerging results from the Los

Angeles basin also show clustering of activity that appears anti-correlated to activity in eastern California. This pattern is corroborated by a new SCEC3-sponsored paleoseismic investigation led by USC Ph.D. student Lorraine Leon together with James Dolan and John Shaw, of recent folding generated by slip on the Compton thrust ramp, a large blind thrust fault that underlies much of the western part of the Los Angeles metropolitan region. The data shown in figure 18 demonstrate that the Compton thrust, considered by some to be inactive (and currently not included in the State of California's data base of active structures) is, indeed, active, and capable of generating large-magnitude earthquakes directly beneath Los Angeles. Specifically, Leon et al.'s data indicate that the the Compton thrust has generated six M>7 earthquakes during the past 14,000 years. Moreover, these data demonstrate that the most recent of these Compton thrust earthquakes occurred as part of a cluster of large-magnitude events beneath the LA region between ~1,000 and 2,000 years ago. Another SCEC3-sponsored study of earthquake clustering focuses on the Calico fault Plamen Ganev, USC, and Kim Le, UCD, both graduate students, together with James Dolan and Mike Oskin. The Calico fault slips about twice as fast as other faults of the eastern California shear zone, thus its frequency of earthquakes will serve as a test of how much strain release is modulated by regional clusters of activity. Trenching across the Calico fault reveals evidence for four surface ruptures during latest Pleistocene-Holocene time, and pending optically stimulated luminescence dates will show whether the well-defined most recent event occurred as part of the ongoing, post-~1,000 AD cluster of earthquakes in the Mojave part of the ECSZ (e.g., 1992 M7.3 Landers and 1999 M 7.1 Hector Mine), or whether the most recent event was a mid-Holocene event. If the latter, the Calico fault may be the likely site of a near-future earthquake.

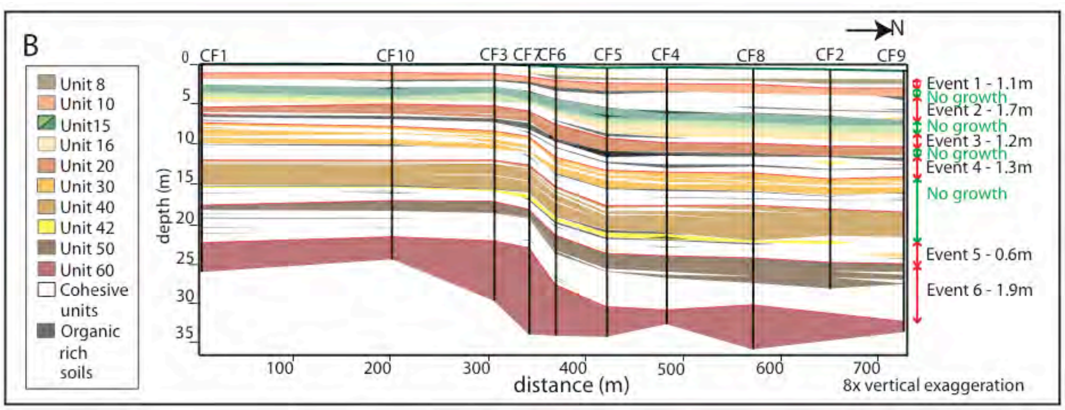

Figure 18. Borehole profile across now-buried fold scarps formed by slip on the Compton blind thrust. Growth strata show evidence of six large-magnitude earthquakes during the past 14,000 years, with the most recent event occurring between 850 and 1,650 years ago.

B. Focus Group Activities

Within the new SCEC structure, the focus groups are responsible for coordinating interdisciplanary activities in six major areas of research: *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 following reports summarize the year's activities in each of these areas.

1. Unified Structural Representation

The Unified Structural Representation Focus Area supports SCEC's science mission by developing and delivering digital models of crust and upper mantle structure in southern California for use in fault systems analysis, dynamic rupture modeling, strong ground motion prediction, and earthquake hazards assessment. These efforts include the development of Community Velocity Models (CVM & CVM-H) and Community Fault Models (CFM & CFM-R), which together comprise a Unified Structural Representation (USR). This past year's efforts have been focused on:

1. Extending the Community Fault Model (CFM) to a statewide California model, through partnerships with the U.S. and California Geological Surveys;
2. Systematically updating the fault representations in the CFM using new relocated earthquake catalogs;
3. Improving the Community Velocity Model (CVM-H), including the development of new regional tomographic models, an upper mantle teleseismic and surface wave model, and a geotechnical layer;
4. Enhancing the code that delivers the model to support grid parameterization and mesh construction; and
5. Supporting development and implementation of promising new approaches for improving 3D structural representations in future versions of the USR, including 3D waveform tomography employing scattering integral and adjoint tomographic methods.

a. Community Fault Model (CFM)

Current efforts in California seismic hazards assessment and fault systems modeling require an extension of the SCEC Community Fault Model (CFM) of southern California to encompass the northern part of the state. Thus, in partnership with the U.S. and California Geological Surveys, SCEC has initiated an effort to develop such a statewide model, consisting of the CFM in southern California (Plesch et al., 2007) and a new, comprehensive representation of faults in northern California. To begin this collaboration, SCEC sponsored a workshop on January 25th, 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 determined 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 later this year. 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., 2007). These updates will be incorporated in a new release of the CFM.

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

This past year's efforts were highlighted by a series of improvements to the community velocity model (CVM-H) (Süss and Shaw, 2003), to better facilitate its use in ground motion prediction. Priorities for model improvement were established at a SCEC workshop in June, 2007, and were subsequently implemented in a new model version (CVM-H 5.0) released at the annual meeting. Improvements to the model include new Vp, Vs, and density parameterizations within the Santa Maria basin and Salton Trough, as well as implementation of a geotechnical layer (GTL) based on the approach implemented in the SCEC CVM 4.0 (Magistrale et al., 2000). In addition, the new basin structures were used as input for the development a new P- and S-wave tomographic velocity models (Hauksson), and a new upper mantle teleseismic and surface wave model (Tanimoto). Basin structures were subsequently embedded in these regional models providing self-consistent Vp, Vs, and density descriptions (Figure 19).

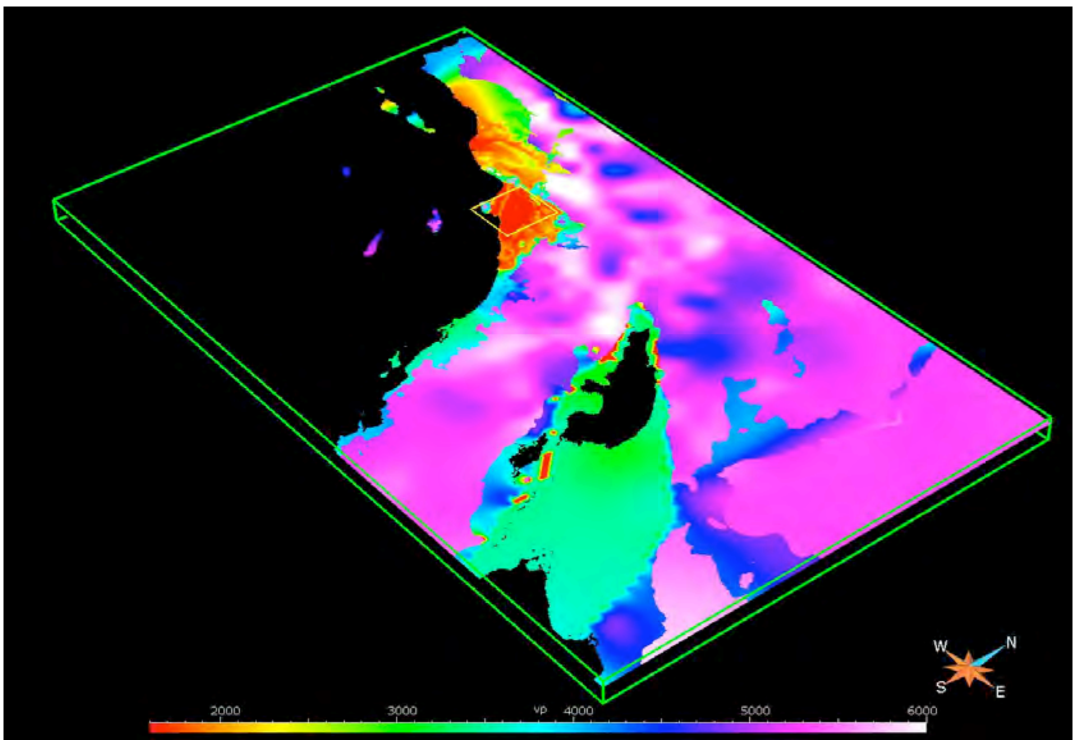

Figure 19: Perspective view of the CVM-H 5.0 showing Vp structure (m/s). Note that the basin structures are embedded in regional tomographic models. The small box centered near Los Angeles defines the area of the high resolution model; the entire region is represented by the medium resolution model.

In addition, a series of enhancements were made to the code that delivers the CVM-H. This code specifies Vp, Vs, and density values at arbitrary points (x,y,z) defined by the user by locating the nearest neighbor grid point in the appropriate CVM-H voxet. The currently model version consists of a high (250m) and medium (1000m) resolutions voxets, or regular grids. Participants at the 2007 workshop who employ the code to help parameterize their computational grids asked for two additional functions. First, they requested that the code provide the location of the nearest neighbor grid point. This would allow them to specify the location where the values were parameterized when the CVM-H was originally constructed, and would ensure that if the CVM voxets were modified in the future (i.e., resampled at a different grid spacing) that the same values could always be retrieved at the original nearest neighbor location. In addition, this information would allow for interpolation schemes, which can be tailored to the users application. Second, they requested that the code provide the depths (distances) from the arbitrary points to the surfaces used to construct the CVM-H, namely the surface topography/bathymetery, the top of crystalline basement, and the Moho. This information is of particular value when using the CVM-H to guide the construction of computational meshes. The latest release of the code provides both the nearest neighbor and horizon distance information.

c. New Approaches for the USR

The USR Focus area, in partnership with other groups in SCEC, also supports the development and implementation of promising new approaches for improving 3D structural representations in future iterations of the community models. This past year, 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) has employed this approach to develop the first fully 3D waveform inversion model of the Los Angeles basin, using the SCEC CVM 3.0 as a starting model and inverting 7364 time- and frequency-localized measurements of phase-delay anomalies relative to synthetics computed from the 3D starting model. The revised 3D provides a better fit to the observed waveform data than the 3D starting model, and represents the first successful application of F3DT using real data in structural seismology. Future iterations of these inverse models will be used to improve the SCEC CVM-H, and thereby enhance our abilities to accurately simulate strong ground motions that will result from future earthquakes.

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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 (A7-A10, B1, B4), 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 (A7-A11)
- 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-A10)
- Investigate the relative importance of different dynamic weakening and fault healing mechanisms, and the slip and/or time scales over which these mechanisms operate (A7-A10)
- Characterize the probability and possible signatures of preferred earthquake rupture direction (A7-A10, B1, B4)
- Develop realistic descriptions of heterogeneity in fault geometry, properties, stresses, and strains, and tractable ways to incorporate heterogeneity in numerical models (A10-11, B1, B4)
- Understand the influence of small-scale processes on larger-scale fault dynamics (A7-11, B1, B4)
- 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 (A7-A10, B1)

FARM encompasses a broad range of basic research aimed at illuminating physical processes of earthquake rupture mechanics. In 2007 research accomplishments included new findings by investigators working on earthquake and faulting problems in field, laboratory and computational settings.

In continuing efforts to develop physics-based models of the nucleation, propagation, and arrest of dynamic earthquake rupture, it is critical to develop realistic models of the geometry and kinematics of fault zones. Over the past year valuable progress was made by FARM scientists in characterizing and understanding on and off-fault damage and its relation to dynamic rupture and energy dissipation through coordinated field and experimental efforts. Through these efforts Sagy et al. (2007; 2008) have provided new information about the interplay of off-fault, bulk deformation of the host rock and the development of topography on principle slip surfaces in low to moderate displacement fault zones using ground-based LiDAR and detailed microscopy (Figure 20). Their data demonstrate that slip surfaces typically bound a cohesive layer that has undergone granular flow, the topography of the slip surfaces reflects variations in thickness of the granular cohesive layer, and this layer becomes progressively thinner with displacement indicating slip progressively localizes. They argue that the cohesive-layer-slip-surface system constitutes a geometric and rheologic boudinage-like inhomogenity. This description has implications for improving models of slip on faults, ones that incorporate realistic geometries, internal yielding and localization as displacement accrues.

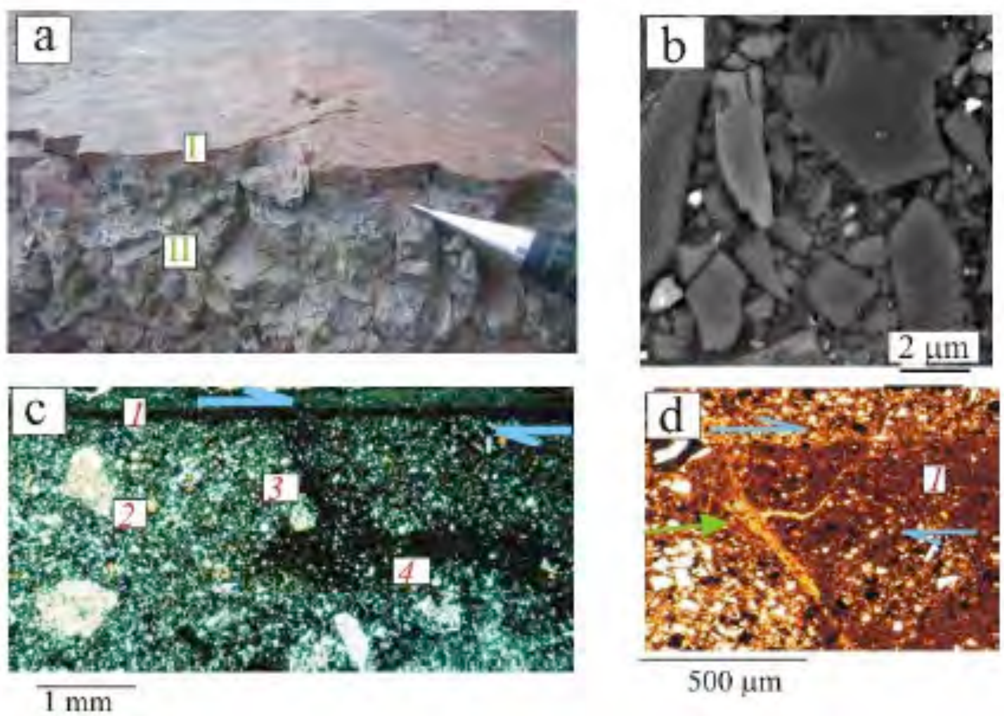

Figure 20. from Sagy et al. (2008)

To understand how frictional resistance on faults changes during earthquakes, Tullis et al. (2007) have continued their laboratory efforts to understand dynamic weakening mechanisms. Theory (e.g., *Rice*, 1999; 2006; *Beeler et al*., 2008) indicates that the weakening velocity at the onset of extreme weakening due to flash heating varies inversely with contact size. It follows that an increase in fault surface roughness, and therefore contact size, should yield predictable decreases in the weakening velocity. To test the theoretical predictions this group conducted experiments on samples with an expanded range of initial surface roughness and noted unexpected results - samples of comparatively large initial surface roughness do not demonstrate dramatic weakening as was observed previously for smoother samples. The difference likely reflects the development and subsequent distributed shearing of a relatively thick gouge layer. The results emphasize the critical importance of slip localization and asperity contact size for determining whether flash heating occurs in nature.

Over the past two years there has been considerable debate as to whether the particle size distributions determined through automated methods represent true particle size populations. Significant progress has been made over the past year exploring techniques to analyze particle size distributions, surface area and pore volume of nano-powders sheared in the laboratory (Reches et al., 2007), and of natural fault cores and crushed breccias found in the pulverized zones bounding surface traces of the San Andreas fault (Rockwell et al., 2007; Sisk, 2007; Sisk et al., 2007). Sisk (2007) and Sisk et. al (2007) analyzed a new suite of samples at Tejon Pass from the same locality studied previously by Wilson et al. (2005) and found that the average particle size of the pulverized granite is much coarser than previously reported; the discrepancy being attributed to a standardized Gaussian distribution assumption employed by the laser diffraction particle analyzer, and the extended spinning time applied in the previous study. It was found that coarser size fractions were deposited during lower spin velocities rather then disaggregating (Rockwell et al. 2007). Exploring various dispersion methods to disintegrate manufactured nano-powders Reches et al. (2007) report that degassing at low temperatures followed by the addition of a dispersing agent may be the most effective method for disaggregating fine-grain clusters. One critical question not addressed by these studies, however, is the role and size of grain clusters during slip and granular flow in a single earthquake event.

Field studies of pulverization along the surface traces of the San Andreas Fault (Dor et al, 2006a, b, 2007, 2008) and a jointly funded 2006 SCEC-DOSECC workshop on pulverization (Evans et al. 2006; Chester et al., 2006) sparked new laboratory and field studies in 2007 directed at understanding the origin of pulverized rock and its relation to the dynamic slip process. Prakash et al. (2007) conducted dynamic compression tests under controlled stress-wave loading conditions using a Split Hopkinson pressure bar apparatus to better understand how peak stress and fragmentation of granite varies with depth. Focusing on spatial relations between pulverization and fault geometry in the field led Rockwell et al. (2007) to conclude that the most extensive pulverization along the San Jacinto Fault is associated with the primary long-term fault trace and not the structural double-restraining bend, suggesting that the pulverization reflects dynamic slip rather than geometric stress perturbations. Shallow drilling and coring the pulverized zone adjacent to the San Andreas fault at Little Rock constitutes the first borehole sampling effort directed at charactering the mesoscale and microscale structure and mechanisms of pulverization, and the role of weathering in the near surface meteoric zone to the breakdown of fractured rock during interseismic periods.

2007 FARM successes derived from computational efforts included discoveries about earthquake friction and earthquake rupture dynamics. PI's Day with researcher Dalguer, PI Beroza with postdoc Ma, PI Rice with researchers Dunham and Dmowska, and PI Day with postdoc Duan all investigated the effect on rupture propagation of non-uniform materials surrounding a fault. All found that having either inelastic off-fault materials, or even elastic off-fault non-uniform materials, significantly affects dynamic earthquake rupture propagation compared to simulations of earthquake rupture in a homogeneous elastic medium. This is important information for future attempts at simulations of large earthquakes. Off-fault deformation is found to intricately link to on-fault deformation and the off-fault deformation not only serves as an energy sink, but may also significantly limit the peak ground motions experienced in the surrounding region. This finding has implications for estimates of peak ground motion and shows that values derived from simple elastic models of the earth's crust may not be sufficient.

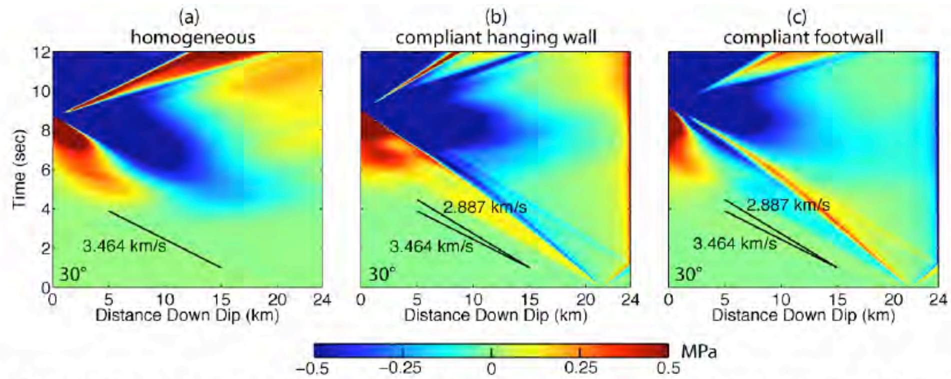

Figure 21. Space-time plot of normal stress change on a 30° reverse fault for (a) homogeneous elastic media; (b) compliant hanging wall; (c) compliant foot wall. Hypocenter is at 21.5 km downdip. Colorscale is saturated to illustrate features better. Effects of the free surface and material contrast reinforce each other in (b) leading to a much larger normal stress change near the surface compared to the homogeneous case. The two effects act to counteract one another in (c) giving rise to a smaller normal stress change. Black lines show the slopes of *S*-wave velocities of the materials.

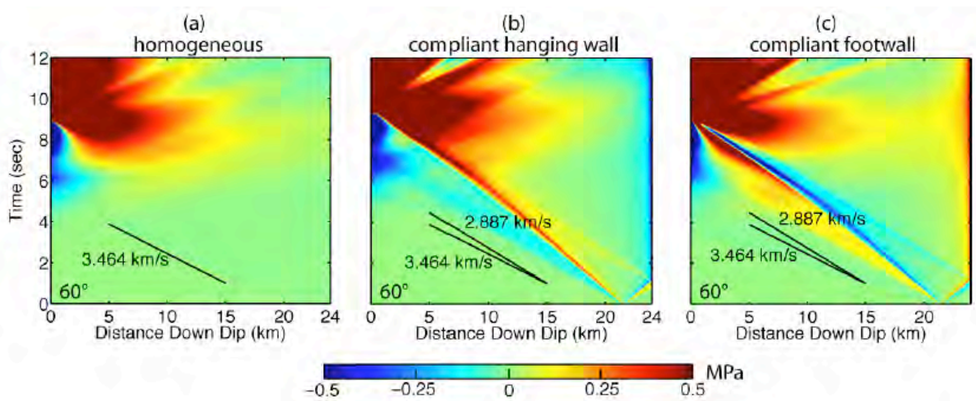

Figure 22. Space-time plot of normal stress change on a 60° normal fault for (a) homogeneous elastic media; (b) compliant hanging wall; (c) compliant foot wall. Hypocenter is at 21.5 km downdip. Colorscale is saturated to illustrate features better. Effects of the free surface and material contrast reinforce each other in (b) leading to a much larger normal stress change near the surface compared to the homogeneous case. The two effects act to counteract one another in (c) giving rise to a smaller normal stress change. Black lines show the slopes of *S*-wave velocities of the materials.

The bi-material problem was tackled by several researchers in 2007, with the work of researcher Dunham showing the effects of poro-elastic material contrasts and work of postdoc Ma demonstrating the elastic-contrast effects for dynamic rupture on a dipping fault. Ma and Beroza (2008) showed that the addition of material complexity to the dip-slip rupture scenario shows yet another complexity that should be considered when producing predictions about future large earthquake behavior (Figure 21,22).

One of the biggest questions for fault and rupture mechanics studies is the mechanism or mechanisms that operate during coseismic rupture. Seismograms collected in the field to date do not produce enough evidence to discriminate among the many proposed mechanisms for coseismic rupture. Therefore experiments in the laboratory, numerical simulations, and, most importantly, more field studies, including geologic studies, are critical for unraveling this problem. PI Goldsby and colleagues used laboratory experiments, PI Carlson with student Daub used numerical simulations based on micro-physics theory and lab experiments, and PI Segall used numerical simulations to tackle this subject. PI Archuleta, with student Schmedes and researchers Campillo and Lavallee investigated how one form of coseismic friction, slip-weakening friction, may appear in the presence of stress heterogeneity, and derived from this a macroscopic friction formulation. This macroscopic view is what is inferred from seismological data, at least with the currently available sets of strong ground motion observations (Figure 23).

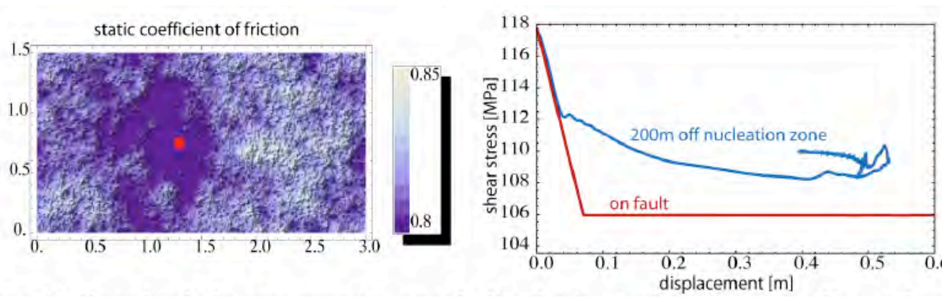

Figure 23. Complete heterogeneous strength distribution and the resulting slip-weakening curve that is 200 m off the fault directly opposite the nucleation zone (red dot).

As more researchers use computer simulations to test ideas about earthquake rupture processes, it becomes critical to make sure that the codes are working properly. This is the purpose of the SCEC 3D Dynamic Rupture Code Validation exercise. In previous years this group has concentrated on 3D spontaneous rupture simulations that use a slip-weakening framework, but using 2007 workshop funds in early 2008, this group held a workshop that discussed the results of benchmarks that also adopted rate-state friction. The few codes that ran the rate-state benchmark were consistent with each other. This is important because most multi-cycle earthquake simulations, including those residing in FARM, the Earthquake Prediction and Forecasting, and WGCEP groups will in the future, if they are physics-based, probably use rate-state formulations. The code validation group also continued its efforts using slip-weakening, performing the last vertical strike-slip benchmarks before venturing into the 2008 assignments of dip-slip faulting on dipping faults. This group of 20 researchers is providing a platform for international testing of spontaneous rupture codes, and a means for both SCEC and non-SCEC researchers to determine which codes they might want to use in their own research projects. The website *http://scecdata.usc.edu/cvws/* is the entrance to the online SCEC code validation effort and presents the benchmarks, the participants, descriptions of the codes, and the comparison tools.

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3. Crustal Deformation Modeling

The SCEC Crustal Deformation Modeling (CDM) group models deformation occurring within the earthquake cycle, at time scales linking dynamic rupture (minutes) to thousands of years. We also use models to study the relationship between interseismic deformation (and geodetically-determined fault slip rates) and longer-term, secular deformation (and geologically-determined fault slip rates). In general, CFEM group models fall into four categories: (1) earthquake simulators, which generate seismicity in accordance with stress evolution and fault friction, (2) kinematic models, which provide estimates of long-term or interseismic slip rates on active faults, (3) dynamic models addressing the physics of fault zone creep and lithosphere deformation throughout the earthquake cycle, and (4) dynamic models of long-term regional deformation which do not explicitly represent faults as surfaces. Models of type (4) are also developed by the Lithosphere Architecture and Dynamics (LADS) group, and the Earthquake Forecasting and Predictability (EFP) group develops models of type (1). The ultimate goal of CDM group research is to understand spatial and temporal variations of stresses in the southern California crust, so this information can be incorporated into time-dependent, physics-based probabilistic seismic hazard assessments.

In the 2007 RFP, the CDM group sought to emphasize models based on SCEC USR data products (the community seismic velocity model CVM-H; and the community fault models, CFM and CFM-R). We also sought studies assessing the level of detail required to adequately model stress evolution in the southern California crust, given available surface deformation and geophysical data. Below, a few examples of CDM projects in each category are highlighted, followed by a brief description of other CDM group research activities.

a. Incorporating the SCEC CFM and CVM into fault system models

Several PI's have begun to revise their fault system models to make use of the SCEC CFM, the CFM-R, and the CVM. These include the developers of finite-element models of long-term deformation (Peter Bird) and coseismic and interseismic deformation (Brad Hager, Carl Gable, and Charles Williams). Michele Cooke has incorporated the SCEC CFM geometry in elastic boundary element models of interseismic deformation for several years. In 2007, her group's research focused on modeling the SAFZ in the San Gorgonio Pass region to select a preferred configuration of faults at depth from several possibilities, given rates of uplift and fault slip.Representing geometrically complicated dipping faults, and their intersections, has long presented a special challenge to finite-element modelers. Unlike earthquake simulators and boundary-element models, finite-element (FE) models require the meshing of volumes bounded by fault surfaces, rather than just the fault surfaces. This is a nasty problem, which is not generally faced by mechanical engineering community, so few tools are available to address it. In the past, the small community of FE modelers who have attempted to model three-dimensional fault networks in southern California have developed meshes from the SCEC community block model (CBM). The idea was that each block could be meshed individually, and that the surfaces of the meshed blocks would be linked with special "contact" elements, representing faults. This approach has been plagued with difficulties, principally because of gaps and overlaps of the meshed (discretized) versions of the blocks. In 2007, Brad Hager, Carl Gable, and Jiangning Lu cut this Gordian knot by using the CFM, rather than the CBM, as the basis for mesh design. In this approach, the modeled faults do not link up, and fault intersections need not fall exactly along element edges. In areas where faults should intersect, a distributed zone of soft elements takes up the strain. Figure 24 illustrates part of a mesh developed using the new method.

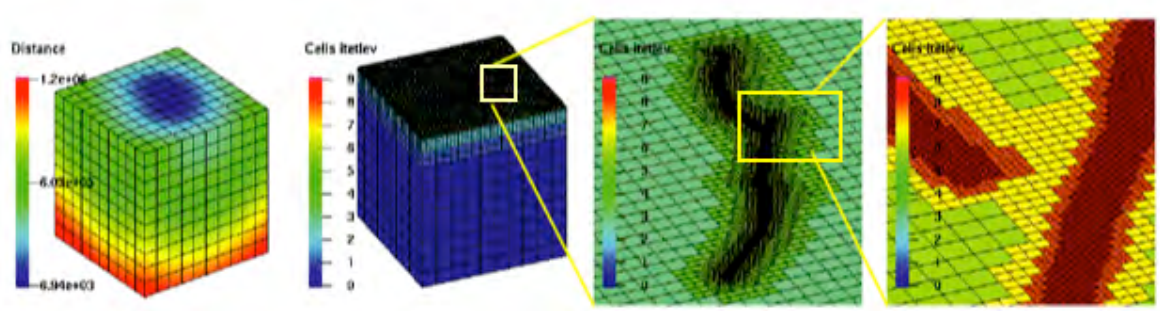

Figure 24. A new approach for meshing geometrically complex, intersecting faults. Fault intersections do not have to fall along specific element edges, but are modeled with a zone of compliant elements.

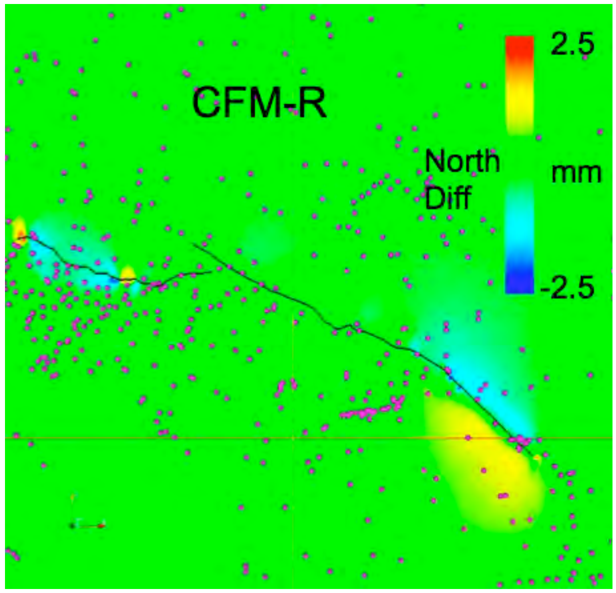

Figure 25. This figure shows the difference between surface displacements modeled with elastic structure based on the SCEC CVM-H, and those computed assuming a uniform Poissonian elastic material. For both models, fault surfaces are based on the CFM-R. The faults in this study include a portion of the southern San Andreas fault, the Sierra Madre fault, and the Cucamonga fault. The red dots indicate GPS stations.

The new meshing approach is being tested by comparing results of elastically uniform models to the results of a reference, elastic block model. The modeled region includes a portion of the southern San Andreas fault, the Sierra Madre fault, and the Cucamonga fault (Figure 25). A preliminary comparison suggests overall agreement, but local discrepancies arise, likely due to small differences in fault geometry (the BEMs used in the comparison were not strictly based on either SCEC CFM). New results for models incorporating both versions of the CFM (CFM and CFM-R), as well as CVM-H, illustrate that at least locally, variations in fault dip at depth can measurably affect surface deformation. Preliminary results also illustrate the effect of incorporating elasticity based on the CVM, rather than assuming uniform elasticity (Figure 25).

These results represent a significant advance in developing realistic FE models of stress transfer among the faults in the CFM. Adding more faults and viscoelastic simulations are far smaller technical challenges than dealing with the meshing issues.

b. Sensitivity of deformation model results to heterogeneous material properties

Several studies address the effect of heterogeneous physical properties on modeled deformation and seismicity. These include an earthquake simulator model of part of the SAF (Terry Tullis), finite-element models of damage evolution and elasticity heterogeneity in the Mojave (Elizabeth Hearn, Yehuda Ben Zion), and finite-element models of long-term deformation in southern California (Thorsten Becker). Terry Tullis' earthquake simulator makes use of innovative numerical techniques to vastly extend the size range of earthquakes he can model, with individual fault patch dimensions as small as 7 meters. The sensitivity of modeled seismicity along the Parkfield section of the SAF to spatial variations in parameters such as a, a-b, and Dc for one form of the rate and state friction evolution equations may be explored, as well as the effect of using different friction evolution laws (e.g., the slip law or the slowness law). Other findings of this modeling (e.g. accelerated seismicity prior to a M 2.2, repeating "mainshock", and detailed images of interseismic slip evolution on the 100-meter-wide mainshock patch) fall under the purview of the FARM and EFP group.

Hearn's research (with student Yaron Finzi) relates to both the formation of fault systems in crust with a damage-controlled rheology, and the coseismic deformation of permanent, shallow damage zones. The fault evolution modeling suggests ~1-2 km-wide damage zones imaged with InSAR extend down to about 5 km or less (except at releasing stepovers, where they penetrate the upper crust) and that their elastic properties evolve only modestly between earthquakes. Finite-element modeling of the coseismic strain of these zones suggests that they do not contract as expected in response to body forces when they soften coseismically. Together, these conclusions suggest that shallow compliant zones do not influence crustal deformation significantly, except locally, and that in system-wide stress transfer models they may be represented with permanently soft material. Below a depth of a few kilometers, compliant fault zones narrow to the point where they may be modeled as contact surfaces using rate-and-state friction. Thus, a full implementation of damage rheology and time-dependent effective shear modulus is probably not required for the purposes of the CDM. More work is required to confirm these conclusions because the dimensions and elastic properties of compliant zones appear to vary substantially.

Dynamic models of long-term, steady state deformation are being developed (by Thorsten Becker, Gene Humphreys, and Noah Fay) to address forces driving southern California deformation, the long-term fault strength (in terms of yield stress), and the effect of regional-scale heterogeneities and mantle tractions on crustal stress. This modeling suggests that to fit GPS data, fault strength must decrease toward the west (e.g., the Indio fault is weaker than the San Jacincto and Elsinore faults). It also highlights how fault interactions, curved fault geometry, and variations in fault strength result in complicated patterns of stresses. Figure 26 shows modeled crustal stresses resulting from slip on a set of smoothed, vertical faults comprising part of the SAFZ in an uniform, elastic-plastic southern California. The faults are actually represented as narrow zones of material with low but spatially variable yield strength, and their "slip" is driven by Pacific-North America relative plate motion. Even given these dramatic simplifications, the resulting stress pattern is fairly complicated.

This result reinforces what the Hager group's otherwise identical elastic models based on the CFM and CFM-R show: that modeled surface velocities (and presumably, stresses) are sensitive to variations in the geometry of the modeled faults. Taken together, these projects show that we need to remain as focused on properly representing fault geometry as we are on incorporating heterogeneous (and sometimes evolving) rheologies. Models incorporating the CFM and the CFM-R are a step in the right direction.

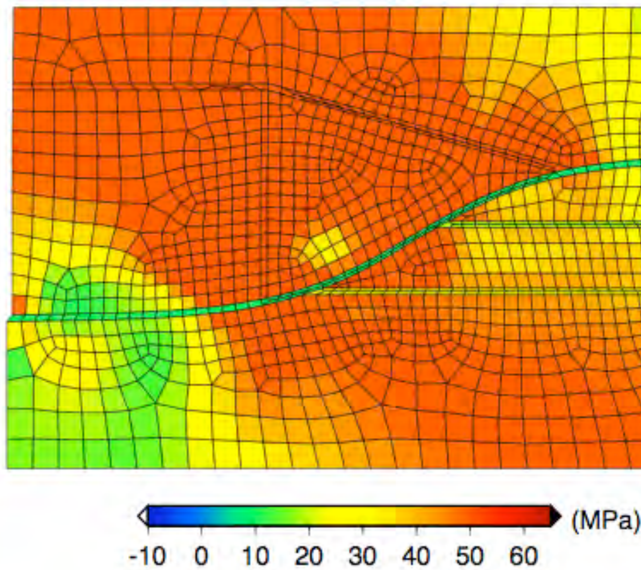

Figure 26. Square root of the second invariant of the deviatoric stress tensor (to provide a scalar measure of the deviatoric stress). The spatially varying fault strength, geometry of the SAF, and interaction of the Elsinore and San Jacincto faults with the SAF/Indio fault result in a complicated stress field.

c. Workshops and interdisciplinary CDM research

The CDM group continues to partner with the NSF and the Computational Infrastructure for Geodynamics (CIG) to sponsor the annual Community Finite-Element Modeling (CFEM) workshop at the Colorado School of Mines in Golden, Colorado. This workshop includes tutorial sessions for meshing and FE modeling codes, as well as opportunities for benchmarking and presentations on topics such as laboratory constraints for appropriate lithosphere and fault zone rheologies. Attendees have found this meeting an indispensable venue for meeting other modelers to solve meshing and other FEM-related problems informally (and quickly!). SCEC also requested that developers of earthquake simulators meet to compare computational results for simple test models, and to share their expertise, at an annual workshop. The first of these workshops was held in November of 2007, with a follow-up meeting in June of 2008.

Other projects under the CDM purview tie in closely to the research goals of the Lithosphere Architecture and Dynamics (LADS), Earthquake Forecasting and Predictability (EFP), and other groups. Examples of these projects include using the results of finite-element stress evolution models to test the accelerating moment release (AMR) seismicity forecasting hypothesis (Roland Burgmann and Andrew Freed), and developing a lithosphere-scale model representing structure and elastic properties of the southern California lithosphere (Paul Davis and Rob Clayton). A detailed study of surface wave and SKS anisotropy (Toshiro Tamimoto and Paul Davis) has identified the locus of strong, shallow mantle anisotropy to just below and west of the SAF, and has determined that a deeper mantle layer with anisotropy consistent with broader-scale mantle flow is also present. The shallower anisotropy suggests localized plate boundary strain below the Moho, and stresses large enough to maintain dislocation creep at this depth interval. This information may lead to constraints on spatial variations in mantle rheology, which could play a role in stress transfer among southern California faults over interseismic time periods.

4. Lithospheric Architecture and Dynamics

The LAD group held a workshop at UCLA March 5-6 2008, with the objective: ‘To review our understanding of the geologic provenance, current structure, and physical state of the southern California Lithosphere and how these relate to absolute stress, it’s evolution and the generation of earthquakes.’ The program is attached as appendix A.

Gene Humphreys has presented the first P-wave tomographic maps (Figure 28) using finite waveform (banana doughnut) kernels. Figure 29 shows an independent surface wave tomogram.

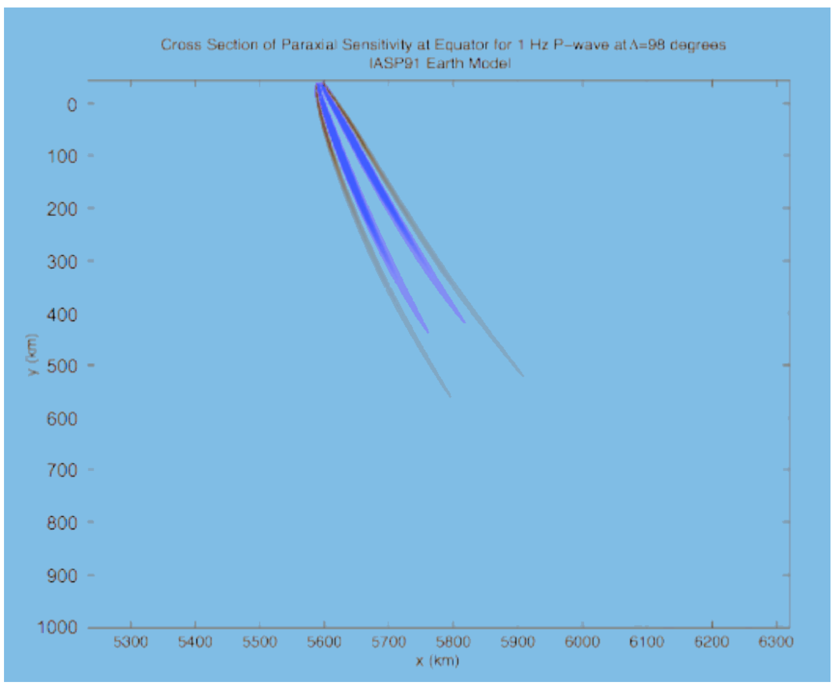

Figure 27. Banana doughnut kernel for 1Hz teleseismic P waves used to construct tomogram in Figure 28.

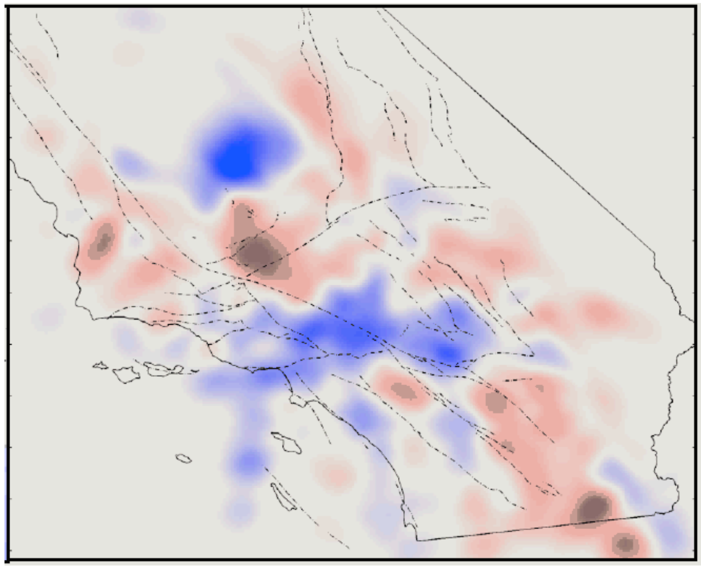

Figure 28. Tomographic inversion for southern California structure at 100 km depth, using 20-km node spacing, and ~20,000 rays to 210 stations using finite-frequency sensitivity kernels, nodes, rays traced in a 3-D Earth.

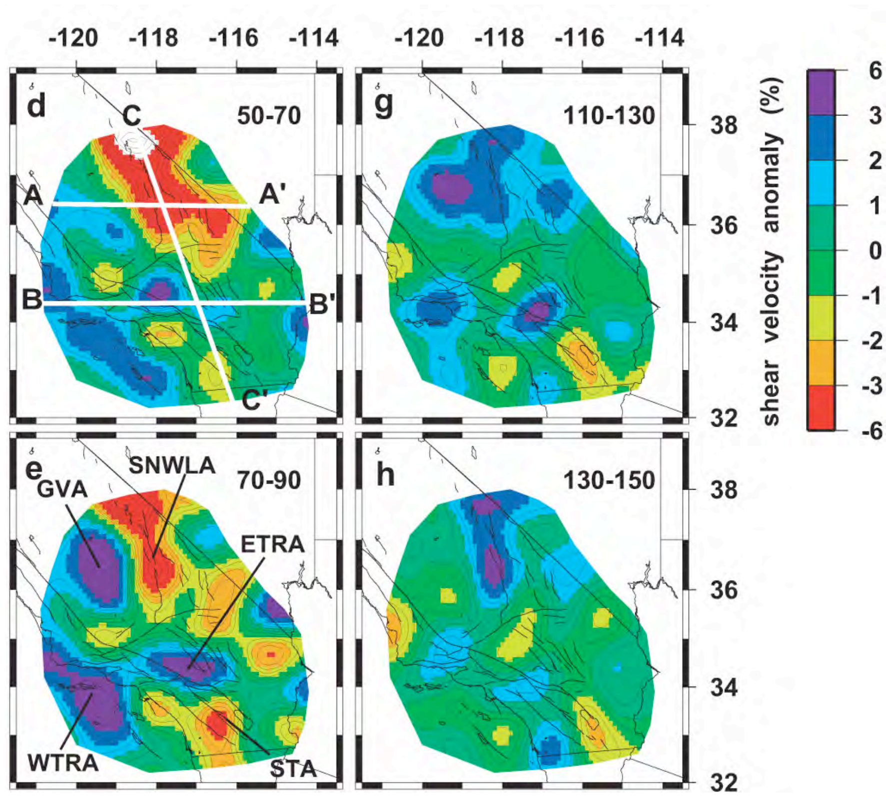

Figure 29. Surface wave tomography southern California (Yang and Forsyth, 2006). WTRA and ETRA are west and east Transverse Ranges anomalies, STA Salton Trough, SNWLA Sierra Nevada Walker lane, GVA Great valley. Figure 29e and 29f compare reasonably well with Figure 28.

Figures 28 and 29e-g show that the major features in the upper mantle are recognized by both surface wave and body wave tomography, which improves confidence in depth resolution, since these two methods are based on near-vertical and horizontal ray paths respectively.

a. SKS splitting and Surface Wave Anisotropy

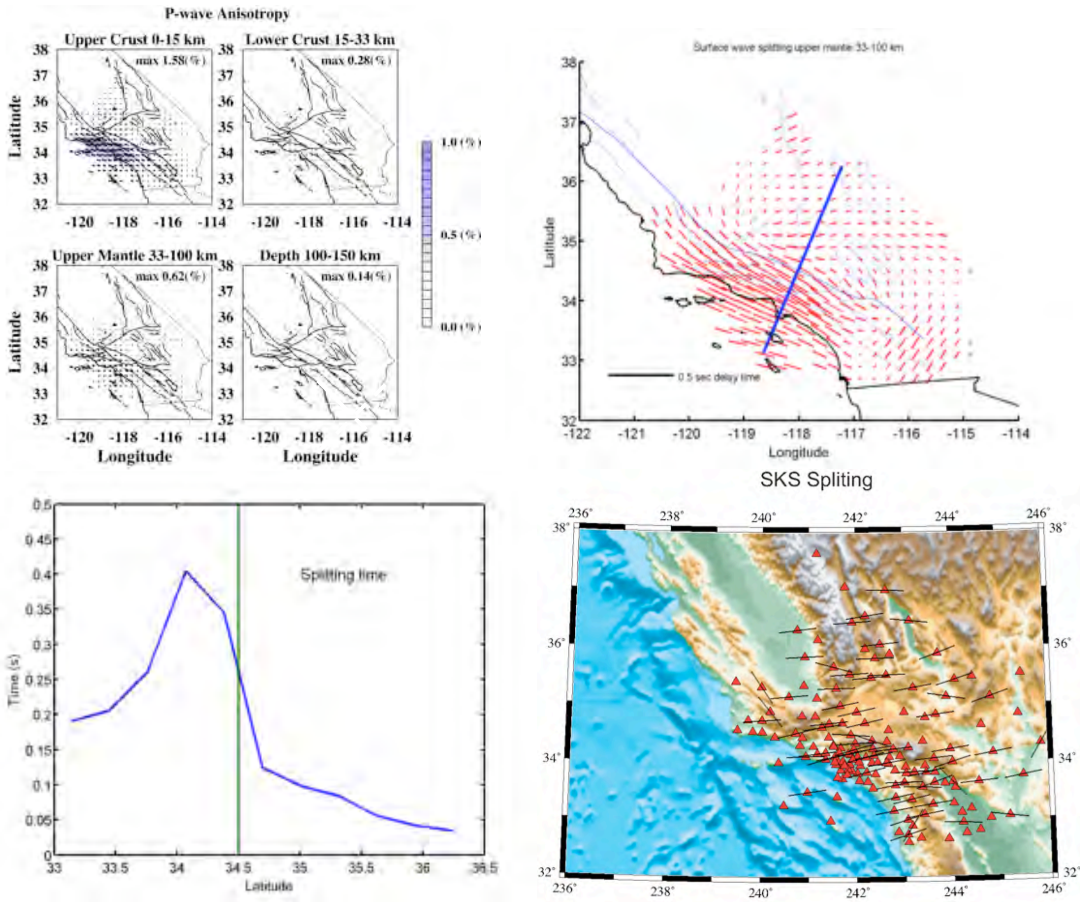

Figure 30. Upper left panel shows azimuthal anisotropy from surface waves, upper right and lower left panels show predicted splitting based on surface wave measurements. Average is about 0.2 sec and near the Big Bend is parallel to the SAF. Lower right panel shows Latest splitting measurements average over 1 second and are E-W suggesting splitting is generated deeper than 100 km.

Recent surface wave analysis (Figure 30) south of the big bend indicates that the anisotropy in the mantle-lithosphere is closely aligned with the San Andreas fault, but is a factor of 5 less strong than that required to explain splitting. This suggests that the transpression associated with the big bend has, indeed, oriented olivines in the mantle, but that the large signal from SKS splitting presumably comes from deeper mantle flow. Anisotropic structure derived from surface waves clearly cannot explain SKS splitting data. South of the San Andreas fault SKS splitting is oriented east-west with over 1 sec delay. The surface waves have split times of <0.4 secs (average 0.2 s) and are oriented WNW. Since SKS waves are sensitive to deeper parts of upper mantle, probably down to 300-400 km (Becker et al., 2006), there is a strong possibility that the fast-axes patterns in SKS data are dominated by deeper flow patterns that are not included in the surface wave results.

b. Lithospheric Dynamics

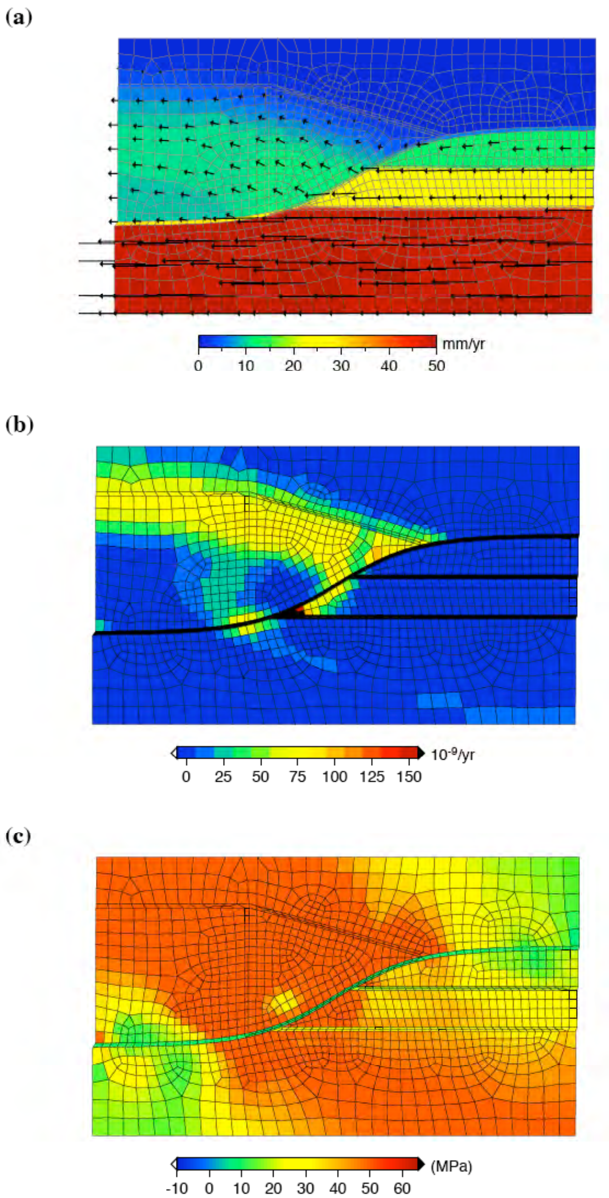

Figure 31. (Velocity (in mm/yr), relative to North America, color gives magnitude, interpolated from nodes to element faces. The step in velocity across the simplified SAF Indio, SJF, and ELS faults toward the right (East) of the model indicates the slip rate of those faults.

(b) Square root of the second (shear) invariant of the deviatoric strain-rate tensor showing distributed off-fault deformation to the NE (in the Eastern California Shear Zone region, where geographic North points to the upper left corner) of the main SAF fault strand. Note the other off-fault strain rate zone (*cf.* Figure 1a) is diminished in this model that more closely resembles the southern California fault system.

(c) Square root of the second invariant of the deviatoric stress tensor. The spatially varying fault strength, geometry of the SAF, and interaction of the ELS and SJF with the SAF Indio result in a complex stress field that can vary both across faults and along-strike (*cf.* Bailey *et al.*, 2008).

Thorsten Becker and Gene Humphreys presented preliminary results from their project to understand how faults in southern California are loaded over long-term, multi-cycle timescales. They are modeling how crustal stress arises due to plate boundary mechanics, as well as topographic and mantle flow loading in the presence of geological heterogeneity. Figure 31 shows results for a model that incorporates a weak (relative to the bulk crust) SAF Indio (10 MPa), a stronger SJF (20 MPa), and an even stronger ELS fault (30 MPa). If strength variations of faults in an otherwise homogeneous crust are the only control on the slip rate distributions, this model illustrates the need for fault strength to decrease further inland in order for fault slip to distribute closer to observations, namely the slip rate of the SAF Indio > SJF > ELS.

In an independent study, Noah Fay, was able to show that the geodetic dilation field in southern California may also be associated with the tractions that are induced by mantle flow as driven by sub-Moho density anomalies. The latter were inferred from seismic tomography, and regions of crustal thinning and thickening overly regions where extensional and compressive stresses, respectively, are exerted by mantle tractions. Figures 32a,b show the dilatational strain rate from the SCEC GPS velocity model compared with crustal dilatation from the finite element model showing appreciable correlation.

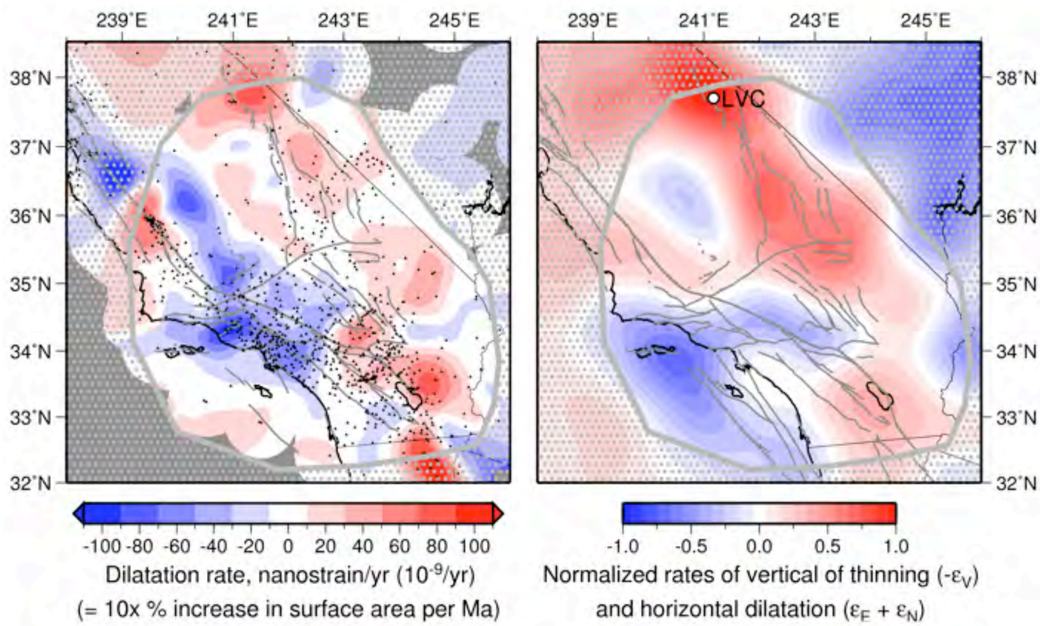

Figure 32. (Fay et al., 2008 in revision G^3) 3D Modeling: Using mantle $\rho(x,y,z)$ to constrain crust $\sigma(x,y,z)$.

c. Topography on the Moho and the Rheology of the Lower Crust and Uppermost Mantle From Receiver Functions

There is no recognized seismic signature of the major strike-slip faults in the lower crust, which has been one of the arguments for a weak lower crust. If there is some vertical motion associated with the strike slip motion, this might cause some topography on the Moho [Yan and Clayton, 2007b].

Yan and Clayton [2007a, 2007b] shows that receiver functions for individual stations in the SCSN can also show dramatic topography on the Moho. The technique used in this study was to sort the receiver functions at a station into azimuthal groups before they are stacked. The variations among azimuth groups can then be used to determine the variation in depth of the Moho, which were found to be significant. Moho offsets have been found under several faults. An example under the San Andreas is shown in Figure 33.

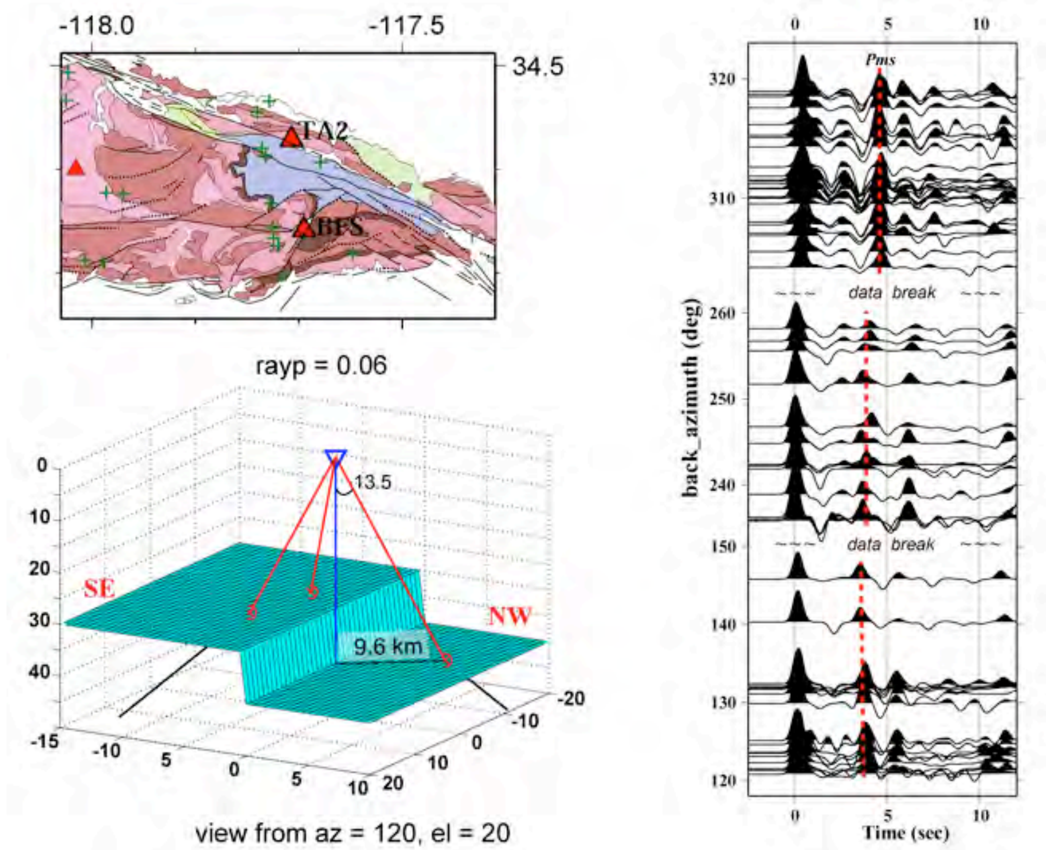

Figure 33. PmS Moho conversions of P waves to S waves provide evidence for a step (bottom right) in the Moho beneath the SCSN station TA2 on the San Andreas Fault (top right), From Yan and Clayton [2007].

d. Full Waveform Tomography

Po Chen and colleagues propose to continue development of the Scattering-Integral (SI) method for full-3D waveform tomography and rapid seismic source parameter inversion, and to extend their study area from the Los Angeles region to 150 stations in Southern California (over 600 km × 300 km × 80 km). They have completed a pilot study in the Los Angeles area (142 km × 84 km × 26 km). This proposal would extend the approach to the TeraShake V3 model volume (600 km × 300 km × 80 km). In addition they will increase the frequencies covered to 1Hz. This has been one of the core SCEC initiatives and its continued success will be one of the highlights of SCEC3. They will use the point force Green's functions to calculate CMTs and for larger events FMTs. They have selected 650 earthquakes at up to 150 stations for the inversion. For larger events will explore the calculation of 3D sensitivity kernels due to a finite rupture model by superposing point forces. They will also vary Q and Moho depths. Validation will be done by comparing waveforms from independent events not used in inversions. They use CVM 4 as the starting model. They are transfer ring to the CVM-H (Harvard) velocity model.

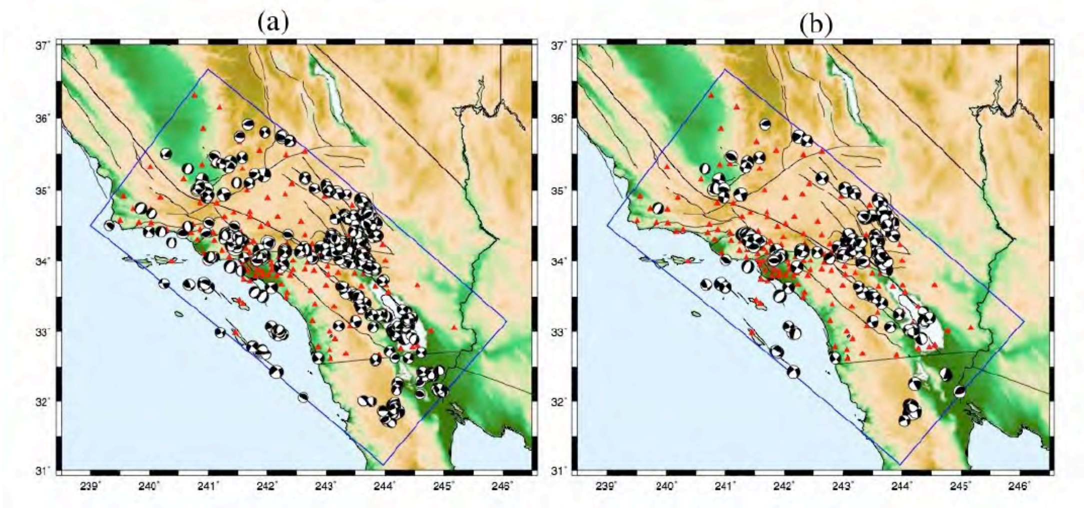

Figure 34. (a) Distribution of the selected 529 earthquakes, shown as beachballs, with local magnitude larger than 4.0. The focal mechanisms were determined by Egill Hauksson from first-motion data. (b) Distribution of the 200 earthquakes selected from the 529 earthquakes in (a) for a new F3DT study.

They use the staggered-grid finite-difference code to calculate the source wave fields **(SWF)** and receiver Green tensors (**RGT**) and associated sensitivity kernels (**K**). Seismograms are decomposed into generalized seismological data functionals (**GSDF**) that depend mainly on amplitudes and travel times of selected phases. Then the model (**m)** and source (**s**) are perturbed based on the Jacobian of the synthetics.

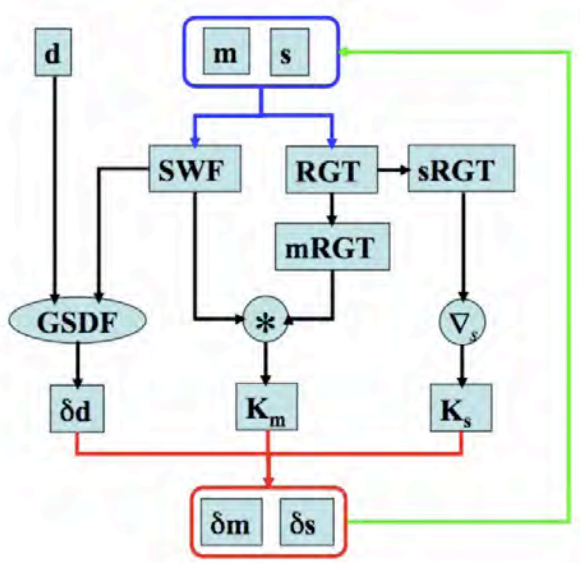

Figure 35. Schematic overview of the F3DT workflow. The meanings of all the symbols are explained in the text.

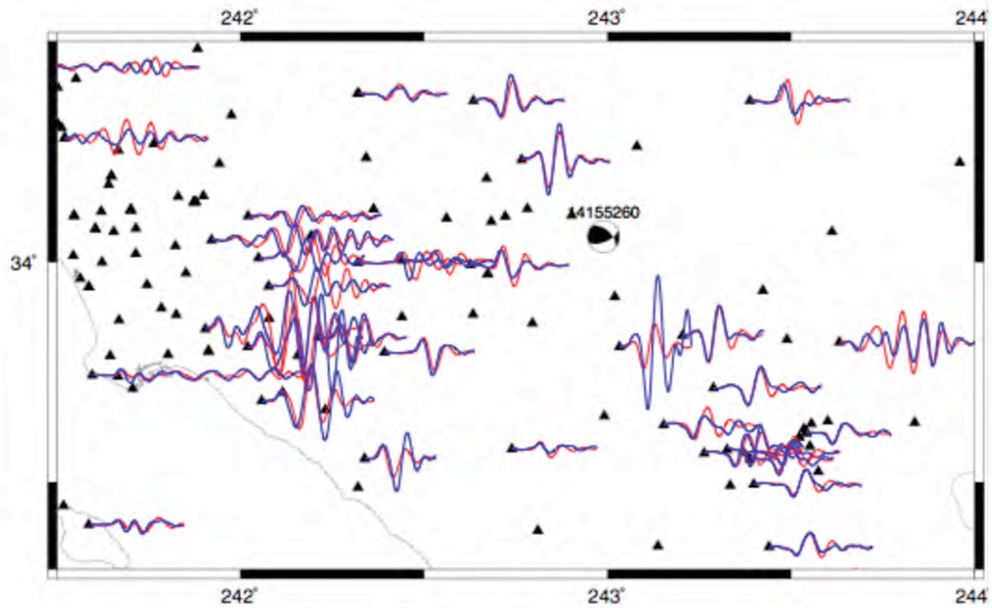

Figure 36. Comparison of the transverse-component synthetic (red) and observed waveforms for the Yucaipa event at selected stations around the Los Angeles basin area. The focal mechanism is plotted at the epicenter. The seismic velocity model used for computing the synthetics is the SCEC CVM4.0. All seismograms have been low-passed to 0.2 Hz.

5. Earthquake Forecasting and Predictability

The Earthquake Forecasting and Predictability (EFP) focus group coordinates two types of research project. One encourages developing 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. The projects in the first category will be briefly listed, with the understanding that further descriptions of them may be included in this or future year's reports on CSEP.

Studies aimed at understanding short-term earthquake predictability of the Epidemic Type Aftershock Sequence (ETAS) type are underway. These include a study by Kagan, Zhuang, and Jackson, "Short-term earthquake forecasting in California," and one by Zhuang, Kagan, Otaga, and Jackson, "Statistical modeling of seismic moment release in SAF system." Another study that forms the basis for a method that can be tested by CSEP is that of Shen and Zeng, "Improvement and earthquake predictability test of the Load/Unload Response Ratio method." 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 real test will come when this method is moved into the CSEP environment. Preliminary interesting results by Shen and Zeng are shown in Figure 37.

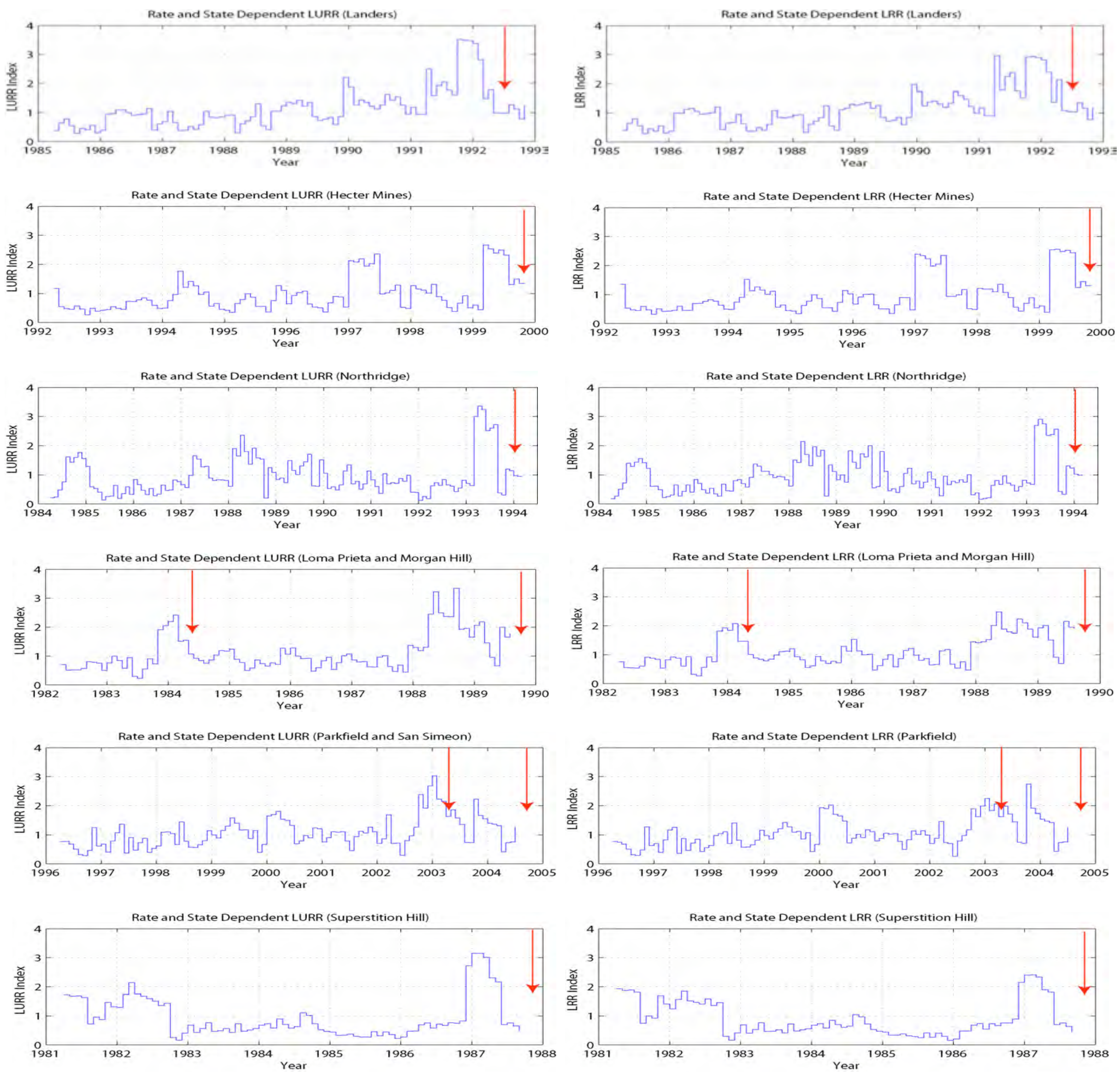

Figure 37. Load/Unload Response Ratio (LURR) on left and Load Response Ratio (LRR) for 8 California earthquakes. Earthquake times are shown by the arrows. LURR and LRR are different ways of portraying how microseismicity (Response) varies during the tidal-loading cycle (Load/Unload or Load/[Load + Unload]). LURR enlarges the portrayal of variations that occur during loading compared to those during unloading, so LRR is a more objective measure. LRR would go from 0 to 1, but here both LURR and LRR have been normalized by the standard deviation for each data set. The claim for this method is that the signal increases prior to major earthquakes.

A study by Zaliapin, "Short-term earthquake forecasting in California and Japan: a Comparison," looked into the question of whether, as has been claimed by several studies, there is a seismic moment deficiency in California, namely that the seismic moment release in California during the 20th century should have been twice as large as the observed in order to match the long-term strain rates determined by geodetic methods and tectonic models. The main conclusion is that the observed discrepancies between the observed and predicted seismic moment release in CA fit a moment release model based on power-law seismic moment distributions and do not justify an increased probability of an impending earthquake, nor support the claimed factor-of-two discrepancy between observed and expected seismicity moment release.

Several investigators have conducted research using Earthquake Simulators, 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.

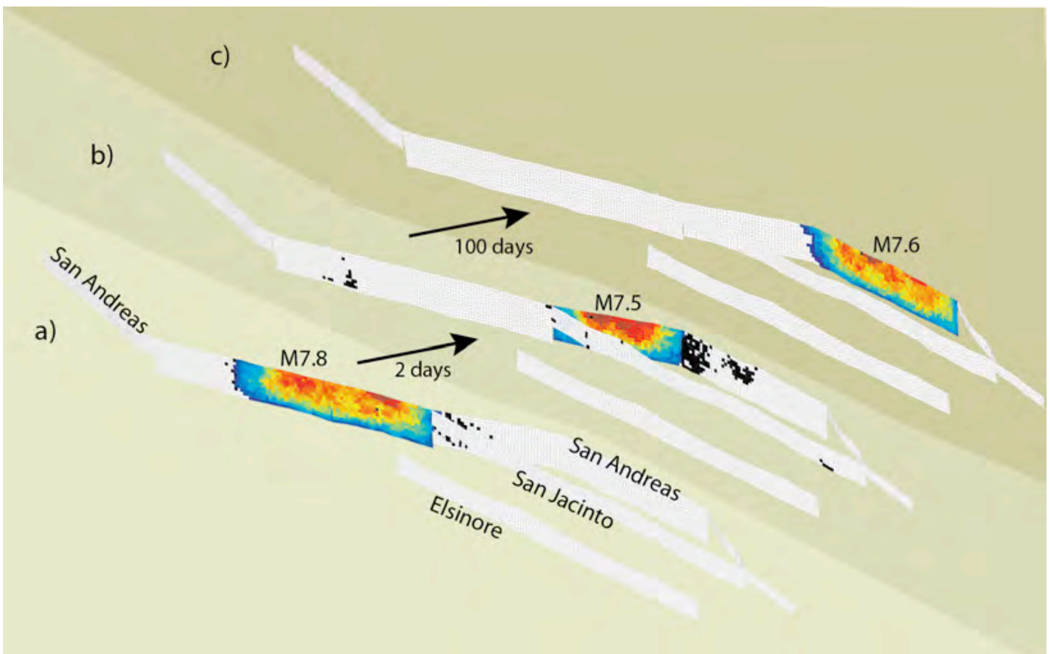

Figure 38. Fault slip in a cluster of large events from a simulation of the southern San Andreas fault system. In the cluster illustrated here, the Big Bend section of the San Andreas Fault broke in an M7.8 event (panel a) followed by an M7.5 on the San Bernardino section (panel b), and an M7.6 event on the Coachella section (panel c). The hypocenters of the large events are shown by a black square within the rupture area. There were 72 aftershocks in the 2-day interval between the M7.8 and M7.5 events and 183 aftershocks in the 100-day interval between the M7.5 and M7.6 events. The locations of these aftershocks are shown in black on panels a) and b), respectively (though many of those in panel a) are hidden behind the San Jacinto Fault).

One promising effort in computing simulated seismicity is the project by Dieterich, "Physics-based simulation of earthquake occurrence in fault systems." He has developed an efficient computational scheme that allows simulating long histories involving many earthquakes on multiple faults and at the same time is able to compute the quasi-dynamic behavior during individual events. The essence of the behavior represented by rate and state friction is approximated in the computations, so this represents the first effort that uses realistic laboratory-based friction to compute large earthquake catalogs. An illustration of a calculation done by this approach on a simplified fault system is shown in Figure 38.

Another earthquake simulation effort that is able to compute long histories of many earthquakes and also represent the behavior during individual events is the project of Ward, “ALLCAL -- An earthquake simulator for all of California.” His approach uses a simplified slip-weakening friction law rather than an approximation to rate and state friction. The ALLCAL-2007 simulator encompasses all 8000 km of the faults in California that slip faster than 1/4 mm/yr; these are represented by several thousand elements. The simulator generates dynamic ruptures from magnitude 8+ down to about magnitude 4, so a 2000 year run produces ~30,000 events. Figure 39 shows a complex Landers-type rupture that occurred spontaneously in the simulator, while Figure 40 shows the time history of slip on the for a 2000 year run on the northern San Jacinto Fault.

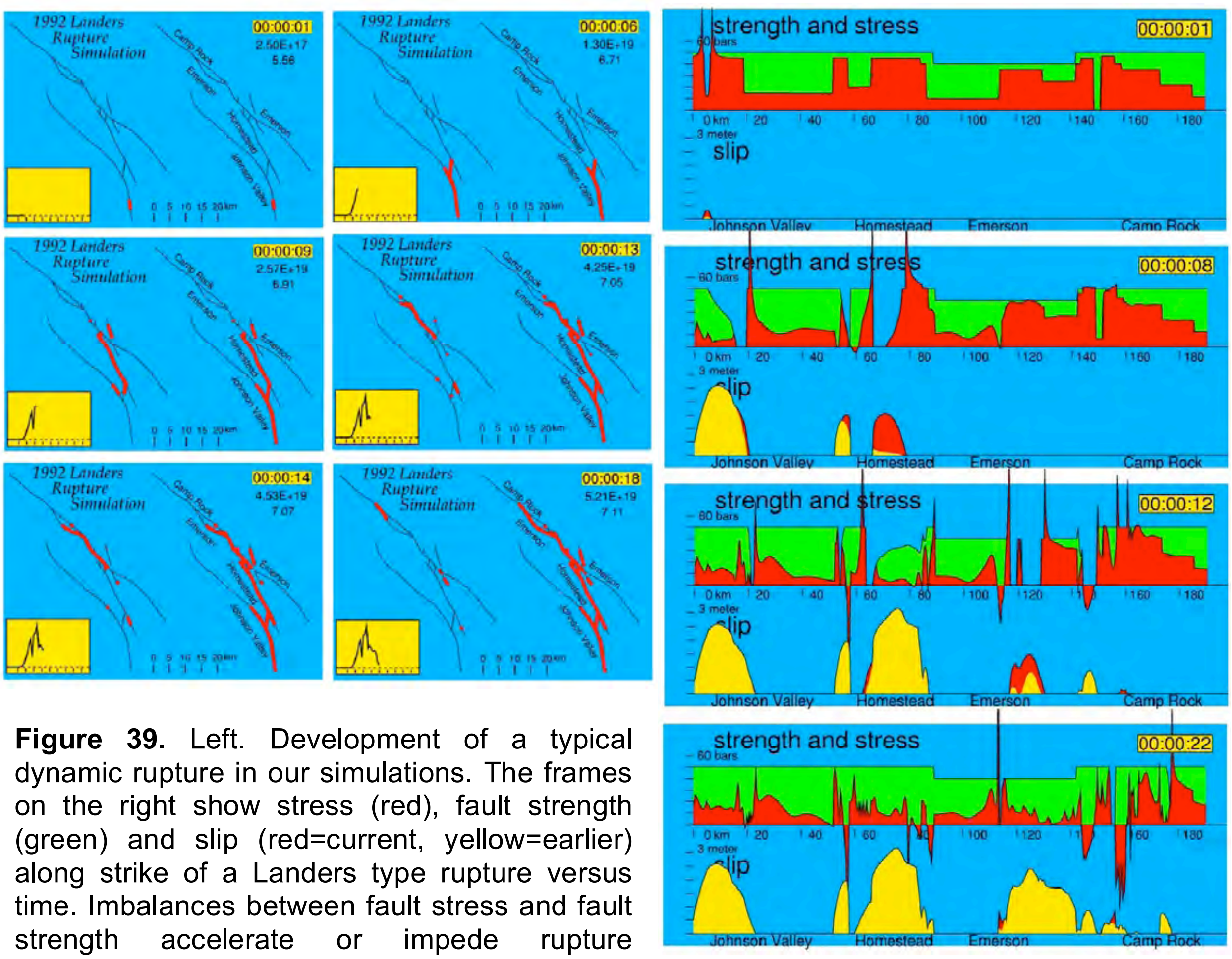

Figure 39. Left. Development of a typical dynamic rupture in our simulations. The frames on the right show stress (red), fault strength (green) and slip (red=current, yellow=earlier) along strike of a Landers type rupture versus time. Imbalances between fault stress and fault strength accelerate or impede rupture propagation and growth. Thousands of such events comprise a single run of the simulator. Movies can be seen at:

Another simulator effort that is aimed at understanding the interactions between earthquakes of a wide range of sizes is the project of Tullis and Beeler, "Quasi-dynamic parallel numerical modeling of earthquake interactions over a wide magnitude range using rate and state friction and Fast Multipoles." This work focuses on simulating earthquakes ranging from M1 to M6 at Parkfield, California, where a large observational database of real earthquakes exists for comparison with the space-time patterns of simulated earthquakes. Figure 41 shows the distribution of the constitutive parameters that should allow simulated seismicity to occur in spatial patterns similar to those at Parkfield, but with a temporal pattern that is determined by far-field loading and stress transfer between earthquakes.

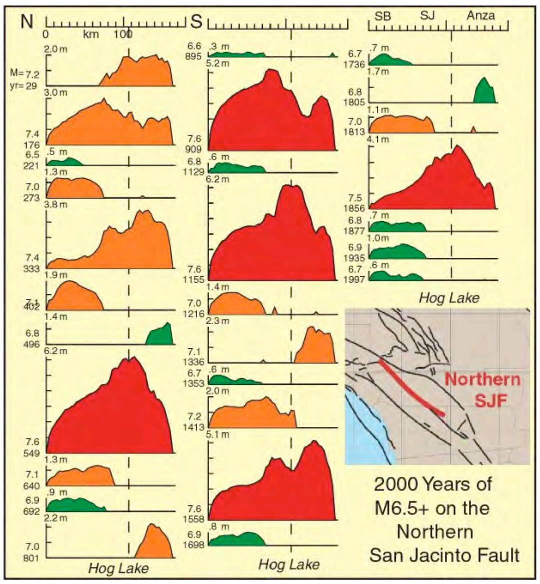

Figure 40. Slip map diagrams for the northern San Jacinto Fault (inset). These maps show the surface offset along strike for a 2000-year run of the simulator. The 22 earthquakes in the simulation over magnitude 6.5 are color-coded by magnitude, and their magnitudes, years of occurrence within the 2000 years of the simulation, and maximum slips are shown. Slip map predictions can be compared directly with field-measured paleoseismic data, such as Hog Lake site on the Anza segment (vertical dashed lines).

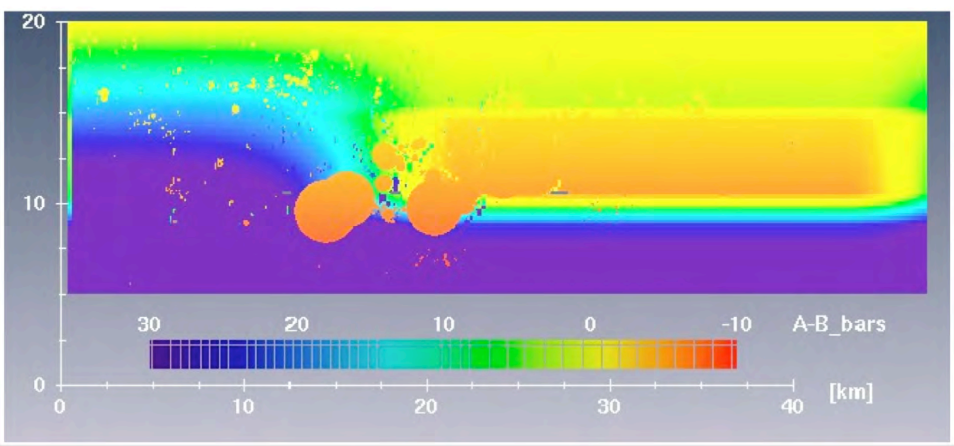

Figure 41. Cross section of San Andreas near Parkfield showing rate and state parameter A-B. The distribution of A-B is based on lab values of a-b, increasing normal stress with depth, increasing T with depth according to the Parkfield geotherm, and the distribution of relocated microseismicity (Jeanne Hardebeck, personal communication) and the M6 Parkfield earthquake. The horizontal axis increases to the SE and Middle Mountain is at ~ 20 km. The multiscale grid underlying the model, the details of which are based on microseismicity, has 1,464,433 elements, and in the areas where the microseismicity occurs the elements are 7.4 m in dimension and range up to 200m.

Figure 42 shows details of the temporal pattern of moment release for one M2 simulated earthquake located just south of the SAFOD target earthquakes. It shows accelerating moment release suggesting that further studies of these detailed simulations may help in knowing what to look for in real seismicity that might allow earthquake forecasting.

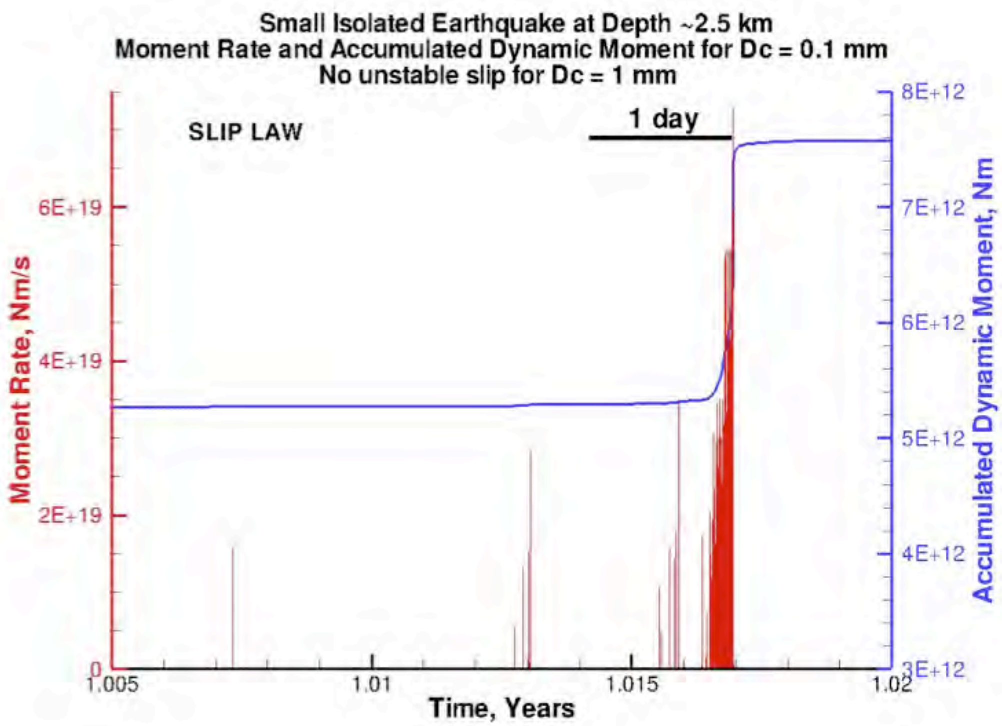

Figure 42. Details of the behavior prior to one M2 event at a depth of about 3 km. The activity begins about 4 days before this small "mainshock" and accelerates in the last few hours before the mainshock. The details of the acceleration for the other repetitions of this earthquake differ, but this is representative.

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.

a. TeraShake 2: Spontaneous Rupture Simulations of Mw 7:7 Earthquakes on the Southern San Andreas Fault

(K. B. Olsen, S. M. Day, J. B. Minster, Y. Cui, A. Chourasia, D. Okaya, P. Maechling, and T. Jordan)

Previous numerical simulations (TeraShake1) of large (Mw 7:7) southern San Andreas fault earthquakes predicted localized areas of strong amplification in the Los Angeles area associated with directivity and wave-guide effects from northwestward-propagating rupture scenarios. The TeraShake1 source was derived from inversions of the 2002 Mw 7:9 Denali, Alaska, earthquake. That source was relatively smooth in its slip distribution and rupture characteristics, owing both to resolution limits of the inversions and simplifications imposed by the kinematic parameterization. New simulations (TeraShake2), with a more complex source derived from spontaneous rupture modeling with small-scale stress-drop heterogeneity, predict a similar spatial pattern of peak ground velocity (PGV), but with the PGV extremes decreased by factors of 2–3 relative to TeraShake1 (Figure 43). The TeraShake2 source excites a less coherent wave field, with reduced along-strike directivity accompanied by streaks of elevated ground motion extending away from the fault trace. The source complexity entails abrupt changes in the direction and speed of rupture correlated to changes in slip-velocity amplitude and waveform, features that might prove challenging to capture in a purely kinematic parameterization. Despite the reduced PGV extremes, northwest-rupturing TeraShake2 simulations still predict entrainment by basin structure of a strong directivity pulse, with PGVs in Los Angeles and San Gabriel basins that are much higher than predicted by empirical methods. Significant areas of those basins have predicted PGV above the 2% probability of exceedance (POE) level relative to current attenuation relationships (even when the latter includes a site term to account for local sediment depth), and wave-guide focusing produces localized areas with PGV at roughly 0.1%–0.2% POE (about a factor of 4.5 above the median). In contrast, at rock sites in the 0–100-km distance range, the median TeraShake2 PGVs are in very close agreement with the median empirical prediction, and extremes nowhere reach the 2% POE level. The rock-site agreement lends credibility to some of our source-modeling assumptions, including overall stress-drop level and the manner in which we assigned dynamic parameters to represent the mechanical weakness of near-surface material. Future efforts should focus on validating and refining these findings, assessing their probabilities of occurrence relative to alternative rupture scenarios for the southern San Andreas fault, and incorporating them into seismic hazard estimation for southern California.

An important conclusion of this study is that much of the variability in long-period ground motion that is subsumed into uncertainty estimates of the current empirical ARs can be modeled and understood deterministically through numerical simulations with results that have significant implications for earthquake hazard assessment. In the three TeraShake2 simulations, we see large systematic amplification effects, both from scenario-specific rupture directivity and region specific geologic structures. Naturally, these complex source propagation, wave-guide, and 3D basin amplification effects, which are of first-order importance in scenario ground motion estimates, cannot be captured by ARs estimated from many earthquakes with a large variation of source, path, site effects (and with limited observational constraint at large magnitude). In particular, the very localized extremes in PGV predicted near Whittier–Narrows, due to focusing of channeled waves, are up to a factor of 5 above the median prediction of the current generation of ARs. The same channeling effect leads to pervasive amplifications in the deep parts of Los Angeles basin that are a factor of 2–4 above the median AR (even when, as in the C&B06 AR, a correction for local basin depth is included). Although we have modeled these effects for a specific set of scenarios, they are sufficiently strong for some sites to influence predictions from ensemble averages of sources, and therefore should be considered in probabilistic seismic hazard analysis (PSHA). An effort to include physics-based 3D ground-motion simulations in PSHA is underway in the SCEC CyberShake project, which can be expected to significantly improve the accuracy of hazard estimation in southern California.

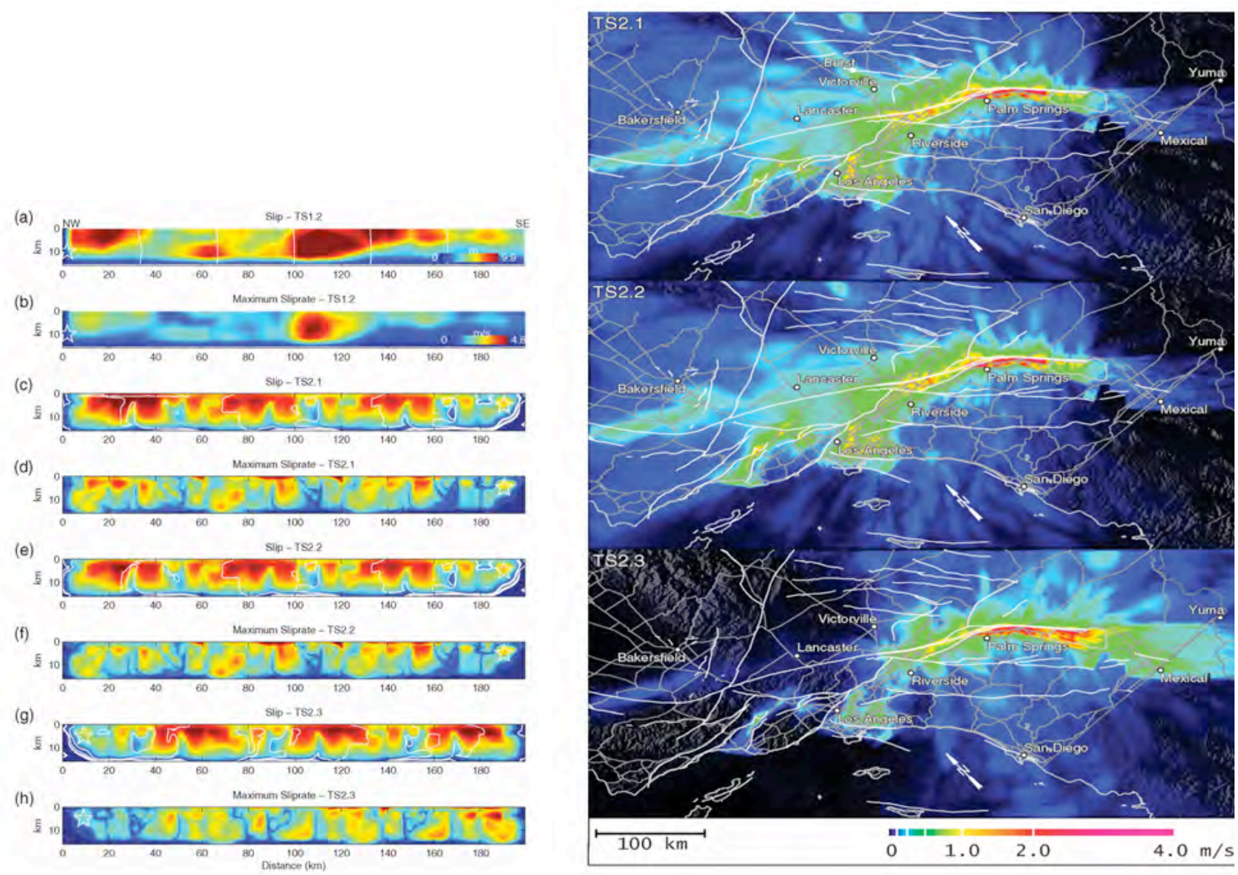

Figure 43. Left panel shows kinematic rupture parameters (slip and maximum slip rate) for the TeraShakeI and TeraShake2 simulations. The white contours depict the rupture time from 10 to 70 sec with 10 sec interval. Right panels shows PGVs for three TeraShake2 simulations. White lines depict fault traces and county lines. The dotted line depicts the part of the San Andreas fault that ruptured in the TeraShake2 simulations.

b. Validation of a Petascale Cyberfacility for Physics-based Seismic Hazard Analysis Using Precariously Balanced Rocks

(M. Purvance, R. Anooshehpoor, J. Brune, R. Graves, B. Aagaard, and K. Hudnut)

In 2008, NEHRP will oversee a massive multi-hazard response exercise based on the damage inflicted by an M=7.8 rupture scenario on the Southernmost San Andreas Fault. Vital aspects of the Great Southern California ShakeOut exercise are the realistic depictions of both the spatial distributions and intensities of damage resulting from strong ground shaking produced by such an event. In this vein, simulated ShakeOut ground motions have been compared with PBRs at 20 sites in Southern California (Figure 44). The simulated ground motions cover a broad frequency range (0-10 Hz) and incorporate effects of complex fault rupture and 3D wave propagation. Purvance et al. (in press) developed PBR fragilities that depend on a vector of ground motion intensities (e.g., PGA and either PGV, Sa(1), or Sa(2)). As the ShakeOut simulation produced broadband ground motions, it is straightforward to calculate the PBR fragilities and estimate the overturning probabilities. As shown in Figure 45, PBRs at only two sites overturn with greater than 50% probability given the ShakeOut ground motions. The broad agreement between the ShakeOut ground motions and the PBR constraints suggests that the ground motions are not unrealistically intense. During the 1952 Kern County Earthquake, a number of transformers were overturned due to intense shaking. This analysis can also be extended to assess the loss of electric transformers given the ShakeOut ground motions. Using these ground motions, a number of electric substations near to the San Andreas Fault may experience significant damage in terms of transformer overturning from such an event. These findings are critical for emergency responders as resources may have to be allocated to deal with the loss of power in these areas.

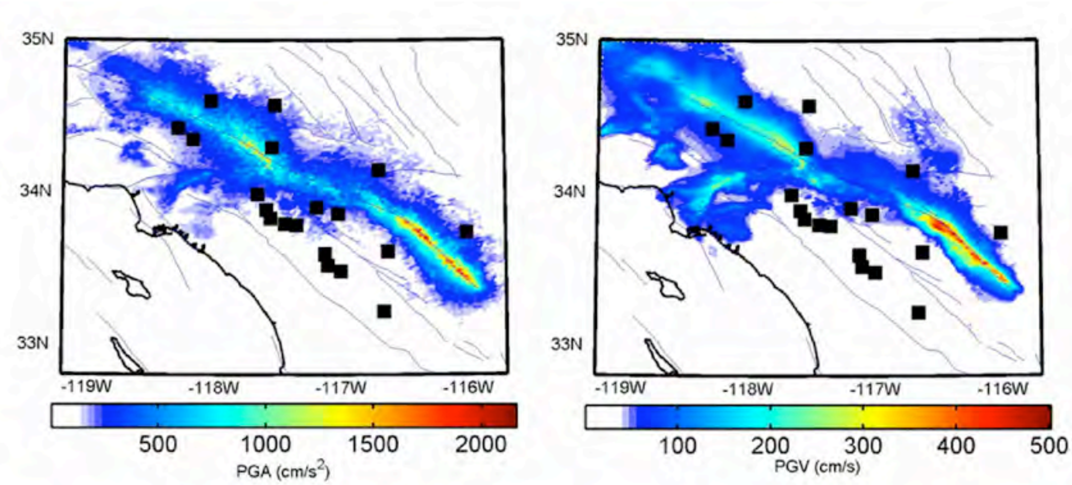

Figure 44. ShakeOut ground motions (PGA left, PGV right) with PBR locations (black squares).

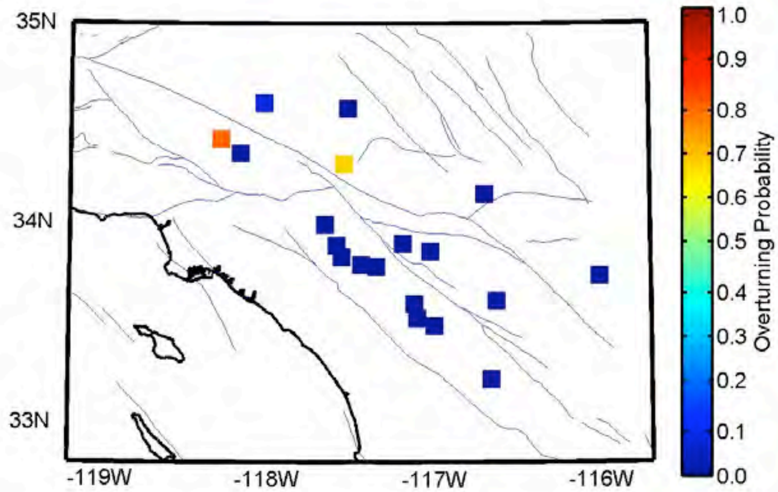

Figure 45. Overturning probabilities of the PBRs given the ShakeOut ground motions.

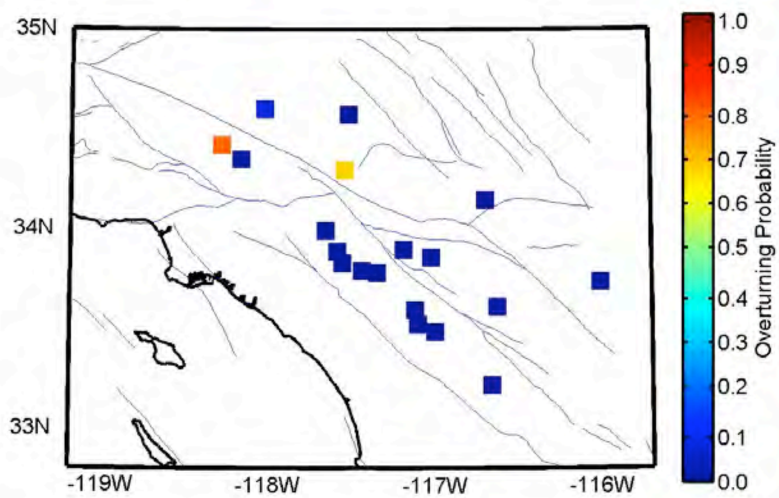

Figure 45. Overturning probabilities of the PBRs given the ShakeOut ground motions.

c. ShakeOut: Broadband Ground Motion Simulations for a Mw 7.8 Southern San Andreas Earthquake

(R. Graves, B. Aagaard, K. Hudnut, L. Star, J. Stewart, K. Olsen, L. Dalguer, S. Day, R. Taborda, J. Bielak)

Using the resources of the Community Modeling Environment of the Southern California Earthquake Center (SCEC), we compute broadband (0 – 10 Hz) ground motions over a large region of southern California for a M_w 7.8 rupture scenario of the southern San Andreas fault. The simulations incorporate a heterogeneous kinematic rupture description, as well as 3D complexity of the crust. Simulated near-fault PGA and PGV values generally range from 0.5 to 1.0 g and 100 to 250 cm/s, respectively. A southern hypocenter efficiently channels energy into the Los Angeles region along the string of basins lying south of the San Gabriel Mountains, while central and northern hypocenters are much less efficient at exciting this response (Figure 46).

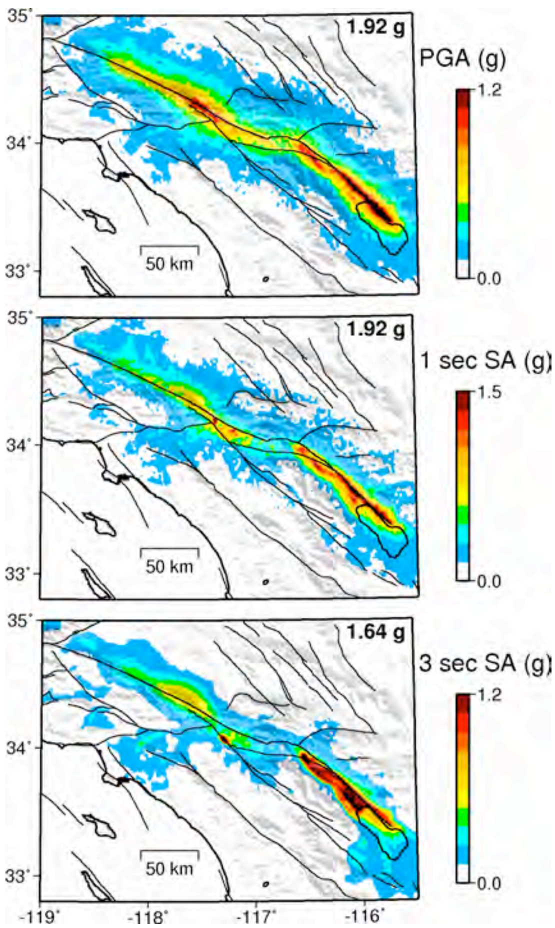

Figure 46. Maps of simulated PGA (top), SA at 1 sec (middle) and SA at 3 sec (bottom) averaged over the three hypocenters. The maximum value for each map is indicated in the upper right corner of each panel (color scale is clipped for display clarity).

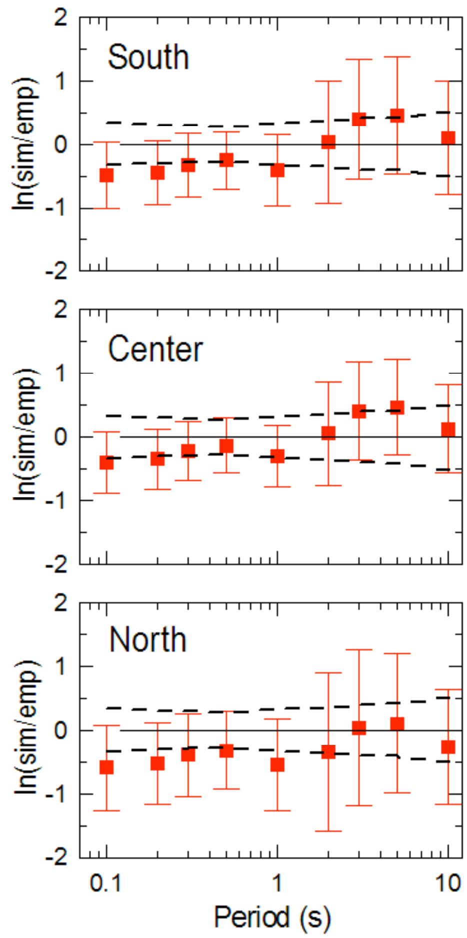

Figure 47. Red squares plot average of residuals between simulations and empirical predictions from model CB08 as a function of period for the three hypocenter cases. Positive values indicate the simulations predict larger motions than the empirical model; negative values indicate smaller simulated values compared to the empirical model. The error bars indicate +/- 1 standard error for the residuals. The heavy dashed line plots the +/- 1 standard error level of the inter-event term from the empirical model.

The residuals shown in Figure 47 correspond to event terms, which express the degree to which a particular event produces, on average, motions offset from GMPEs (a positive residual implies recordings > model). The scatter of event terms observed from past earthquakes is reflected by the dotted lines in Figure 47. The scenario event terms are within the ± one standard deviation, indicating that the overall ground motion levels associated with the simulations are consistent with prior experience. Nonetheless, the kinematic rupture description used in this scenario is just one of many possible ruptures that might occur along the southern San Andreas fault. Ongoing studies using fully dynamic rupture simulations for ShakeOut-type events will provide valuable insight on the effects of source complexity on the level and variability of the resulting ground motions (Day et al., in preparation).

The ground motions described here will be used for several types of damage and loss estimate studies as part of the multi-hazards response exercise. These studies include landslide and liquefaction analysis, lifeline fragility, loss estimates (via HAZUS), and dynamic response of built structures. An effort to realistically estimate the fatalities and casualties, as well as both short- and long-term social and economic impacts is being made on the basis of the ground motions computed and described in the present study. The results of these ongoing studies will be presented in November 2008.

7. Seismic Hazard and Risk Analysis

a. Comparison between Precariously Balanced Rocks and ShakeOut Simulation

The Great Southern California ShakeOut exercise involves realistic depictions of both the spatial distributions and intensities of damage resulting from strong ground shaking caused by such an event. Purvance et al. (2007) used simulated ShakeOut ground motions provided by Robert Graves et al. (2007) to assess precariously balanced rocks (PBR’s) at 20 sites in Southern California (Figure 44). The simulated ground motions cover a broad frequency range (9-10 Hz) and incorporate the effects of complex fault rupture and 3D wave propagation. Purvance et al. (in press) developed PBR fragilities that depend on a vector of ground motion intensities (e.g. PGA and either PGV, Sa(1), or Sa(2). As the shakeout simulation produced broadband ground motions, it was straightforward to calculate the PBR fragilities and estimate the overturning probabilities. As shown in Figure 45, PBR’s at only two sites have overturning probabilities greater than 50% given the ShakeOut ground motions. The broad agreement between the ShakeOut ground motions and the PGR constraints suggests that the ground motions are not unrealistically intense.

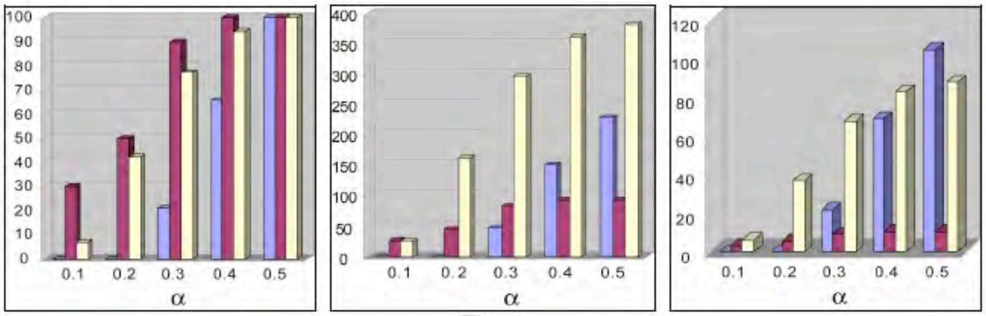

Fig. 1

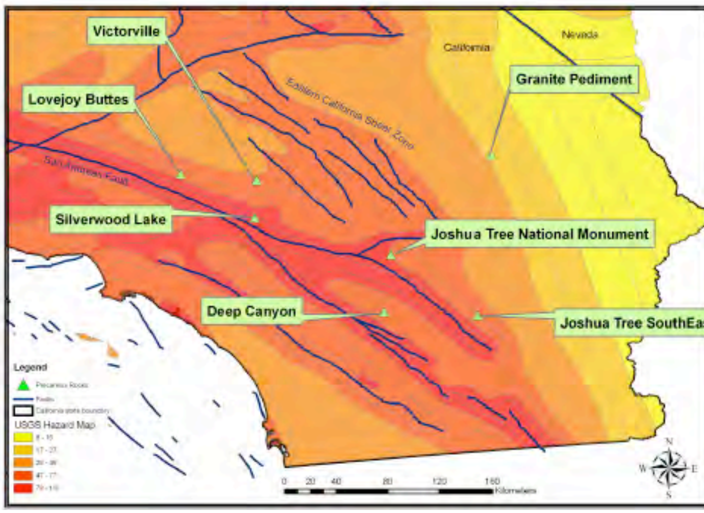

Figure 48. Top shows distributions of alpha for precariously balanced rocks. Raw numbers are shown on the left panel, the numbers normalized to 100 at *alpha* of 0.5 in the center, and number normalized to area on the right. Blue indicates data for Lovejoy Buttes (~15 km from SAF), maroon data for Victorville (~30 km from SAF), and yellow, data for Granite Pediment (remote from SAF).

b. Statistical Distribution of Aspect Ratios of Precarious Rocks at Lovejoy Buttes, Victorville, and Granite Pediment

Brune (2007) performed an analysis of aspect ratios of precarious rocks in Southern California. Precariously balanced rocks are usually not found closer than about 15 km from the San Andreas Fault in the Mojave Desert. With increasing distance the toppling acceleration (TAs) of the most easily toppled rocks decreases, roughly from about 0.4 g at 15 km to about 0.25 g at 30 km, a result of the attenuation of ground motion with distance from the fault. Difficulty of toppling is measured by the aspect ratio (shape) of the rock, termed ***alpha***. There are hundreds of such rocks in the Mojave Desert. This allowed Brune to roughly estimate, using reconnaissance surveys, the frequency of occurrence of rocks of different ***alphas*** (about 30% less than TAs) as a function of distance from active faults.

Brune presented preliminary results from reconnaissance in three areas; Lovejoy Buttes (about 15 km), Victorville (about 30 km), and Granite Pediment (in the middle of the Mojave Desert, hundreds of km from the San Andreas fault, and about 100 km from the nearest active fault, source of the Hector Mine earthquake of 1999). At Lovejoy Buttes there are no rocks with *alphas* of 0.2 g, whereas at Granite Pediment there are a number of such rocks. Figure 48 shows the raw data, the approximate area covered in each case, the numbers normalized to 100 at *alpha* of 0.5, and the number normalized to area. The preliminary interpretation of these data is that rocks with *alphas* of 0.1 and 0.2, and many with *alphas* of 0.3 have been knocked down at Lovejoy Buttes, but many remain at granite Pediment, with Victorville being intermediate.

c. Validation of Ground Motion Simulations for Engineering Applications

Baker (2007) undertook to validate ground motion simulations for engineering applications, too see if simulated ground motions have impacts on buildings that differ from those of recorded ground motions. The elastic response spectrum is important because it often serves as the link between seismic hazard analysis and structural response calculation. Mean spectra are important, but standard deviations and correlations also affect structural response. Baker compared response spectra from recorded and simulated ground motions having similar magnitudes and distances. The spectra look reasonably similar, except at short periods where the simulations appear to be lower in amplitude and have less record-to-record variability.

Baker then compared the means and standard deviations of residuals from ground motion prediction models, for recorded and simulated ground motions with magnitude > 6.5 and Vs30 > 300 m/s. The simulations show reasonable agreement with empirical observations at periods longer than one second, and less good agreement at shorter periods. The correlations between spectral values at multiple periods illustrate the "bumpiness" of the spectra, a factor known to affect response of nonlinear and multi-degree-of-freedom structures (Baker and Cornell 2006). The simulations appear to have a correlation structure that is not in close agreement with comparable empirical models.

Real structures are expected to behave nonlinearly in strong ground shaking, so the inelastic response spectrum (which measures peak responses of nonlinear oscillators) provides a proxy for the effect of ground motions on nonlinear structures. Assuming that elastic response spectra of the simulated motions appear reasonable, a simple way to study inelastic spectra is to consider the ratio of inelastic to elastic response. Both the elastic and inelastic response ratios agree well with comparable recorded ground motions at periods larger than 1 second. However, at shorter periods, the variability of the simulated elastic spectra is lower than the observed spectra and the inelastic response ratios of the simulations appear to be too high. The large inelastic response ratios may be due to differences in the mean elastic spectra, which could affect softening nonlinear oscillators.

d. Efficient Approach to Vector-Valued Probabilistic Seismic Hazard Analysis of Multiple Correlated Ground Motion Parameters

Vector Valued Probabilistic Seismic Hazard Analysis (VPSHA) quantifies the joint probability of exceeding specified threshold levels two or more different ground motion parameters such as peak acceleration and the response spectral acceleration at a specified period which may be the fundamental mode of a structure (Bazzuro, 1998; Thio, 2003). The currently available VPSHA codes address only two parameters, have sparse documentation, and the Bazzuro (1998) method is unable to identify the scenarios that control the joint hazard via the deaggregation procedure. To circumvent these limitations, engineers have used scalar PSHA for single ground motion parameters that are a combination of multiple ones (e.g. the geometric mean of the spectral accelerations at the first period of vibration in the two main horizontal directions of the building).

To facilitate the use of VPSHA, Bazzuro et al. (2007) proposed an alternative, approximate method for computing the joint hazard that can be implemented with any standard scalar PSHA software. The scalar PSHA code needs only to be modified to provide disaggregation of the scalar hazard for all of the parameters considered in the ground motion prediction equations used in the PSHA (e.g. magnitude, distance, rupture mechanism, etc.). In addition, this method requires the covariance matrix of the ground motion parameters for which the joint hazard is sought, which for spectral quantities has recently become available in the literature. This indirect approach to VPSHA is computationally efficient, delivers the disaggregation of the joint hazard, and can accommodate up to four or five ground motion parameters with the current computer limitations without significant loss of accuracy. This study provides the methodology and an illustrative example for the evaluation of the joint hazard for three spectral acceleration quantities at a San Francisco site.

e. Automated Calculation of Damage State Exceedance Probabilities from Aftershocks

Gerstenberger (2007) developed a system for the automated calculation of damage state exceedance probabilities from aftershocks. The primary outcome has been the development of a workflow that incorporates all of the necessary steps for an automated tool to perform the calculations in real-time. Many of the steps listed below are now in place. The initial goal, with added flexibility and complexity to be added later, was decided to be to produce a map of probability of complete damage (or collapse) after a main shock that reflects the associated probabilities of aftershocks.

1. Obtain magnitude & location of main shock (eg, all events magnitude ≥ 5).
2. Get the probability distributions of ground motion from ShakeMap for the main shock.
3. Calculate (look up) the fragilities for undamaged structures.
4. Integrate the main shock ground motion distributions with the undamaged fragilities to calculate the probabilities of various damage states after the main shock.
5. Using the STEP model, calculate the forecast aftershock rates. Using these, calculate the exceedance probabilities for SA .3s, SA .5s, SA 1s, and SA 2s. This is currently calculated only for rock sites. Aftershock rates will initially be Poissonian rates for a 24 hour period.
6. To calculate (look up) the appropriate fragilities for each possible damage state, the next step is deaggregation of the aftershock ground motion probabilities to determine the appropriate magnitude and distance.
7. Fragility for a given post-main shock, or “initial” damage state: calculate (look up) the probability of a new damage state (e.g., complete damage) given the initial damage state (following the main shock) and possible aftershock ground motions.
8. Integrate the ground motion probabilities calculated in step 5 from the forecast aftershocks with the damaged-building fragilities calculated in step 7. This is essentially the same calculation as that performed in step 4.

9. Finally, integrate over the possible initial (post-main shock) damage states to give the probability of complete damage given only the main shock earthquake information and structure type as input.

f. End-to-End Modeling of Woodframe Building Performance

A pilot study in the end-to-end (E2E) modeling of woodframe building performance was conducted by Porter et al. (1997) as part of the California Earthquake Authority (CEA). This note briefly summarizes major features of the study, some scientific and engineering innovations and findings, and some open questions the study raised.

The research produced earthquake ground-motion maps for several versions of a M7.15 earthquake on the Puente Hills Blind Thrust Fault in Southern California. It used a mathematical model of the rupture and the propagation of the seismic waves through the earth's crust and to the earth's surface, a process called physics-based modeling. The maps are more realistic than ones produced with seismic attenuation relationships such as the Next Generation Attenuation (NGA) relationships, because physics-based modeling accounts for directivity and the heterogeneous nature of the earth's crust in Southern California, whereas NGA does not.

The research simulated the structural response of 6 hypothetical woodframe buildings subjected to the scenario earthquake, imagining each building placed at each of 648 gridpoints in the epicentral region. The index buildings are typical of Southern California construction since 1940. Multiple nonlinear dynamic structural analyses were performed of each building at each gridpoint, to capture variability produced by uncertainties in rupture characteristics, wave propagation, and the building's orientation, strength, stiffness, and energy-dissipation characteristics. These uncertainties are considered the most important ones to the uncertainty in structural response given the earthquake magnitude and location. The research employed an efficient method for propagating these uncertainties. The method, termed moment matching, is more widely known as quadrature. It is neither experimental nor esoteric, though it appears not to have been used before in loss estimation, where Monte Carlo simulation and variants such as Latin Hypercube sampling are common.

For comparison with E2E, shaking intensity at each gridpoint was also calculated using NGA, which primarily considers magnitude, distance, and site soil characteristics. NGA is blind to directivity and other aspects of the path the seismic waves must travel to go from the rupture to a site, aspects that E2E explicitly captures. One might hypothesize that NGA would therefore produce greater uncertainty in structural response because of the ignored information. One might also expect that where directivity matters, such as on the hanging wall of a thrust fault, structural response using NGA would be systematically different from E2E, again because NGA is blind to path. By re-using samples from E2E analyses, it was practical to create comparable maps for an NGA approach.

The research did more than demonstrate the viability of E2E modeling. It supported both hypotheses: (1) that E2E modeling reduces uncertainty in performance, and (2) in places where directivity matters, E2E avoids systematic error in structural response estimates (and by implication loss). But it also raised interesting practical questions: Given newly available, massively parallel computing capabilities, is E2E practical for estimating portfolio loss exceedance relationships, where computational demands are much greater than in a single scenario? How can one use E2E to estimate the effect on loss from readily observable building features (rating factors), such as foundation type, site slope, plan and vertical irregularities? By how much would E2E reduce uncertainty in repair cost or insurance loss? How many index buildings are needed to create a sample set that is statistically representative of the real building population, or of a particular insurance portfolio?

It also raised interesting questions of a more academic nature: Would increasing the order of quadrature (the number of samples of each input variable) significantly change the estimated mean and uncertainty in performance? How much would other seismological and structural uncertainties, if modeled, increase uncertainty in performance? How many Monte Carlo simulations are required to produce equally accurate estimates of mean and variance in performance? The research team hopes to pursue all these questions in the future.

g. SCEC Broadband Strong Motion Simulation Platform

SCEC strengthened its capabilities in broadband simulation of strong ground motion for use in the next phase of the NGA Project. We initiated development of a platform for broadband simulation that allows users other than the developers of the software modules to use them in verification exercises, validation against recorded data, and simulations of scenario earthquakes. This platform will provide objectivity and transparency in the testing and application of broadband simulation procedures, enhancing confidence in their use in earthquake engineering.

We developed additional broadband strong motion simulation procedures based on conventional source representation (slip as a function of time and position on the fault) and seismic wave propagation at long periods (based on calculated Green's functions). We verified the strong motion simulation procedures using simple test cases, and performed the design and preliminary implementation of a platform for broadband ground motion simulation. Each of these accomplishments was a necessary step in the demonstration of the broadband platform. First, the development of additional broadband strong motion simulation procedures made a total of three alternative procedures available for use in the Platform. Second, these procedures needed to be verified before being incorporated into the Platform. Third, the Platform needed to be designed and its prototype developed.

A prototype of the SCEC Broadband Strong Motion Simulation Platform was demonstrated to individuals outside SCEC on two occasions – November 2, 2006 and April 27, 2007. Next, we demonstrated a fully functional version of the SCEC Broadband Strong Motion Simulation Platform. The demonstration consisted of two parts: demonstration by a person outside SCEC, and demonstration of the capability to perform large scale ground motion simulations of interest to the PEER NGA Program.

The objective of the first demonstration was to show that a person outside SCEC who has no prior knowledge of the Platform and has not participated in the development of any of the computer codes that it uses is able to perform ground motion simulations on the platform without assistance. This demonstration was done by Ms. Katie Wooddell of PG&E. Ms Wooddell works with Dr Norm Abrahamson of PG&E, who is a member of the project management committee of the PEER NGA Program.

The first part of the demonstration was conducted on November 15, 2007, when Ms Woodell visited the SCEC Headquarters at USC. The participants in the workshop included the developers of the three broadband simulation methods that are available on the Platform. Developers who were present at the workshop are shown in italics.

UCSB: *Ralph Archuleta, Jan Schmedes*, Peng-Cheng Liu (Liu et al., 2006)
URS: *Robert Graves, Arben Pitarka* (Graves and Pitarka, 2004).
SDSU/ETHZ: *Kim Olsen*, Martin Mai (Mai and Olsen, 2005)

The SCEC participants also included Director Tom Jordan, IT Architect Phil Maechling, and Seismic Hazard and Risk Analysis Focus Group leader Paul Somerville. One week before the Demonstration, information about the demonstration exercise was sent to Ms Wooddell. The exercise prepared for Ms Wooddell consisted of Exercise BB01, which had previously been done by the three groups listed above as part of the validation of the methods. This verification is described in SCEC CEA Report#7. The verification exercises were designed by Robert Graves.

In the morning session of the workshop on November 15, Ms. Wooddell successfully performed Exercise BB01. Later that morning, she performed an additional test in parallel with Dr Robert Graves. The test involved setting up an exercise to model hanging wall effects. She was able to set up the test and then execute it, obtaining the same result as that obtained by Dr Graves. Following her visit to SCEC, Ms Wooddell ran two exercises from a remote location. She prepared a report to PG&E on December 28, 2007 describing her experience with the Platform.

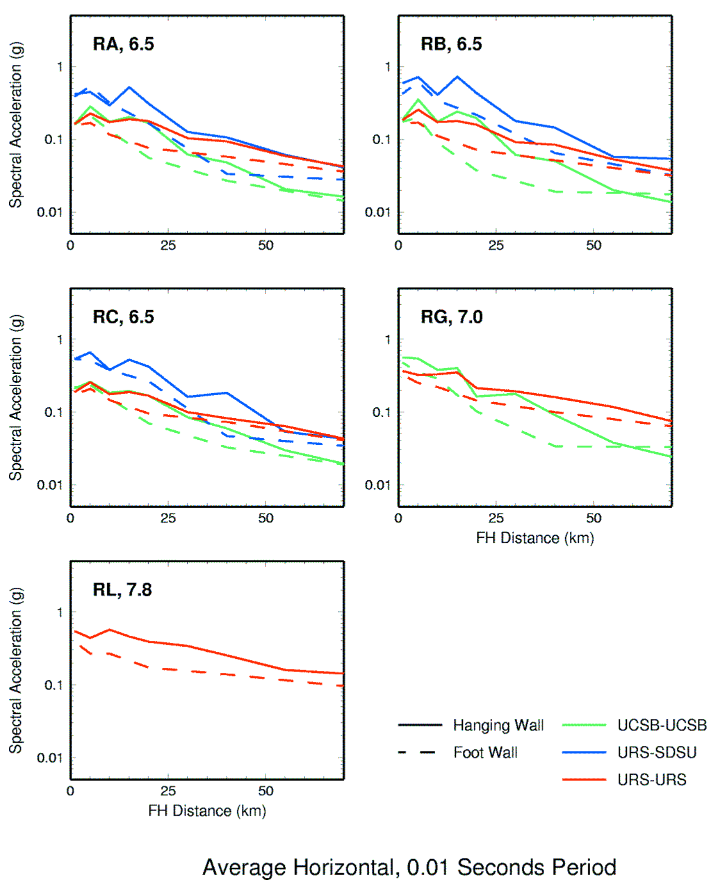

Figure 49. Comparison of foot wall and hanging wall 0.01 sec response spectra

The objective of the second demonstration was to show that large scale ground motion simulations can be run on the platform by individuals other than those who developed the seismological components of the computer codes that constitute the Platform. This demonstration was done by Phil Maechling, the SCEC IT Architect. The demonstration involved large scale simulations of hanging wall effects on strong ground motions, a topic that is of interest to the PEER NGA Program.

The fault geometries and station geometries were of the hanging wall simulations were taken from the previous NGA-E rock ground motion simulations (Abrahamson and Chiou, 2003) for reverse fault dipping at 30 degrees to the east. Figure 49 shows the absolute value of the response spectral acceleration for 0.01 seconds (equivalent to peak acceleration), plotted as a function of distance from the fault, with foot-wall values (dashed lines) superimposed on the hanging wall values (solid lines) to facilitate comparison. Inspection of these results indicates that the Platform is performing as intended. The general characteristics of hanging-wall effects that are observed in strong motion recordings are evident in the results. At periods of 1 second and less, there are quite large differences between foot-wall and hanging-wall ground motions. These differences diminish at periods of 2 seconds and longer. This period dependence is similar to that observed in recorded ground motions.

h. Ground Motion Simulations for the Tall Buildings Initiative

The Pacific Earthquake Engineering Research Center is actively pursuing a research agenda in support of the development and application of alternative design concepts for earthquake engineering of buildings, as described in the Tall Buildings Initiative (Moehle, 2006). The Southern California Earthquake Center is pursuing a research agenda to provide earthquake ground motion simulation capabilities to support this cutting-edge earthquake engineering of buildings. The City of Los Angeles, the City and County of San Francisco, and other communities simultaneously are confronted with a boom in the construction of highrise buildings that involve a variety of unusual configurations, innovative structural systems, and high performance materials. Various jurisdictions, with the active involvement of peer review committees, are considering performance-based methods to assess the adequacy of these new designs. These parallel efforts create a timely opportunity for collaboration to improve and increase the application of performance-based designs for tall buildings, thereby assuring that new highrise construction meets intended safety and performance objectives, ensuring safe and usable buildings after future major earthquakes.

One of SCEC's main roles in the Tall Buildings Initiative is to generate ground motion time histories in San Francisco and Los Angeles for large earthquakes on the major faults in the region, using validated broadband ground motion simulation procedures. The time histories were simulated for geographic areas of specific interest for San Francisco and Los Angeles. These broadband simulated time histories contain long period effects such as rupture directivity effects and basin effects that are specific to the fault geometry and geological structure of the regions. Robert Graves generated suites of time histories for the Puente Hills Blind Thrust scenario earthquakes (Graves and Somerville, 2006). The broadband time histories were calculated at sites on a 1 km square grid centered over the fault planes and extending out to about 60 km. Brad Aagaard and a large group of investigators (Aagaard et al., 2008) generated suites of time histories for 1906 San Andreas scenario earthquakes. Documentation of the simulations and data files, and digital sets of simulated ground motion time histories were provided to the TBI for review. The group led by Brad Aagaard is now developing suites of time histories for scenario earthquakes on the Hayward Fault. Robert Graves and others are generating broadband ground motion time histories for the 1857 earthquake on the San Andreas fault as part of the ShakeOut Project.

i. References

Baker, J.W. (2007). Validation of Ground Motion Simulations for Engineering Applications. Annual report, 2007 Project #07069.

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Purvance. M., R. Anooshehpoor, and J. Brune (2007). Validation os a Cyberfacility for Physics-Based Seismic Hazard Analysis using Precariously Balanced Rocks. SCEC Annual Report.

i. Reports to the California Earthquake Authority (CEA)

Report#7. Participate in Phase NGA-H of the Next Generation Attenuation (NGA) Project, February 28, 2007

Report#8. Index woodframe houses and their response to Puente Hills scenario earthquakes, February 28, 2007

Report#9. Index woodframe houses and their response to Puente Hills scenario earthquakes, June 30, 2007

Report#11. Demonstration of the SCEC Broadband Strong Motion Simulation Platform, December 28, 2007.

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 *Working Group on California Earthquake Probabilities (WGCEP)*, the *Collaboratory for the study of Earthquake Predictability (CSEP)*, the *Extreme Ground Motion Project (ExGM)*, and the *Petascale Cyberfacility for Physics-Based Seismic Hazard Analysis (PetaSHA)*.

1. Southern San Andreas Fault Evaluation

The Southern San Andreas Fault Evaluation (SoSAFE) Project is 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. 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. Since then, SoSAFE workshops have been held at each SCEC Annual Meeting and also one was held jointly with Fault Systems in early 2008. Special project funding has been provided by USGS and will likely end after one more year, since the Multi-Hazards Demonstration Project is moving on to emphasize other hazards after completion of the ShakeOut scenario in late 2008. Discussion at the upcoming SoSAFE workshop in Sept. 2008 will consider the future direction of this special project in this context.

Work conducted by SoSAFE researchers is being funded by the USGS Multi-Hazards Initiative 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 will furthermore link 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.

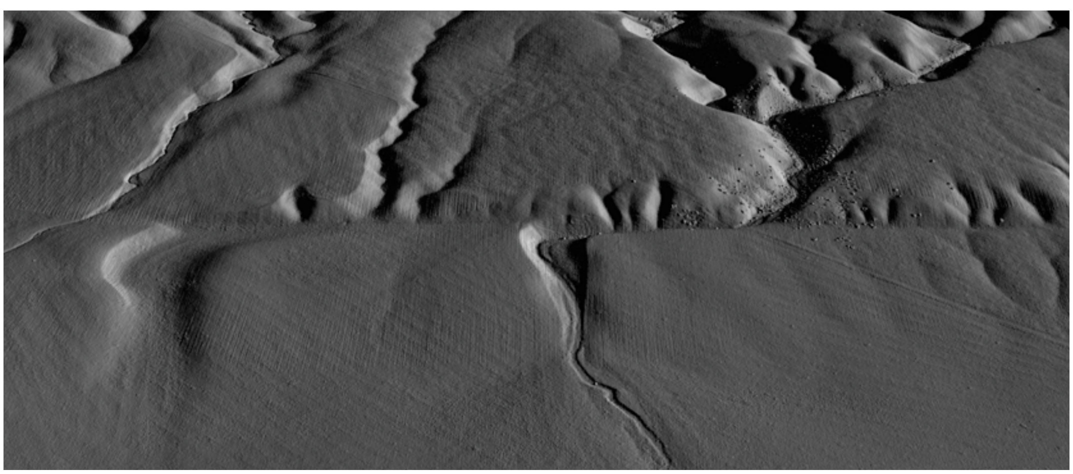

Figure 50. Oblique view of Wallace Creek, the classic San Andreas slip rate site in central California, as imaged by the B4 Project and gridded at 0.25 m resolution. The 1857 Fort Tejon earthquake (M_W 7.9) produced the most recent ~9 m of slip at this location. Note the offset stream channels.

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 mentioned in the Geology report by use cosmogenic and U-series dating, as well as soils analysis, 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.

Work at the Frazier Mountain site, as discussed and shown in the Geology section of this report, 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. 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. Furthermore, the SoSAFE group contributed heavily to definition of the ShakeOut earthquake scenario source description. These early successes of SoSAFE have been followed by much work that is still in progress, and that is included in individual PI's detailed project reports.

Figure 51. Excavation in progress at Biskra Palms, revealing a relationship at the intersection of the Banning fault with the downstream channel margin. Evidence here is crucial to understanding the long-term slip rate at this site. In addition to re-sampling and dating the T2 surface, numerous excavations were used to test key geological hypotheses related to total offset of the fan surface. Whitney Behr and Nate Guzman discuss new evidence with Prof. Doug Yule (CSUN).

2. Working Group on California Earthquake Probabilities

California's 35 million people live among some of the most active earthquake faults in the United States. Public safety demands credible assessments of the earthquake hazard to maintain appropriate building codes for safe construction and earthquake insurance for loss protection. Seismic hazard analysis begins with an earthquake rupture forecast—a model of probabilities that earthquakes of specified magnitudes, locations, and faulting types will occur during a specified time interval. This report describes a new earthquake rupture forecast for California developed by the 2007 Working Group on California Earthquake Probabilities (WGCEP 2007).

a. 2007 Working Group on California Earthquake Probabilities

WGCEP 2007 was organized in September, 2005, by the U. S. Geological Survey (USGS), the California Geological Survey (CGS), and the Southern California Earthquake Center (SCEC). It was charged with two tasks: (1) collaborate with the National Seismic Hazard Mapping Program (NSHMP) in producing a revised, *time-independent* forecast for California as input to the 2007 revisions of the national seismic hazard maps, and (2) create a uniform, statewide, *time-dependent* model that, among other purposes, could be used by the California Earthquake Authority (CEA) in setting earthquake insurance rates.

The national seismic hazard maps utilize a time-independent forecast, in which the probability of each earthquake rupture is completely independent of the timing of all others. Time-dependent models are based on the concept of stress renewal: the probability of a fault rupture drops immediately after a large earthquake releases tectonic stress on the fault and rises again as the stress is regenerated by continuous tectonic loading. However, observations in California and elsewhere show that the earthquake cycle associated with this elastic rebound theory can be highly irregular, owing, for example, to stress interactions among neighboring faults. We do not understand these interactions well enough to model them explicitly; therefore, variations in the earthquake cycle must be calibrated empirically using historical observations of seismicity and geologic data on the dates and sizes of prehistoric earthquakes (paleoseismology).

Time-dependent earthquake rupture forecasts, in which the probabilities of future events are conditioned on the dates of previous earthquakes, have been the focus of five previous Working Groups on California Earthquake Probabilities (WGCEP 1988, 1990, 1995 & 2003). Each of these working groups has expanded on its predecessors, improving the data and forecasting methodology, and each has drawn on input from broad cross-sections of the earth science community. Building on this experience, we calculate time-dependent probabilities of large earthquakes on major faults (generally those with the highest rates of slip) where the requisite information is available: the expected mean frequency of earthquakes and the elapsed time since the last earthquake. Where such information is lacking, we use time-independent probabilities, which require only an estimate of earthquake frequency.

The WGCEP 2007 study differs from previous WGCEP efforts by:

- reporting earthquake probability for the entire state of California instead of subregions;
- using uniform methodology across all regions;

- using the same earthquake rate model as the 2007 National Seismic Hazard Map Program;
- compiling and using updated, uniform, and publicly accessible statewide data;
- developing new methods to make models more rigorously adherent to observational data, particularly fault slip rates (moment balanced);
- making analysis tools and data available through a readily accessible web-based interface.

In general, we have adopted the results from previous working groups where justified and have updated the model only when compelled to by new information or understanding, or by necessity to conform the analysis to a uniform statewide approach and with the NSHMP assessment.

b. Review and Consensus-Building Processes

All UCERF 2 model elements and WGCEP 2007 documents were reviewed by an internal Scientific Review Panel (SRP) comprising experts who were not WGCEP 2007 members. The SRP reported to the Management Oversight Committee (MOC), which coordinated the review and oversaw consensus-building processes. External oversight and review was provided by the National Earthquake Prediction Evaluation Council (NEPEC) and the California Earthquake Prediction Evaluation Council (CEPEC), as well as CEA's Multidisciplinary Research Team. CEPEC and NEPEC tracked model development throughout the WGCEP 2007 process and reviewed the final report.

Advice and comment from the scientific and engineering communities was sought regularly through open meetings and workshops during the several phases of UCERF development. Participants included experts from academia, private and corporate providers of hazard assessments, consulting companies, and government agencies. WGCEP progress was reported at major scientific gatherings such as annual meetings of the American Geophysical Union, the Seismological Society of America, and the Southern California Earthquake Center.

c. Model Framework

We have built on previous WGCEP and NSHMP efforts to quantify regional earthquake probabilities in California, using the best available science to develop a new framework for a Uniform California Earthquake Rupture Forecast (UCERF). The UCERF framework comprises a sequence of four model types: a *fault model* that gives the physical geometry of the larger, known faults; a *deformation model* that gives slip rates and aseismicity factors to each fault section; an *earthquake rate model* that gives the long-term rate of all earthquakes of magnitude five or greater ($M \geq 5$) throughout the region; and a *probability model* that gives a probability of occurrence for each earthquake during a specified (future) time interval. This report presents the latest versions of each of these models, including the statewide time-independent earthquake rate model incorporated into the 2007 revisions to the national seismic hazard map (ERM 2.3) and the time-dependent earthquake probability model derived from ERM 2.3 (UCERF 2). The results are intended for use in forecasting the intensity of ground shaking throughout California.

The model incorporates both aleatory uncertainties (arising from natural variability) and epistemic uncertainties (resulting from lack of knowledge). The latter were included by constructing a logic tree with branches representing viable alternative hypotheses. We restricted our consideration to data and methods that have been published, or accepted for publication, in peer-reviewed scientific journals or as U.S. Geological Survey Open File Reports. If relevant published models differed significantly, we applied logic-tree weighting to represent the alternatives. Generally, two alternatives were given equal weight in the absence of any clear evidence to favor one over the other. When there was evidence to favor a given branch, the assignment of relative weights was made though a consensus-building process, which we describe for each case.

d. Earthquake Rate Model

The WGCEP 2007 earthquake rate model features a new fault geometry with more accurate values of dip and seismogenic depth, and new compilations of fault slip rates and paleoseismic events. The final version, ERM 2.3, includes two alternative fault models for southern California thrust-fault geometry and three alternatives representing the uncertain slip distribution between the southern San Andreas and San Jacinto faults. A significant logic-tree branching involves the choice of the magnitude-area relationship, which is used to translate from fault slip rates to earthquake rates; the global database of rupture areas and magnitude determinations has significant spread, leaving room for alternative interpretations.

Another important model branching incorporates alternative representations of the earthquake rates on major faults. We compiled an *a priori* earthquake rate model derived by a community consensus of paleoseismic and other geologic observations. We also calculated a moment-balanced version of the model, which modifies the earthquake rate to match the observed long-term slip-rate data; the resulting rates were constrained to fall within the ranges derived from paleoseismic observations. These two models balance a consensus of geologic and seismologic expert opinion with strict adherence to specific observational data.

We tested ERM 2.3 in three different ways: by comparing the predicted magnitude-frequency distributions of earthquakes with a unified historic and instrumental earthquake catalog for California and surrounding regions, by comparing integrating measures of deformation across the plate-boundary zone with the plate rate, and by comparing the distribution of source types in the model with historical data. A major issue was overprediction of the rate of $M \geq 6.5$ earthquakes, known informally as “the bulge”, a problem common to previous WGCEP and NSHMP studies. ERM 2.3 predicts an annual rate for $M \geq 6.5$ earthquakes of 0.32 events/yr, which exceeds the historically observed rate of 0.24 events/yr by about a third, though it lies within the 95% confidence bounds on the observed rate (0.13-0.35 events/yr). In comparison, the NSHMP 2002 model for California exceeded the observed rate by a factor of two.

e. Time-Dependent Earthquake Probability Model

We tightly coordinated the development of the earthquake rate models for California with NSHMP, so that both the 2007 revisions of the national seismic hazard maps and UCERF 2 are based on ERM 2.3. Constructing an earthquake rupture forecast from ERM 2.3 required a probability model that specifies how events are distributed in time, and here we departed from the NSHMP 2007 conventions by considering, along with a time-independent (Poisson) forecast, time-dependent forecasts that use stress-renewal assumptions to condition the event probabilities for the most active faults on the date of their last major rupture.

Our choice of UCERF 2 model branches was based on a careful review of all available probability models. A particularly influential branching is the "empirical" probability model, which includes a geographically variable estimate of California earthquake rate changes observed during the last 150 years. We lack consensus on the underlying physics that causes broad earthquake rate changes, though there is much promising research involving fault interactions. Rather than applying complex physical models to adjust probability, WGCEP 2007 relies on the simpler empirically-based correction.

An important seismic hazard for California is the Cascadia subduction zone, which extends about 1200 km from Vancouver Island in British Columbia to Cape Mendocino in California and is capable of generating an earthquake of M 9 or larger. Because this fault lies mostly outside the state, we treated it as a special case with its own logic tree, which included two rupture scenarios: (1) M 8.8-9.2 events that rupture the entire Cascadia subduction zone every 500 years on average, and (2) M 8.0-8.7 events whose ruptures cover the entire zone over a period of about 500 years. A time-independent model was applied to the M 8.0-8.7 scenario, and a time-dependent model to the M 8.8-9.2 scenario.

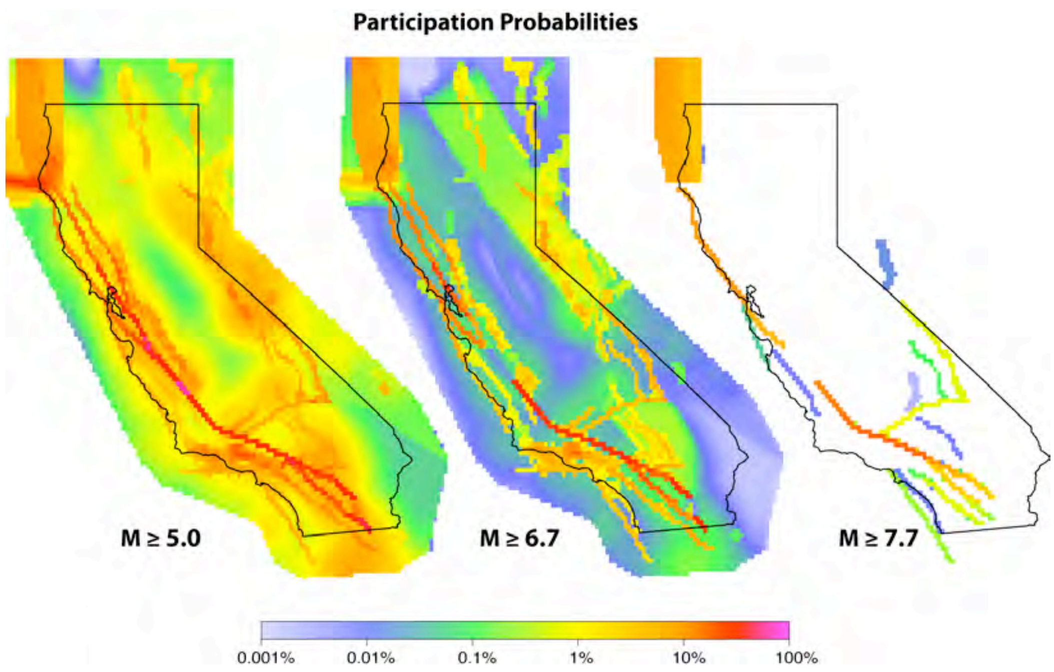

Figure 52. Participation probability maps, displaying the mean UCERF 2 probabilities that an individual 0.1° × 0.1° cell in the statewide grid will be involved in a fault rupture of any source type above the specified magnitude threshold during the next 30 years. The magnitude thresholds shown here are M ≥ 5.0, 6.7, and 7.7. Probability color scale is logarithmic; i.e. each decrement unit represents a 10-fold decrease in probability.

In computing event probabilities, the branches were weighted by expert opinion gathered in open workshops. The UCERF 2 model has been implemented in a modular (object-oriented), extensible framework using the OpenSHA platform, so that experiments with alternative branch weights can be easily investigated and future updates can be quickly accommodated as new data and methods emerge. The final UCERF 2 logic tree incorporated 480 branches that received nonzero weight, each of which produces a separate set of probabilities for all earthquakes in California. We take the mean and spread of these results to represent the best estimate of earthquake probability and its sensitivity to parameter uncertainty.

f. Results of Probability Calculations

According to UCERF 2, a $M \geq 6.7$ earthquake is virtually assured in California during the next 30 years (99.7% probability of occurrence). Larger events are less likely: the mean 30-year UCERF 2 estimate gives a 94% chance of a $M \geq 7.0$ earthquake, a 46% chance of a $M \geq 7.5$ shock, and 4.5% chance of a $M \geq 8.0$ event. The UCERF 2 range for these latter probabilities is 85-99%, 29-65%, and 0-11%, respectively. In addition, we estimate a 10% probability of a $M \geq 8.0$ earthquake somewhere along the Cascadia subduction zone (perhaps far from California) in the next 30 years. We emphasize that the probabilities calculated for the largest magnitude events should be used with caution, because they depend critically on rupture scenarios that involve fault lengths longer than historically observed ruptures, as well as an extrapolation of scaling relationships, such as the magnitude-area relationships, beyond the limits of the empirical data.

Dividing the state into two approximately equal areas, we find the 30-year probability of a large earthquake to be higher in the southern half: a $M \geq 6.7$ earthquake has a 97% chance of occurring in southern California in 30-years, compared to a 93% probability in northern California, and the odds for a $M \geq 7.5$ event are doubled (37% vs. 15%). In addition to state-wide and regional estimates, our report gives probabilities for individual faults and fault segments throughout the state, as well as a geographically variable background rate.

The UCERF 2 earthquake rupture forecast can be visualized by mapping the mean probability that an element of area on a statewide grid will include a fault rupture of any source type above a specified magnitude threshold during the next 30 years. Figure 52 presents these "participation probability" maps for three magnitude thresholds. For events with $M \geq 5.0$, the areas where the participation probabilities exceed 1% (yellow or warmer in color) include over half the state, reflecting the widespread distribution of California seismicity, much of which is represented in the model as "background." At $M \geq 6.7$, this same probability level is confined to the major faults, and at $M \geq 7.7$, it is generally restricted to the longer strike-slip strands of the San Andreas fault system.

Table 1 summarizes the mean probabilities for $M \geq 6.7$ events on the principal strike-slip faults of California, which accommodate most of the motion between the North America and Pacific plates, and it compares our results with those of WGCEP 1995 for southern California and WGCEP 2003 for the Bay Area.

Table 1. 30-year probability of M ≥ 6.7 events on the Type-A faults, rounded to the nearest percent.

Fault	WGCEP (2007) Mean [Min-Max]	WGCEP (2003) Mean [2.5% and 97.5%]	WGCEP (1995) Mean
S. San Andreas	59% [22-94]		53%
Hayward-Rodgers Creek	31% [12-67]	27% [10-58]	
San Jacinto	31% [14-54]		61%
N. San Andreas	21% [6-39]	23% [3-52]	
Elsinore	11% [5-25]		24%
Calaveras	7% [1-22]	11% [3-27]	
Garlock	6% [3-12]		

The most dangerous fault is the southern part of the San Andreas, which has a 59% probability of generating a M ≥ 6.7 earthquake in the next 30 years. This compares with 21% for the northern San Andreas fault.

We have enough data to calculate time-dependent earthquake probability on the principal strike-slip faults in Table A. These faults exist within a web of faults with lower slip rates that we know less about, which are consequently treated as time-independent sources. In southern California, the contribution to overall regional probability from these lower slip-rate faults, which include the reverse faults of the Transverse Ranges, exceeds that of the principal strike-slip faults.

g. Reliability of Results

The larger the area considered and the longer the time considered generally makes a probability calculation more reliable. Thus the statewide 30-year probability values are more reliable estimates than those for individual faults. However, even the most reliable of our calculations are subject to considerable sensitivity to parameters. For example, across the 480 branches of the logic tree we find a minimum 30-year probability of 29% for a M ≥ 7.5 earthquake, and a maximum of 65%. Calculations are quite sensitive to parameter choices on individual faults; while the mean calculated probability on the southern San Andreas fault is 59%, we find that the value could reasonably be anywhere between 22% and 94% (see Table 1).

There are known limitations with the WGCEP 2007 model, which are discussed in detail in the main report. More research time will bring improvements in key topical areas. For example, new earthquake faults will continue to be discovered. Improvements in our methods for determining maximum magnitudes associated with poorly understood faults are needed. A related major research challenge involves improving our ability to forecast more complex earthquake ruptures that include fault jumps, branching, and segment-breaking ruptures.

h. Comparisons with Previous Studies

The 30-year probability of a M ≥ 6.7 earthquake striking the San Francisco Bay Area is 63% for UCERF 2, which is indistinguishable from the 62% value reported by WGCEP 2003 (see Table A). Moreover, the extrema calculated from all of the UCERF 2 branches [0.41-0.84] approximate the 95% confidence interval of WGCEP 2003 results for the aggregate Bay Area probabilities [0.38-0.85]. This agreement indicates that we succeeded in capturing the most important epistemic uncertainties (in part because we were guided by the comprehensive uncertainty analysis of the WGCEP 2003 report).

As shown in the table, there are differences between WGCEP 2007 and WGCEP 2003 calculations for individual fault probabilities in the Bay Area. However, none exceed the uncertainty ranges reported by either working group. The differences resulted primarily from inclusion of paleoseismic observations in UCERF 2 and the restricted inventory of probability models that could be used for our statewide analysis.

The differences in the mean 30-year probabilities for $M \geq 6.7$ events between the 1995 and 2007 studies are more significant. The most important arise from new paleoseismic data and analysis, new geodetic data, and an earthquake rate model that allows a greater variety of rupture sizes on faults. One important change is to the San Jacinto fault, where the probability has been halved from 61%, reported by WGCEP 1995, to 31% [14%-54%] calculated by WGCEP 2007 (see table). Similarly, Elsinore fault probability is halved from 24% to 11% [5%-25%] because of the increased array of possible earthquake magnitudes allowed in the model.

i. Recommendations

The comprehensive nature of the UCERF 2 analysis has identified many opportunities for future model improvements, and we outline in the report specific recommendations for further research. Examples include the relaxation of fault segmentation and the inclusion of fault-to-fault ruptures, which may be in part responsible for the "bulge" problem; the inclusion of earthquake triggering and clustering, as manifested in aftershock sequences; and improved magnitude-area relationships.

j. Reference

2007 Working Group on California Earthquake Probabilities, 2008, The Uniform California Earthquake Rupture Forecast, Version 2 (UCERF 2): U.S. Geological Survey Open-File Report 2007-1437 and California Geological Survey Special Report 203 [http://pubs.usgs.gov/of/2007/1091/].

3. 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.

To address these problems, the Working Group on Regional Earthquake Likelihood Models (RELM), sponsored by the Southern California Earthquake Center (SCEC), the U.S. Geological Survey (USGS), and the National Science Foundation (NSF), recently established a facility for prospective testing of scientific earthquake predictions in California (Schorlemmer & Gerstenberger, 2007). A number of experiments are now underway (Field, 2007; see papers in *Seismol. Res. Lett.,* **78***, no. 1*, 2007).

a. The Collaboratory Structure

A collaboratory is a networked environment with the computational and communication tools for supporting a geographically distributed scientific collaboration (National Research Council, 1992). CSEP instantiated this concept in a framework comprising four major components:

Testing facilities for conducting and evaluating prospective prediction experiments.

Regional **testing regions** that provide authoritative data for earthquake prediction experiments.

Working groups for setting data, model, and testing standards and for managing collaboratory infrastructure.

A **communication grid** with protocols for conveying research results to the wider scientific community as well as users of earthquake information.

b. Testing Facilities

The CSEP core group at USC (T. Jordan, M. Liukis, P. Maechling, D. Schorlemmer, J. Yu, J. Zechar) developed during the year 2007 the first two released versions of the CSEP Testing Center Software. Version 1.0 was officially released in September 2007 at the SCEC Annual Meeting and the CSEP Testing Center at SCEC started automatic processing of the 19 5-year RELM models. The Testing Center system consists of four different components: (1) The development computer on which all Testing Center codes are developed or model codes are introduced. Working codes are moved to (2) the certification computer. This computer is identical to the operational computer and is used for testing the system and model codes. An automated build system is compiling and testing all codes on a daily basis. Every three months, with each new release of the Testing Center software, the new codes and models are moved to the (3) operational system on which they are run by a scheduler and without human interaction. All results are copied to the (4) webserver for presentation.

The Testing Center software is mainly developed at USC. M. Liukis is the maintainer and is incorporating patches and contributions from other Testing Center users. This ensures that all contributions are centrally maintained and redistributed to all participating Testing Centers. Even local extensions like region-specific data retrieval are in the main software repository.

The CSEP team in New Zealand (M. Gerstenberger, D. Rhoades, M. Stirling, M. Savage, D. Harte, D. Vere-Jones, E. Smith, R. Brownrigg) also installed the Testing Center software in version 1.0 and customized it for the use (data retrieval, model installation, etc.). Together with the help of the USC core team, the New Zealand team started manual testing of the implemented models.

Similarily, the European team (F. Euchner, S. Wiemer, J. Woessner) installed the version 1.0 system and tested the installation. Due to delays in the specification of the the first testing region in Europe, no automated testing has yet started. With three installed Testing Centers, CSEP has become a globally operating project, leveraging multiple efforts in many countries.

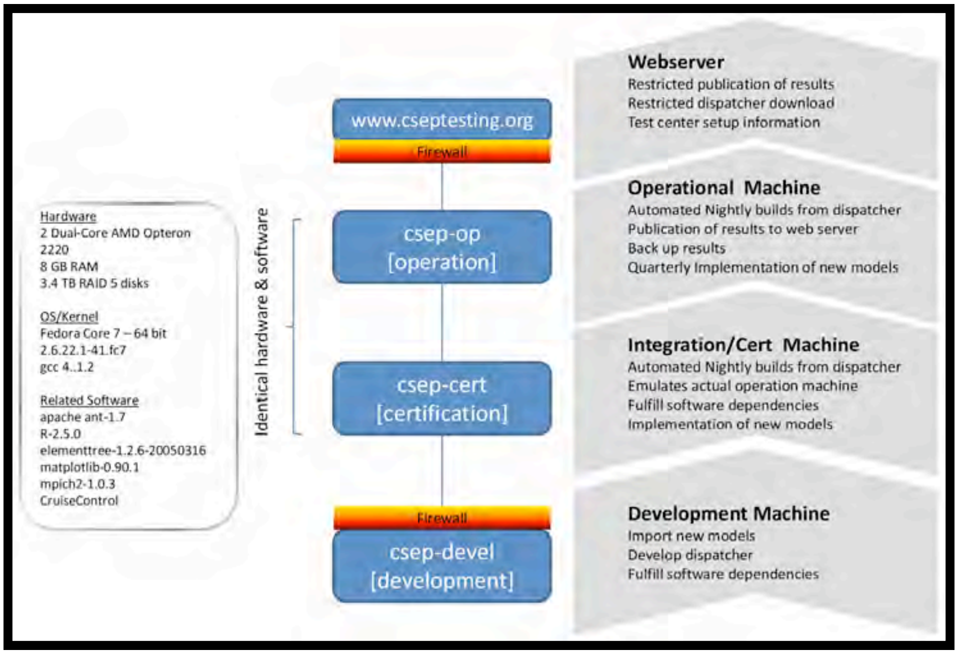

Figure 53. The CSEP computer system.

c. Testing Regions

CSEP inherited the California testing region from RELM (Schorlemmer & Gerstenberger, 2007). This testing region was defined for 5-year and 1-day grid-based forecast models (see Figure 54). At the end of the RELM project, 19 5-year models have been submitted for testing and are now part of the CSEP testing. The CSEP core group additionally introduced two 1-day models (STEP & ETAS) to the California testing regions. Unlike the 5-year models, these models fully satisfiy the CSEP rules and are installed as open-source running code in the Testing Center. Furthermore, the testing region is expanded to 3-month models and testing of 7 3-month models started 1 January 2008.

At the Data Working Group Meeting at USC (23 April 2007), the participants discussed a possible Basin & Range testing region. Careful examination of this possible future testing region revealed that earthquake data for forecast generation and testing is provided by ANSS but collected from eight different sources without previous homogenization of magnitudes. The CSEP group decided to postpone the Basin & Range testing region due to the enormous effort necessary to update the existing ANSS catalog for this region and to prepare for future real-time data with homogeneous magnitudes.

The CSEP group in New Zealand fully defined the New Zealand testing region (Figure 54), following mainly the definitions made by Schorlemmer & Gerstenberger (2007) for California. D. Schorlemmer investigated during a summer visit the completeness of the catalog of the

Istituto Nazionale di Geofisica e Vulcanologia (INGV) in Italy using the recently developed PMC method (Schorlemmer, D., & J. Woessner, in print). From this analysis, D. Schorlemmer and the CSEP team in Italy (W. Marzocchi, F. Mele, M. Cocco) derived the future Italian testing region (Figure 54) which will become the first region to implement testing in Europe.

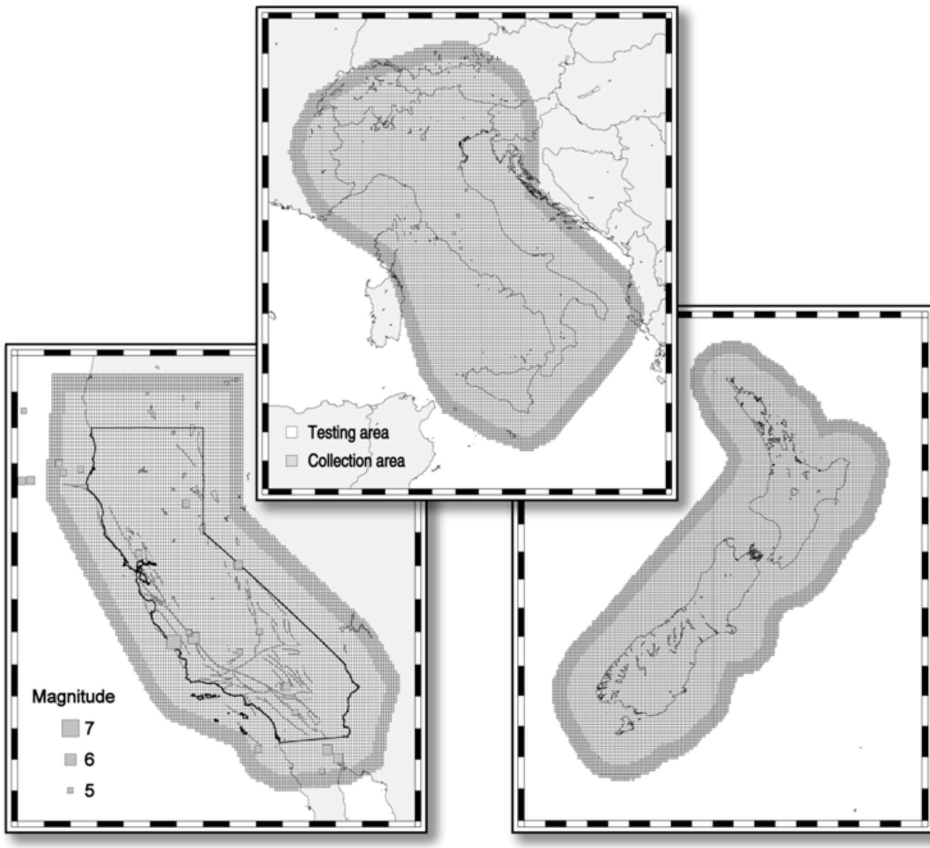

Figure 54. Testing and collection areas of the three defined testing regions. (left) California. (center) Italy. (right) New Zealand.

d. Working Groups

The CSEP core group formed several working groups to discuss and decide about necessary standards regarding data quality and characterization, model submission, testing procedures, and general policies. The first group that held a meeting (23 April 2007 at USC) was the Data Working Group, investigating the quality of the ANSS catalog used for the California testing region and possibly for a future Basin & Range testing region. After the release of version 1.0 of the Testing Center software, the Cyberinfrastructure Working Group held a meeting (19 November 2007 at USC) to discuss the software release and to revisit the software concept of CSEP. Suggestions of this meeting were implemented in the subsequent releases of the Testing Center software. Three more working Groups were formed without holding a meeting in 2007: Testing, Model, and Global Working Group.

e. Communication Grid

The CSEP core set up an efficient communication grid for the wider and global CSEP group. D. Schorlemmer, T. Jordan, and J. Zechar hosted sessions at the Annual Meeting of the Seismological Society of America (Kona, HI), at the StatSei 5 Meeting (Erice, Italy), and at the Fall Meeting of the American Geophysical Union (San Francisco, CA). The CSEP core group hosted together with SwissRe and the CSEP Europe group the Swiss Re Conference on Earthquake Predictability and Time-Dependent Forecasting in Rueschlikon, Switzerland.

The CSEP core group developed a web server concept, that functions as a forum for the different testing centers. Each testing center can host a wiki-based website at USC to present the development of the respective testing center. The web server concept also includes a cental facility to automatically present all results that were computed in any testing center. This structure is designed to be extensible, so that additional natural laboratories and testing centers can be easily incorporated. The web server concept is updated simultaneously with each software release.

f. References

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National Research Council (1993), *National Collaboratories: Applying Information Technology for Scientific Research*, National Academies Press, Washington, D.C.

Schorlemmer, D., & M. C. Gerstenberger (2007), RELM testing center, *Seismol. Res. Lett.* **78***,* 30-36.

Schorlemmer, D., & J. Woessner (in press), Probability of Detecting an Earthquake, *Bull. Seismol. Soc. Am.*

4. 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 (computer) simulations of earthquake rupture are used by SCEC researchers for a variety of purposes – from ground motion prediction at specific sites, such as in the Extreme Ground Motion and PetaSHA DynaShake projects, to the basic research goal of a better scientific understanding of earthquake source physics, an ultimate objective for the SCEC3 FARM and Ground Motion Prediction groups. 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. To date no single numerical method has been shown to be superior for all of the types of problems. Therefore a number of numerical codes are being used, each with its own advantages. These methods 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, other types are better at simulating geologically realistic fault geometry or the propagation of waves through the surrounding heterogeneous rocks.

A 3D rupture dynamics code validation workshop was carried out in March, 2008, using 2007 funds in Pomona, California. The rupture dynamics code validation website is *http://scecdata.usc.edu/cvws/*. This website lists the benchmark descriptions, the participants, and many of the codes being used by modelers, all in an easy-to-use format that is open to the entire SCEC community, as well as being available to scientists outside SCEC.

b. Statistics of Ground Motions in a Physical System

Anderson and colleagues analyzed the statistics of ground motion in a foam rubber analog system. Brune (1973) pioneered the use of foam rubber to investigate the characteristics of dynamic ruptures in a physical system. Foam rubber models have provided valuable insights into earthquake predictability and triggering (Brune et al., 1989), fault normal vibrations and associated slip pulses (Brune et al., 1989; Brune et al., 1993; Anooshehpoor and Brune, 1994), and the lack of frictional heat production during dynamic stick-slip events (Anooshehpoor and Brune, 1994). Previous SCEC funding has been used to record and analyze ~1,400 foamquakes in the strike-slip model (Figure 55) to delineate the particle motion distributions produced by dynamic ruptures in this analog model of an earthquake fault. The strike-slip model consists of two ~ meter sized foam blocks driven past one another via a hydraulic piston. The foam blocks have been instrumented with 64 piezoelectric accelerometers and 6 displacement sensors. We have increased the number of recorded and analyzed events to greater than 6,800, approaching the stated goal of 10,000 events recorded and analyzed in this model. This study developed preliminary descriptions of the statistical characteristics of the particle motion distributions with special attention paid to the largest amplitude motions.

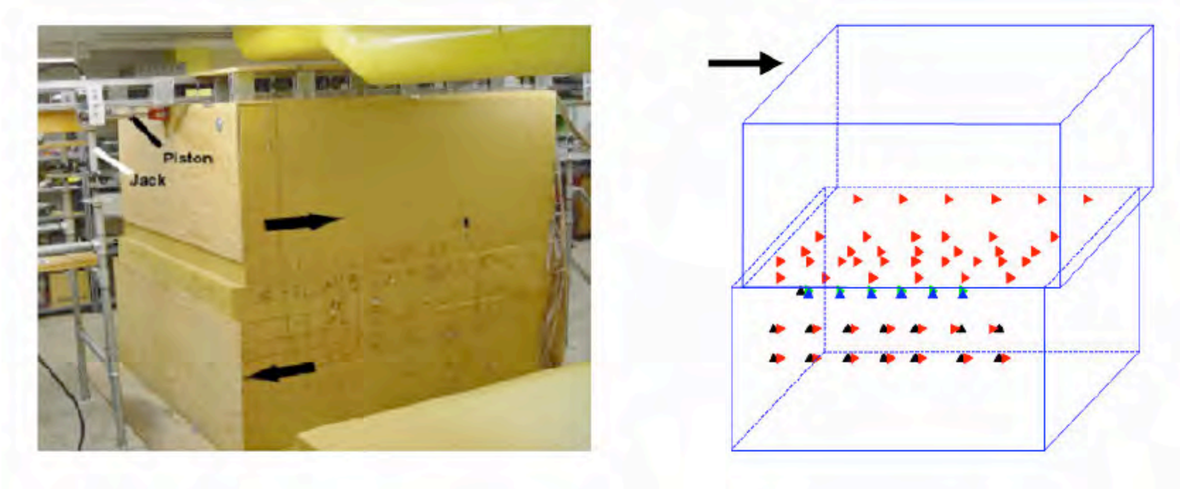

Figure 55. Left: Picture of the strike-slip rupture model constructed of foam rubber. Right: Instrumental layout of accelerometers (red and black) and displacement sensors (blue and green). The front face is similar to the surface of the earth.

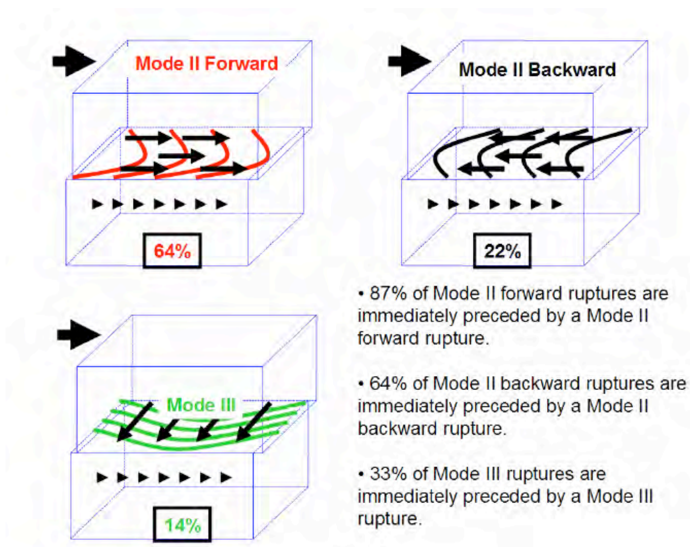

Figure 56. Styles of rupture. Upper left: MIIF; upper right: MIIB; lower left: MIII.

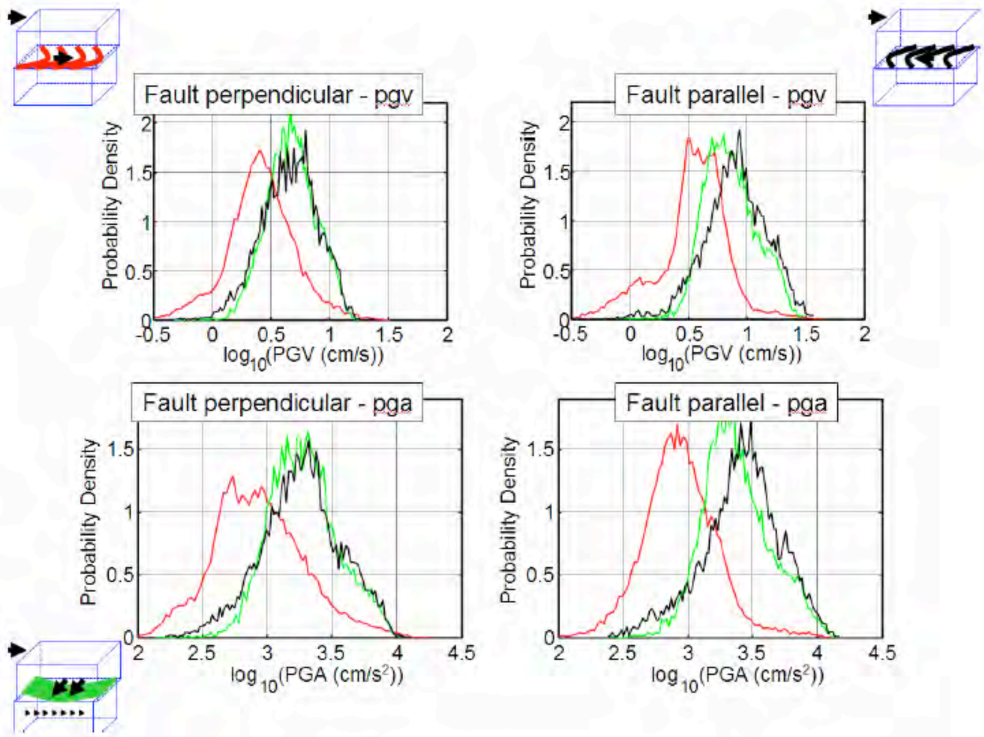

Figure 57. Stacked particle motion distributions for fault parallel/perpendicular PGA and PGV. The colors represent the various rupture styles: red = MIIF, black = MIIB, and green = MIII.

The goal of the project is to record 10,000 events (currently the number stands at 6,800). Observed rupture styles (Figure 56) are correlated in time and particle motion distributions (Figure 57) are inconsistent with the lognormal assumption. The tails of the particle motion distributions are consistent with the reverse Weibull distribution which is bounded. The implications of a bounded distribution for PSHA are that at lower exceedence probabilities, the ground motion amplitudes do not increase forever (unlike the lognormal case). This is of obvious importance for sensitive structures, which require seismic hazard estimates over very long time periods.

c. Inelastic Off-fault Processes During Earthquakes

Dmowska and Rice studied how inelastic deformation (pressure-dependent "plastic" yielding in off-fault damage zones) interacts with the rupture dynamics, with a focus on the origin and evolution of plastic shear strain localization. Templeton and Rice [2007a,b] and Templeton et al. [2007] performed studies on how initial stress state, off-fault yield criterion, and fault friction control rupture speed and off-fault plastic deformation. They conducted plane-strain finite-element analyses of dynamic rupture propagation along a planar fault. In the equivalent plastic strain fields, finger-like patterns of high equivalent plastic shear strain (Figure 58) are apparent for high angles of the most compressive stress. Those shear-band-like features may be evidence of strain localization in the material due to the pressure dependent elastic-plastic yielding. Localization features signal that no conventional continuum solution exists for the model. They began studies to understand the localization features and to address the following questions:

1. Are these features evidence of real strain localization?
2. How do their shape and spacing depend on grid size, mesh alignment, and element type?
3. Is their spacing purely dependent on grid size, or is it related to a physical length scale?

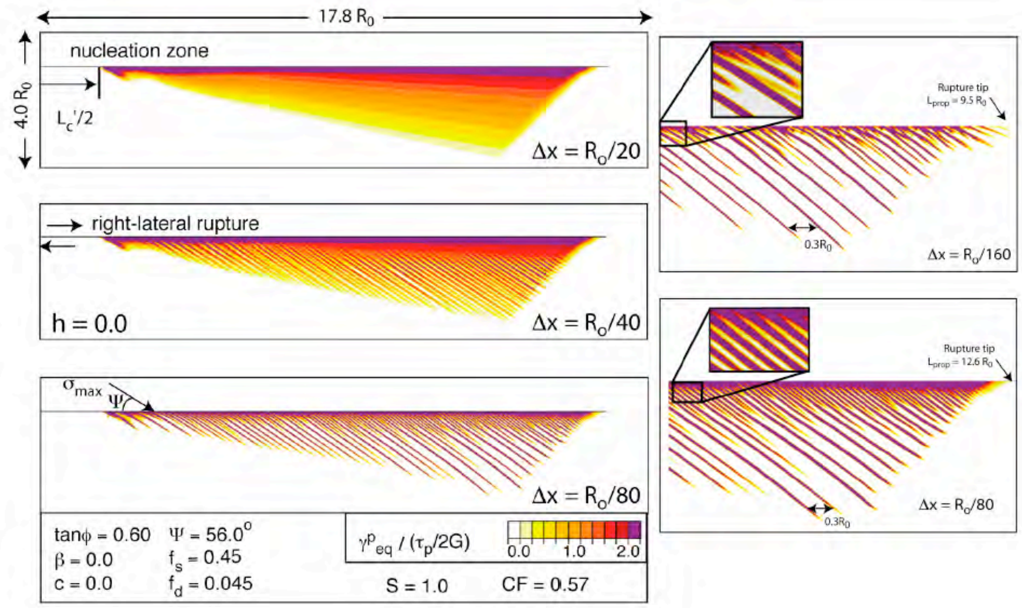

Figure 58. (a) Contours of equivalent plastic shear strain $\gamma/(\tau_p/2G)$ for a high angle of most compressive stress at varying levels of mesh refinement. (b) Contours of equivalent plastic strain near the rupture tip for extremely refined meshes showing spacing between longest localization features of ~3 times the slip-weakening zone length, R_0,

The presence of the localization features, and the recognition that no conventional continuum solution exists, requires that a localization-limiting procedure be added to the constitutive law. To gain insight into the behavior of the system, they used the finite grid size to limit localization.

With adequate mesh refinement, long localization features emerge (Figure 59). They have an average spacing on the order of ~0.3 R_0, which appears to scale not with grid size, but with a relevant physical length scale in the problem. The spacing 0.3 R_0 amounts to 24 and 48 elements. Although the analyses do have inherent mesh dependence at the smaller scales near the rupture surface, and in the thickness of the shear bands, it appears that a characteristic length scale between the long localization features emerges which is independent of mesh refinement.

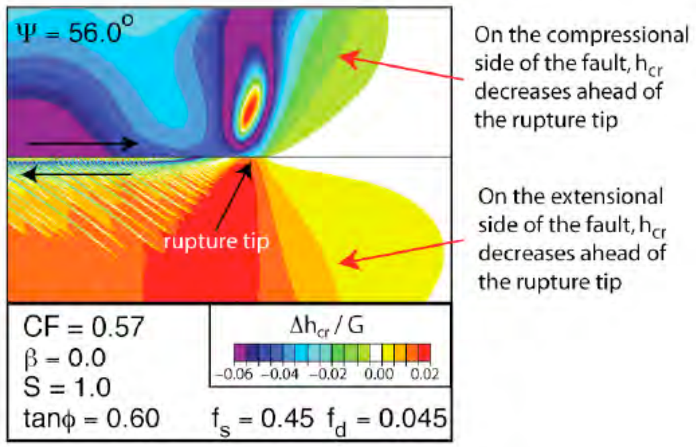

Figure 59. Contours of change in critical strain hardening, h_{cr}, $\Delta h_{cr} = h_{cr} - h_{cr}$, near the tip of a dynamically propagating sub-Rayleigh rupture.

Figure 60 shows the complete elimination of plastic shear strain localization, by including sufficient hardening h in the material description such that h is greater than the maximum local h_{cr} that occurs during the dynamic rupture process. Localization then cannot occur, and the elastic-plastic model becomes well posed, with convergent numerical solutions.

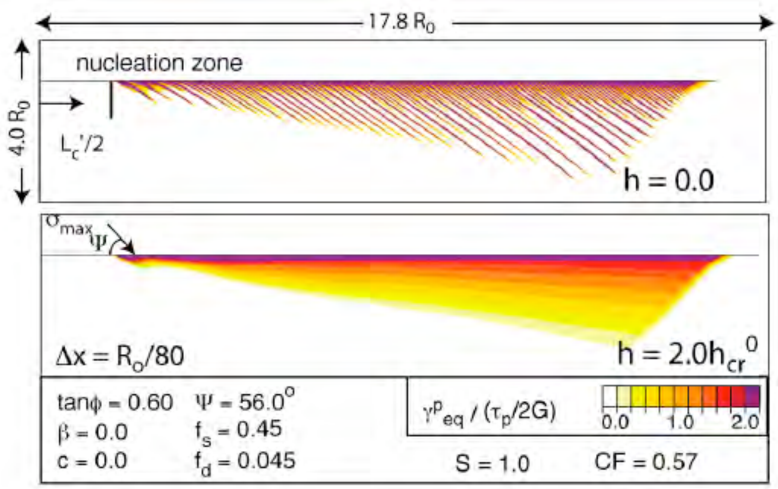

Figure 60. Contours of plastic shear strain for a high angle of most compressive stress and low seismic *S* ratio are shown for a high level of mesh refinement. When the hardening *h* is less that *h*cr, bands of high plastic shear strain emerge in the strain field. These features are not present when *h* is everywhere greater than the local *h*cr, as in the lower panel.

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5. Petascale Cyberfacility for Physics-Based Seismic Hazard Analysis

During this year on the SCEC PetaShake project, the SCEC Community Modeling Environment (SCEC/CME) collaboration has rapidly advanced the capabilities of its geoscientific research codes on the largest and most capable NSF computational systems including the two currently available Track 2 machines, TACC Ranger and NICS Kraken.

An important focus of the SCEC PetaShake project is the development of the SCEC PetaShake computational platform. The PetaShake platform is a high-performance numerical modeling system that enables SCEC researchers to perform basic geoscientific research in the areas of earthquake rupture processes and earthquake wave propagation. The PetaShake platform extends two high-performance, open-source scientific modeling codes—the finite-difference (FD) Olsen code and the finite-element (FE) Hercules code—towards petascale capability. These operational codes are being widely applied to wave propagation simulations, dynamic fault rupture studies, and full 3D tomography. The PetaShake project is also developing the CyberShake computational platform in order to develop its physics-based probabilistic seismic hazard calculations. The CyberShake platform, with its need for ensemble calculations, makes extensive use of grid-based workflow technology on the TeraGrid.

During this performance period, the PetaShake project has produced significant accomplishments in the computational capabilities of the SCEC codes as well as significant geoscientific results running at the largest scales ever attempted by SCEC researchers. We ported one of our PetaShake capability codes AWP-Olsen to the Ranger and used it for science runs. We demonstrated the scalability of our code by running on both NSF Track 2 sites TACC Ranger and NICS Kraken. We designed and configured milestone 1Hz wave propagation simulations on Ranger. This doubled the previous upper frequencies (a 16 times increase in computational requirements) for the codes. Beyond benchmarking of our codes, we performed large scale science runs on Ranger when we ran several large scale simulations in support of the USGS emergency management exercise, the Great Southern California ShakeOut. We also extended the CyberShake Probabilistic Seismic Hazard Analysis Platform to include the latest

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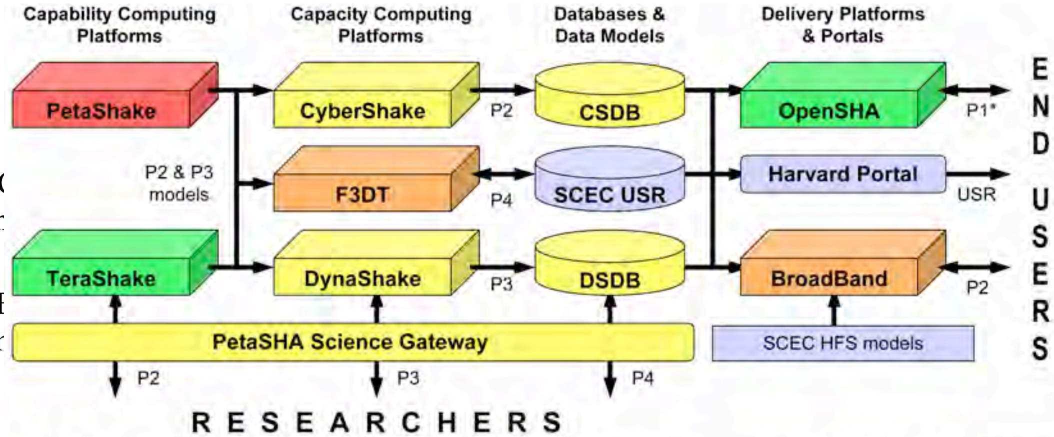

Figure 61. SCEC Computational Platform development is an important focus of the SCEC PetaShake Project. The PetaShake project develops new platforms and extends existing platforms for use on NSF petascale systems.

a. PetaApps Research Using SCEC Computational Platforms

The main science goal of the SCEC CME Collaboration is to transform seismic hazard analysis (SHA) into a physics-based science through high-performance computing (HPC). Our terascale experience on the NSF ITR SCEC/CME project (now completed) has demonstrated that petascale HPC will be required to fully realize this scientific transformation and put it to practical use. Petascale computing is just emerging as a functionally technology, and the NSF has identified a goal of making petascale computing available for qualified academic researchers by 2010. The emerging availability of petascale computing is well aligned with the needs of the geoscience community as we seek to study geosystems and other complex natural phenomena in more detail, at higher resolution, with more realistic physical simulations, and at larger scales.

The SCEC PetaShake project is working to develop new, petascale computational platforms and to extend the capabilities of existing SCEC computational platforms in order to make use of NSF petascale facilities as they become available. Figure 61 shows an overview of the SCEC Computational platforms several of which are being developed and used on the SCEC PetaApps project.

b. SCEC PetaShake Scientific Research Results

Our PetaShake development approach alternates between code development and use of the codes on real scientific problems in leading edge research efforts. By moving back and forth between code improvements and milestone research runs, we verify that the improvements are more than just benchmarking improvements. The application of the improved code to actual research problem ensures that the code can be used for scientific purposes.

The SCEC/CME earthquake system science research program is designed to help SCEC perform transformative geophysical research. The current scientific objectives of the SCEC/CME projects can be summarized in terms of three science thrusts:

1. Improve the resolution of dynamic rupture simulations by an order of magnitude and investigate the effects of realistic friction laws, geologic heterogeneity, and near-fault stress states on seismic radiation.
2. Extend deterministic simulations of strong ground motions to 3 Hz for investigating the upper frequency limit of deterministic ground-motion prediction.

3. Compute physics-based Probabilistic Seismic Hazard Attenuation (PSHA) maps and validate those using seismic and paleo-seismic data.

In the following section, we will describe a number of the more significant scientific results from this year's research program using the current TeraGrid allocation.

i. Dynamic Rupture Slip Matching Technique

The AWP-Olsen codes include numerical modeling subroutines that simulate dynamic rupture processes. The AWP-Olsen codes were used during this performance period to investigate the physics of earthquake ruptures including friction effects, area magnitude relationships, and effects of material contrasts between fault surfaces on rupture behaviors. SCEC researchers, led by Steve Day and Luis Dalguer, 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. The team then used the AWP-Olsen code to implement and evaluate their technique using TeraGrid resources at SDSC (DataStar) and TACC (LoneStar).

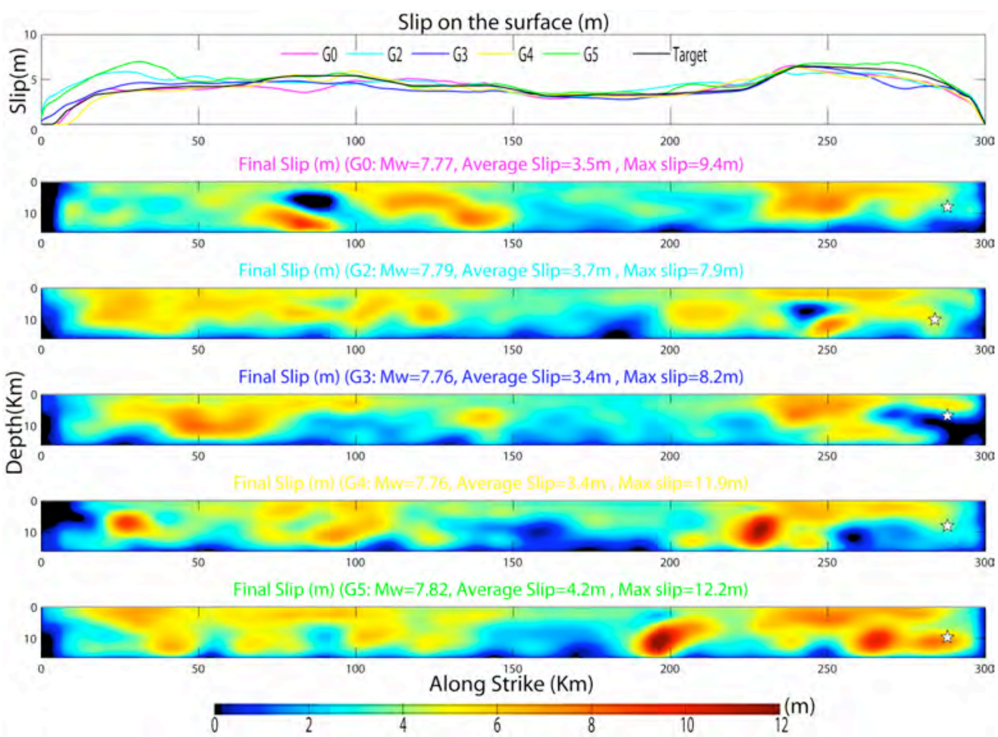

Figure 62. Dynamic rupture simulations of the ShakeOut scenario exhibiting equivalent final surface slip.

This simulation technique produces suites of rupture models with large variation in slip and sliprate, but all satisfying pre-specified slip constraints from observational data or model assumptions. This technique was applied to a large San Andreas Fault scenario earthquake through a series of large-scale TeraGrid simulation which used several million TeraGrid SUs. The resulting ruptures represent a class of ruptures that match constraints on slip, stress drop and moment release along the fault from estimated from historical earthquakes. A collection of these ShakeOut ruptures is shown in Figure 62.

ii. High Frequency Wave Propagation Simulations

A critical goal for the SCEC PetaShake project is to increase the frequencies at which SCEC can run deterministic wave propagation simulations. It is critical to increase the frequencies because the higher frequencies are of interest to civil and building engineers as they seek to understand how structures will respond to earthquakes. Increasing the supported frequencies for deterministic simulations is difficult for both computational and scientific reasons. The computational requirements, using regular mesh in an FD code, increases by a factor of 16 when we double the frequencies (e.g. going from 0.5Hz to 1.0Hz). In addition, there are basic scientific questions as to where and why the simulation results diverge from observational data as simulated frequencies are increased.

SCEC researchers are working to increase the valid frequencies for the deterministic wave propagation simulations of earthquakes. In a series of major SCEC research simulations, three SCEC/CME groups ran high frequency (1.0Hz) simulations of the ShakeOut scenario rupture which used several million TeraGrid SUs at several sites including San Diego Supercomputer Center, TACC LoneStar and TACC Ranger, and Pittsburgh Supercomputer Center.

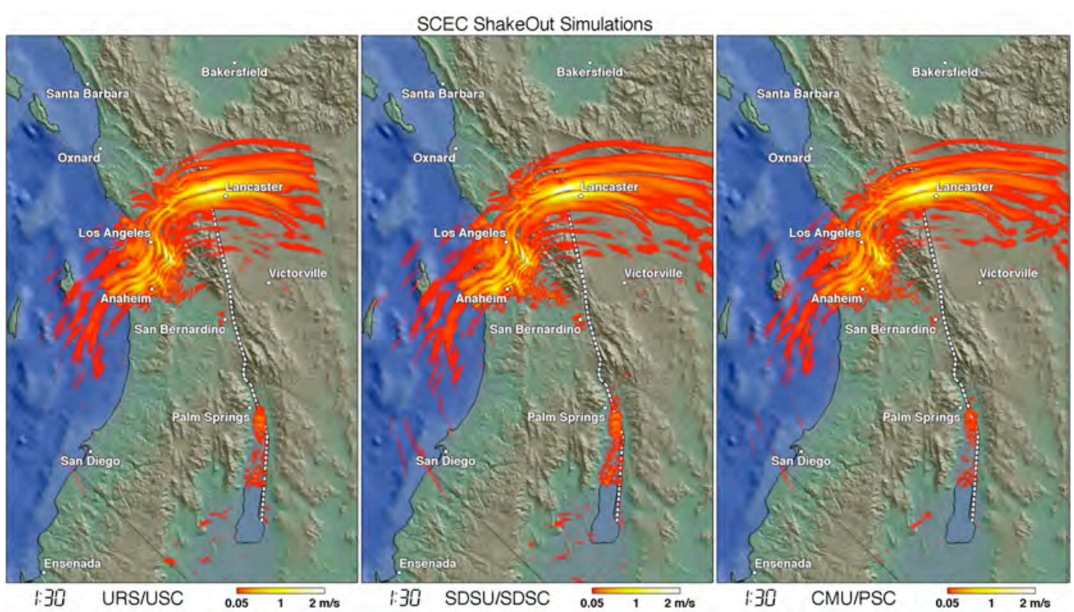

Figure 63. Comparison of ShakeOut (1.0Hz) simulations done by SCEC researchers at USC, TACC, and PSC. The similarities in results build confidence in the modeling codes and approaches.

There are several aspects to the scientific value in these simulations. First, each group was able to extend their simulation capabilities up to 1.0 Hz from the previous limit of 0.5Hz. This doubling in frequency represents a factor of 16 greater computational scales (for the FD codes), and it advances the simulations toward the higher frequencies of interest to building engineers. Next, the collaborative nature of this simulation exercise helped to build confidence in the results. The good match between the levels of ground motion projected by the three simulations, using different codes on different computers, helped to build confidence that the results are valid. A comparison of ShakeOut simulation results is shown in Figure 63.

The SCEC ShakeOut simulations were done in collaboration with the USGS which is using the simulation results as the basis for a large scale emergency management exercise called the Great California ShakeOut. The Great California ShakeOut Exercise, scheduled for November 13, 2008, is the first emergency management exercise that is based on waveform modeling data, a clear indication of the increased acceptance of simulation results. The use of SCEC simulation results in this large-scale USGS public exercise is a good example of how the SCEC research program on the TeraGrid has a direct public impact.

iii. Physics-based PSHA Curves using UCERF2.0

SCEC is working to transform traditional probabilistic seismic hazard analysis (PSHA) by introducing the use of full 3D waveform modeling into the calculations. This is the scientific goal behind the CyberShake project. PSHA uses two critical inputs; 1) an Earthquake Rupture Forecast (ERF), and (2) an attenuation relationship. During this project year, a new ERF for California was released by USGS. 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). Our previous CyberShake hazard curves used a previous generation ERF, so the release of the new ERF prompted recalculation of hazard curves for sites of interest using this new ERF. We integrated the new UCERF2.0 ERF into our CyberShake hazard curve calculations and we are currently re-generating CyberShake hazard curves for sites in southern California to better understand the impact of the new UCERF2.0 on seismic hazards.

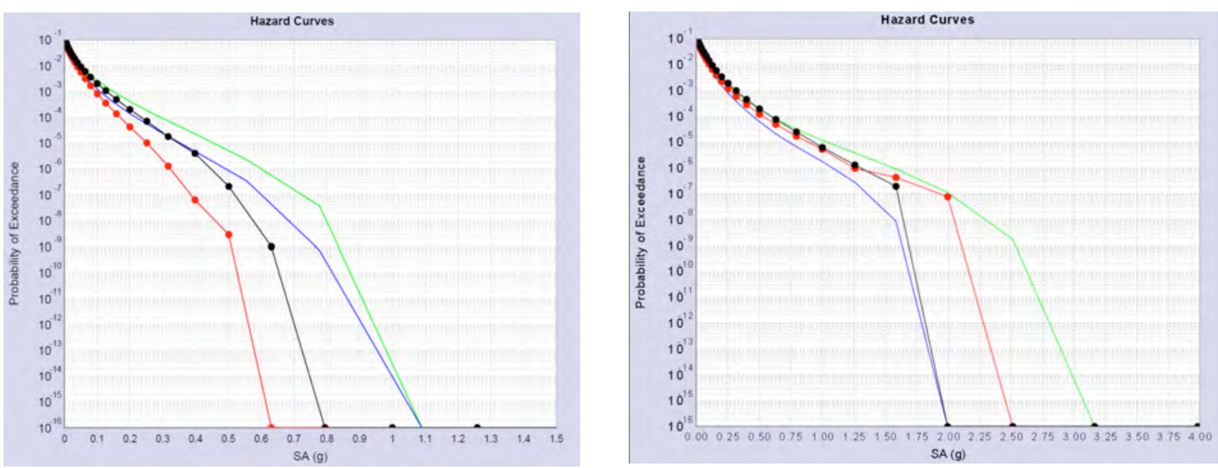

Figure 64. Hazard curve for a Los Angeles area rock site (Pasadena) (left), and a Los Angeles basin site (USC) (comparing) comparing physics-based CyberShake2008 – UCERF2.0 (Black) and CyberShake2006 UCERF 1.0 (Red) to empirically derived hazard curves (Blue, Green).

We used TeraGrid resources at NCSA to calculate physics-based (3D waveform modeling based) probabilistic seismic hazard analysis (PSHA) curves using our CyberShake computational platform. As described earlier, SCEC uses a workflow system based on NSF-funded tools including Pegasus, Condor, and Globus to perform these very large ensemble calculations. During this year, we have extended our workflows to both halves of the simulation (the MPI half and the post-processing half) and we doubled the number of earthquakes we simulate for each site from 200,000 to over 400,000. When we include the seismogram extraction, the peak spectral acceleration calculation, and the data transfers from TeraGrid back to SCEC, our workflows approach 1,000,000 jobs. Two PSHA hazard curves for sites in the Los Angeles area (Pasadena and USC) resulting from these new calculations are shown in Figure 64. Our workflow tools enabled us to scale up without significant redevelopment, and support by the TeraGrid for grid-based job submission enables us to run jobs at multiple computing centers.

c. SCEC OCI 2008 Narrated Video

A narrated video that provides an overview of the SCEC computational research program was produced and contributed to an NSF OCI meeting. A copy of this video is posted on the PetaShake project web site at*: http://scecdata.usc.edu/petasha/documents/scec_movie_xvid.avi*. A higher resolution (500MB) version is also available. This high resolution is nearly 500 MB in size. *http://www.usc.edu/schools/college/multimedia/for_scec/*

d. SCEC PetaShake Project Summary

The SCEC PetaShake project has made significant progress towards our goal of transformative geoscience research using petascale high performance computing. As a broad scientific collaboration with multiple on-going research efforts, we are often an early adopter of NSF and TeraGrid cyberinfrastructure. We believe we are performing a useful role as early scientific users of NSF cyberinfrastructure. In this role, we provide feedback to groups within NSF based on our experiences using NSF cyberinfrastructure for large-scale science research. The PetaShake project continues and encourages this partnership with NSF.

The SCEC PetaShake Project continues to make good progress running on the largest available NSF Track 2 computers. We have good benchmarking results for our capability codes on both NSF Track 2 machines. And we are actively using the systems, especially TACC Ranger, to perform our scientific runs. The SCEC projects are producing significant new scientific results using the HPC resources emerging from the NSF high performance computing initiative.

The NSF petascale initiative is critical to the SCEC science program and we will continue our efforts on this project to make use of the Track 1 system when it becomes available.

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6. CISN Earthquake Early Warning – From Web Site to Testing Center

During this year, a system and software development Group at SCEC worked on the development of the CISN Earthquake Early Warning Project. This year, SCEC research group has extended the CISN EEW web site (*www.scec.org/eew*) to include comparison of CISN EEW reports against ANSS catalog data.

The CISN EEW work this year reflects an important change in how the CISN EEW groups view EEW algorithm performance evaluation. During the first year of the project, the CISN EEW performance evaluation focused on comparing the performance of two or more EEW algorithms. In the second year, the CISN EEW performance evaluation focused on comparing the performance of EEW algorithms against observed seismicity. This shift in emphasis has led to a shift in thinking about what the CISN EEW collaboration wants developed. Original, the SCEC EEW performance evaluation development was envisioned as a web site that presented results from multiple algorithm implementations. This concept has now been refined. The CISN EEW collaboration recognizes that what is needed is an EEW algorithm performance testing center which compares algorithm performance against observed seismicity and delivers its results through a web site. The SCEC development activities this year reflect this shift in thinking by the CISN EEW development collaboration.

We summarize the significant developments during this year, by SCEC researchers in collaboration with UCB, Caltech, and ETH on this project in the following way:

1. We have established routine delivery of CISN EEW reports from two algorithm developments to the CISN EEW webs site and testing center.
2. We have defined a series of performance summaries which compare EEW algorithm reports against observed California earthquake data.
3. We have implemented an automated system which retrieves ANSS earthquake data and generates nightly EEW performance summaries and posts these results automatically on the EEW web site.

a. Web Site Interface Improvements

Improvements to the appearance and usability of the CISN EEW were made this project year. Both the appearance and contents posted on the web site have been updated based on feedback from site users. The home page for the web site is shown in Figure 65. Currently the CISN EEW web site has 23 registered users.

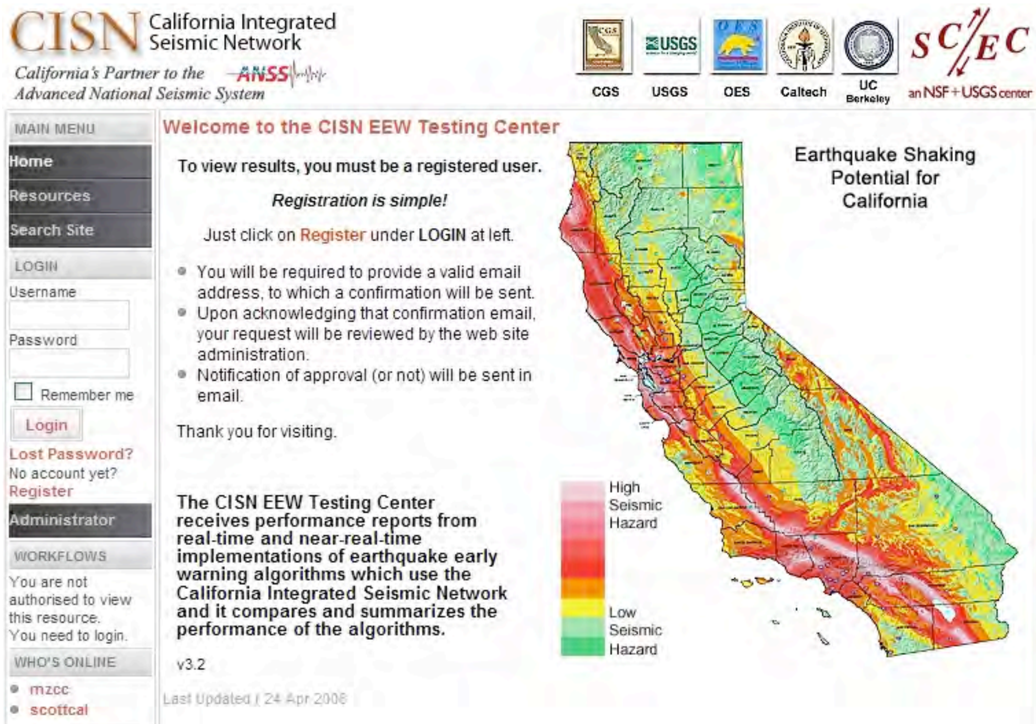


Figure 65. The home page for the CISN EEW Web site (*http://www.scec.org/eew*).

b. Definition of Reporting Times

During this project year, the CISN EEW groups developed refined approaches to time reporting for EEW algorithms. The CISN research groups reviewed how time was reported by the algorithms within the Project and as an outcome of those discussions, two specific types of times (Algorithm Time and Alert Time) have now been identified for EEW reports. Algorithm time and alert time both refer to the time stamps that are placed on "warnings" produced by EEW algorithms.

When an algorithm reports a warning, a time is associated with the warning. We now recognized that the timestamp on an EEW warning report may represent the time stamp on the data used, or it may represent the time the warning was produced. Both of these time stamps may be included in an EEW warning report. Time stamps in EEW warning reports should identify which type of time is being reported.

We define algorithm time as the "largest" time on any data used in the warning. The algorithm time represents the "best case" time that the algorithm can produce for a specific warning. No telemetry delay or processing delay affects the algorithm time. The algorithm time should be reproducible even in off-line or batch-oriented implementations of the EEW algorithms.

Certain algorithms, such as the OnSite algorithm, require specific amounts of data, such a p-wave arrival plus four seconds of data, to produce a warning. These algorithms are expected to produce EEW reports with algorithm time stamps that equal the P-wave arrival at the reporting station plus four seconds.

We define alert time for an EEW warning as the “real-time” or the “wall-clock time” that that warning was produced by the EEW algorithm and processing system. The Alert Time on an EEW warning includes the real-world time delays including telemetry and processing delays. The EEW alert time will be vary (get larger) if EEW algorithms are run in a delayed or off-line mode. However, the alert time is critical to real EEW performance because alerts distributed to users will always be equal to or greater than the alert times. These definitions are included in the 03 March 2008 EEW performance evaluation testing document described below.

c. EEW Exchange Format

During CISN EEW project year 1, the collaboration developed an EEW algorithm data exchange format. This XML format provides a standardized way for EEW algorithms to report the information that they produce during earthquakes. This format is not expected to be used as a real-time format.

During year 1, the formats were designed, and initial implementations were created. During year 2, improvements and modifications were made to these reporting formats based on our Year 1 experiences. A new XML reporting format, called a “Triggered Format” was introduced. This format was introduced for use by the Caltech OnSite algorithm. The ElarmS algorithm continues to report its results in a time series format. An example of the recent CISN EEW Triggered XML format is included in the appendices. The XML formats were updated to include more complete Station, Network, Channel, Location codes when reporting predicted amplitudes. This additional information helps us map forecasted ground motions with observed amplitudes. The XML formats were also expanded to include specification of both the Algorithm Time and the Alert time as discussed above.

d. Performance Reporting Specification

An important CISN EEW Project document titled *EEW- Algorithm Testing Document* was produced on 3 March 2008 in which the collaboration defined the performance summary reports which were to be produced by the CISN EEW Testing Center. The development of this document was initiated at a CISN EEW meeting in Pasadena in March 2008, and was lead by Caltech’s Egill Hauksson and Maren Boese. The document that emerged provides a clear definition of terms used in CISN EEW algorithm development, and defines how EEW algorithm performance will be compared against observed seismicity. This document calls for the following performance summaries:

1. **Magnitude Summary.** How closely do the EEW algorithms forecast the final magnitude of the event?
2. **Location Summary.** How closely do the EEW algorithms forecast the location of the event?
3. **Ground Motion Estimates Summary.** User MM Intensity, how closely do the EEW algorithms forecast the peak ground motions within their networks?
4. **System Performance Summary.** What percentage of the networks stations are operating and reporting on EEW for each event?
5. **False Triggers Summary.** Create a list of false triggers, that is, a list of EEW reports that are not correlated with actual earthquakes.

6. **Missed Triggers Summary.** Create a list of missed triggers, that is, a list of events greater than a specified magnitude (e.g. 4.0) for which no EEW reports were generated

The production of these performance summaries helps to define the development activities for the CISN EEW testing center and web site for year 2 and year 3 of this project.

e. Testing Center Infrastructure

The functionality of the CISN performance evaluation web site was significantly enhanced this year by the inclusion of observed ANSS data into the algorithm performance evaluation processing. In order to implement the ANSS catalog retrieval capabilities in rapid an inexpensive fashion, SCEC leveraged a software code base from another SCEC testing project called the W.M. Keck Collaboratory for the Study of Earthquake Predictability (CSEP) (*http://www.scec.org/csep*).

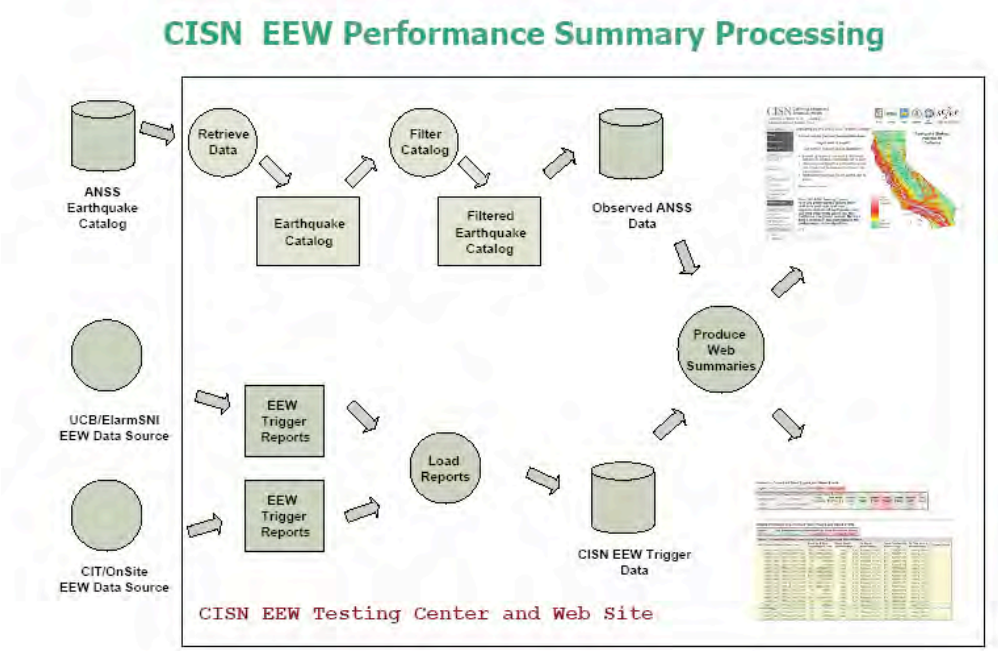


Figure 66. The CISN Testing Center retrieves ANSS data to evaluate the CISN EEW algorithms.

The goal of CSEP is to develop an earthquake forecast testing center that can evaluate a wide range of scientific earthquake prediction experiments in multiple regional or global natural laboratories. 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. Initial development of the CSEP testing center is funded by the W. H. Keck Foundation.

Based on strong similarities in both the scientific goals of the CSEP and EEW warning performance evaluation systems, and the software infrastructure required to test short term earthquake forecasts (CSEP) and real-time early warning forecasts (CISN EEW), we have adapted a version of the CSEP testing framework for use with CISN EEW testing center. The CSEP software framework is an open-source, freely distributed, testing framework that is primarily developed at SCEC and which has been adopted for use at other seismic testing centers including GNS in New Zealand and at ETH. An overview of how the CSEP testing center framework interfaces to the ANSS data source is shown in Figure 66.

f. Performance Summaries

Once the CISN EEW testing center was able to access ANSS data, we were able to begin to implement the EEW Performance Summaries identified in the EEW testing document. Three of the 6 performance summaries have been prototyped, and the other 3 additional summaries are under development. In addition to the summaries specified in the EEW Performance Evaluation, we have identified and implemented a small number of additional summaries that we feel are useful to the CISN EEW researchers. As of July 1, 2008, the following summaries are posted on the CISN EEW web site:

1. Cumulative Catalog. This shows the current event information we retrieved from the ANSS catalog. This is the reference data against which we compare the EEW reports
2. Cumulative Location Summary. This compares the Latitude Longitude estimates for the EEW triggers against the Latitude and Longitude results in the ANSS catalog for each event.
3. Cumulative Magnitude Summary. This compares the EEW trigger predicted final magnitude for the event against the final magnitude from the ANSS catalog.
4. Cumulative Trigger Summary. This compares the triggers reported by the EEW algorithms against the events in the ANSS catalog showing hits and misses.
5. Cumulative Warning Performance Summary. Prototype of Warning Summary – this summary has no live data and the summary shown on the web site a static format prototype.
6. Data Sources Summary. Describes which Algorithm implementations are sending data to the CISN EEW testing center and web site.

These performance summaries are updated nightly. The CISN EEW web site requires a login. A login can be easily requested through the public portion of the web site.

i. Example of EEW Performance Summaries

Below is an example of a performance summary currently being generated on a by the CISN EEW testing center. These performance summaries are produced on a daily basis and are available by logging into the web site. This report shows a list of ANSS events (Ml >3.0), and also show that an EEW algorithm at CIT has reported EEW performance for some of these events. ANSS events are shown with the most recent events at the top and older events following in chronological order. When an EEW trigger correlates to an actual ANSS event, additional checks are done before a “correct trigger” is declared. The EEW trigger must predict the Magnitude within 1 unit, and the event origin time must be within 30 seconds. The detailed trigger summary page is shown in Figure 67.

Starting at the top of this detailed trigger summary, we can see that several Ml > 3.0 ANSS events occurred on June 28 and June 27 for which no EEW triggers were reported. On June 26th, an Ml 3.66 event occurred. The Caltech OnSite EEW Algorithm running on niobite1 declared an event and forecast a final magnitude that was within 1.0 units of the actual final magnitude. Several more events and triggers are shown in which the OnSite algorithm triggered and produced information close to the observed information.

We are working to improve and finalize these performance summaries and put them online so that they accurate describe the CISN EEW performance. We will announce to the group when the system is 'operational' and the performance summaries reflect true EEW algorithm performance for the CISN.

Detailed information on Correct and False Triggers, and Missed Events

Legend	Only those parameter cells responsible for these situations are colored.				
ANSS Events	Correct Triggers	Missed Events	False Triggers	Data Agreed	Data Disagreed

Phase 1: For each ANSS Event, searching for Correct Triggers and Missed Events

ANSS Event *or* Trigger Status,	Time	Event Net & ID *or* Trigger Report Time		Event Mag *or* allowed range		Est Mag *or* allowed range		Event Time (sec) *or* allowed range		Est Time (sec) *or* allowed range		Trigger Source	
ANSS Event	2008-06-28 04:02:20	CI	14377764	Mag	3.41	*Allowing* (-1.0+1.0)		EVt	1214625740	*Allowing* (-0+30)			
ANSS Event	2008-06-27 19:04:13	CI	14377656	Mag	3.02	*Allowing* (-1.0+1.0)		EVt	1214593453	*Allowing* (-0+30)			
ANSS Event	2008-06-27 17:44:19	CI	14377620	Mag	3.14	*Allowing* (-1.0+1.0)		EVt	1214588659	*Allowing* (-0+30)			
ANSS Event	2008-06-26 04:03:59	CI	14377236	Mag	3.66	*Allowing* (-1.0+1.0)		EVt	1214453039	*Allowing* (-0+30)			
Correct Trigger	2008-06-26 04:04:16	*2008-06-26 04:04:27*		Mag	3.66	EstMag	4.65	EVt	1214453039	ESt	1214453056	Src	niobite1
ANSS Event	2008-06-26 01:42:35	CI	14377180	Mag	3.66	*Allowing* (-1.0+1.0)		EVt	1214444555	*Allowing* (-0+30)			
Correct Trigger	2008-06-26 01:42:49	*2008-06-26 01:43:00*		Mag	3.66	EstMag	3.53	EVt	1214444555	ESt	1214444569	Src	niobite1
ANSS Event	2008-06-25 20:24:56	CI	14377108	Mag	3.40	*Allowing* (-1.0+1.0)		EVt	1214425496	*Allowing* (-0+30)			
ANSS Event	2008-06-23 14:14:57	CI	14376612	Mag	4.00	*Allowing* (-1.0+1.0)		EVt	1214230497	*Allowing* (-0+30)			
Correct Trigger	2008-06-23 14:15:05	*2008-06-23 14:15:11*		Mag	4.00	EstMag	3.54	EVt	1214230497	ESt	1214230505	Src	niobite1
Correct Trigger	2008-06-23 14:15:03	*2008-06-23 14:15:13*		Mag	4.00	EstMag	3.56	EVt	1214230497	ESt	1214230503	Src	niobite1
Correct Trigger	2008-06-23 14:15:07	*2008-06-23 14:15:13*		Mag	4.00	EstMag	3.60	EVt	1214230497	ESt	1214230507	Src	niobite1

Figure 67. Prototype cumulative trigger summary

ii. Warning Performance Summary

In addition to the performance reports in the 03 March 2008 document, we have defined an Earthquake Early Warning Performance Summary. The goal of this report is to identify which stations within a network would have received an early warning for a given event if the CISN EEW algorithms were distributing warnings to users. This performance summary uses the "alert time" produced by the EEW algorithms and the time of observed peak ground motion as recorded by the network. This performance summary attempts to answer the practical question of whether useful early warnings are produced by the current algorithms. A prototype of this report is shown in Figure 68.

Back **Cumulative Warning Performance for Mag > 3.0 Jan 1, 2008 - Jun 28, 2008 for California Region**

Network ID	Event ID	Event Time	Mag	# Stations with Obs	Data Source	Stations Receiving Early Warning			Stations Receiving Late Warning		
						Accurate Amp	Underpredicted Amp	Overpredicted Amp	Accurate Amp	Underpredicted Amp	Overpredicted Amp
CI	10319993	2008-04-23 01:55:29	4.14	143	cinnabar	2	5	13	43	62	18
CI	10319993	2008-04-23 01:55:29	4.14	143	elarmsNI	3	5	8	27	32	68

Figure 68. Prototype of Early Warning Performance Summary (Prototype - Not Actual System Performance).

g. Summary of EEW Testing Center Benefits

We believe that ideas behind the CISN EEW testing center have developed into positive and useful concepts which have significant value to the CISN and the USGS as they work towards an operational EEW system in California. The primary benefits of an EEW testing center may be identified as the following:

1. A testing center encourages algorithm developers to produced equivalent and comparable results.
2. A testing center helps define the evaluation criteria, and to create well defined rules for testing such as region under test, time under test, earthquake magnitudes to be considered, and data sources which are considered the authoritative.
3. A testing center operated by a neutral third party helps to reduce the controversy about performance claims by any one algorithm developer.
4. A testing center which provides transparent and reproducible results will build credibility in performance claims.
5. A testing center doing prospective tests helps eliminate the bias inherent in standard retrospective approaches.

IV. CEO Report

A. Introduction

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

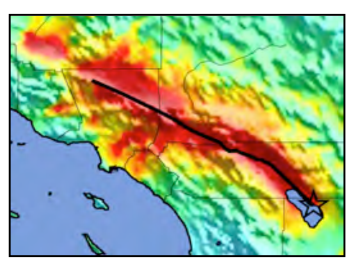
- Coordinate productive interactions among a diverse community of SCEC scientists and with partners in science, engineering, risk management, government, business, and education;
- Increase earthquake knowledge and science literacy at all educational levels, including students and the general public;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

These goals were identified through several workshops involving SCEC scientists and our partner organizations, who were also involved in developing and fulfilling CEO short-term objectives 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.

A key aspect of SCEC's success is the many partnerships that have been sustained to achieving SCEC's mission, research objectives, and outreach goals. These partners include: other science organizations such as IRIS, EarthScope, and UNAVCO; engineering organizations such as PEER, CUREE, and EERI; Education organizations such as Los Angeles County Unified School District, Southern California County Offices of Education, USC Family of Schools, museums, and the National Association of Geoscience Teachers (NAGT); and Public Service / Risk Management organizations such as California Office of Emergency Services, the California Earthquake Authority, FEMA, and the American Red Cross.

The following are select Public Outreach and Education highlights of activities in the last year.

B. Public Outreach Activities



Great Southern California ShakeOut. The major focus of the 2007-2008 CEO program has been co-organizing this week of special events featuring the largest earthquake drill in U.S. history, developed to inspire Southern Californians to get ready for big earthquakes, and to prevent disasters from becoming catastrophes. At 10 a.m. on November 13, 2008, millions of southern Californians will "Drop, Cover, and Hold On" to practice what to do when a major earthquake happens. Individuals, families, businesses, schools and organizations will join firefighters and other emergency responders (involved in the statewide "Golden Guardian" exercise the same week) in our largest-ever earthquake preparedness activity.

As of August 29, over 2.5 million participants have been registered to participate at www.ShakeOut.org. The goal is for 5 million people total to participate on November 13. Registered participants will receive information on how to plan their drill, connect with other participants, and encourage a dialogue with others about earthquake preparedness. This is the largest public outreach activity for earthquake awareness and preparedness ever attempted (perhaps in the country) and an unprecedented opportunity to educate the public.

ShakeOut is based on a potential 7.8 magnitude earthquake on the southern San Andreas Fault. This type of earthquake occurs in southern California every 150 years on average, and the last was 151 years ago! Dr. Lucy Jones (USGS) has 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 many who produced the ShakeOut Simulation. The final simulation used in analysis of losses was by Rob Graves, and the visualization was by Geoff Ely.

In summary, the ShakeOut Scenario estimates this earthquake will cause some 2,000 deaths, 50,000 injuries, $200 billion in damage and other losses, and severe, long-lasting disruption. The report has regional implications and is a dramatic call to action for preparedness, and is available at www.ShakeOut.org.

In addition to the ShakeOut drill, the City of Los Angeles and the Earthquakes and Megacities Initiative (of which SCEC CEO director Benthien is the Los Angeles liaison) is hosting an International Earthquake Conference November 12-14, bringing together over 45 international experts to discuss policy, planning, and preparedness with U.S. counterparts. Online registration is available, and early registration incentives are available through the end of August. More information can be found at www.iec.lacity.org.

On Friday, November 14, Art Center College of Design will present the “Get Ready Rally” at the new Nokia LA Live in downtown Los Angeles to engage the public in earthquake preparedness. All southern Californians are invited to celebrate the success of the Drill and share their experiences. There will be food, entertainment, and vendors.

Organizers and participants of the ShakeOut include: 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 business, schools and governments in Riverside, San Bernardino, Orange, Los Angeles, San Diego, Imperial, Kern, Santa Barbara, and Ventura Counties. Also, many other members of the Earthquake Country Alliance.

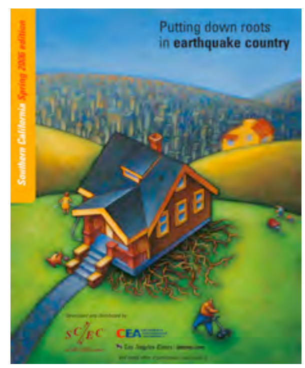
To be able to reach communities throughout southern California, the ECA is launching “Regional Associate” groups in each county, charged with spreading the word locally to encourage residents to register to participate in the ShakeOut:

- The San Bernardino County is co-chaired by County Supervisor Brad Mitzenfelt and ESRI President Jack Dangermond.
- The Los Angeles Group led by County Fire Chief P. Michael Freeman and LA Area Chamber of Commerce President Gary Toebben.

- Riverside County Associates are led by Congresswoman Mary Bono Mack and County Emergency Manager Peter Lent.
- San Diego County Associates are led by County Emergency Manager Ron Lane, City of Vista Fire Chief Gary Fisher and City of La Mesa Fire Chief David Burk.
- Orange County Associates are led by County Emergency Manager Donna Boston and County Office of Education
- Associate groups for other counties are in formation.

Sponsors of the Great Southern California ShakeOut activities include USGS, National Science Foundation, FEMA, California Office of Emergency Services, Home Depot, City of Los Angeles, State Farm, California Earthquake Authority, Kaiser Foundation Health Plan, Tyco Electronics, Provention Consortium, Dewberry, Degenkolb, Network for Earthquake Engineering Simulation, Institute for Business & Home Safety, ABC7, and others soon to be announced. Organizations wishing to support ShakeOut activities can learn more at www.ShakeOut.org/sponsors.

All SCEC members are encouraged to participate. G to www.ShakeOut.org and register your family, school, business, or organization's participation in the drill. Registered participants will receive information on how to plan their drill, encourage others to participate, and improve their earthquake preparedness. It all begins with registering, which is free and open to everyone.



Putting Down Roots in Earthquake Country. In 1995 the Southern California Earthquake Center (SCEC), US Geological Survey (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.

For the 10-year anniversary of the Northridge earthquake, a new version was produced by SCEC and the newly-formed Earthquake Country Alliance. The updated handbook features current understanding of when and where earthquakes will occur in Southern California, how the ground will shake as a result, and descriptions of what information will be available online. The preparedness section is now organized according to the "Seven Steps to Earthquake Safety." These steps provide a simple set of guidelines for preparing and protecting people and property.

Since 1994, over 2.2 million copies have been distributed of the new version, with 1.3 million copies distributed via the Los Angeles Times as a "topper"- the booklet was bound on the cover of the Sunday, April 9, 2006 newspaper. Copies of the document have been distributed at home improvement centers (on tables with preparedness products), by the American Red Cross (at neighborhood safety trainings), and by many others. A major revision incorporating new research will be produced in September, 2008. The updated handbook is now 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.

A notable acheivement in early 2006 was the first-ever Spanish version of Putting Down Roots. A team of Spanish-speaking scientists, emergency managers, and educators worked together to translate the text. 100,000 copies are now being distributed in Southern California. In Spring 2007, a new printing of 600,000 copies (funded by CEA) were distributed through Hoy (LA Times Spanish-language newspaper), the Los Angeles Mexican Consulate, and other venues, with media promotion on TV and Radio. In September, 2007, another 450,000 copies were be distributed in La Opinion newspaper and through other partners, with an even larger media promotion on Univision.

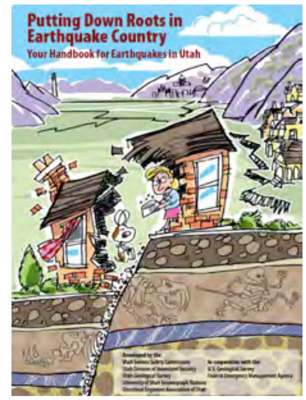
Putting Down Roots is the principal SCEC framework for providing earthquake science, mitigation, and preparedness information to the public. The "Roots" framework extends beyond the distribution of a printed brochure and the online version. For example, the Birch Aquarium in San Diego developed an earthquake exhibit which featured a "Seven Steps" display, and the Emergency Survival Program (managed by LA County) will be basing it's 2006 campaign around the "Seven Steps." In October 2004 over 15,000 copies were included in the Earth Science Week packets distributed to science teachers and others nationwide.

The new version of Putting Down Roots was designed to allow other regions to adopt its structure and 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. The handbook was revised with Bay Area hazards and a new section called "Why Should I Prepare?" was added that includes scenarios for likely damage, casualties, etc., and how life will change during a large earthquake in the region. Over 750,000 copies were printed in September, 2005, with funding from the California Earthquake Authority, USGS, FEMA, Red Cross, OES, CGS, and several others). 500,000 of these copies (with an inserted coupon for furniture straps and other mitigation products) were distributed in the San Francisco Chronicle. To commemorate the Centennial of the 1906 San Francisco earthquake, an additional one million copies were printed and distributed in many Bay Area newspapers, the USGS, and other partners, along with a calendar of activities for the anniversary. In Spring, 2007, 500,000 more copies were printed (with minor updates, including a new "Seven Steps" image). The Bay Area booklet can also be accessed from www.earthquakecountry.info/roots. All printings of the Bay Area version to date have been coordinated through SCEC.

In 2006, the USGS with many Bay Area partners created a new booklet in the Putting Down Roots series, featuring primarily the "Seven Steps" content and produced in two versions- English and Spanish in one booklet, and English, Chinese, Korean, and Vietnamese in another booklet. This new product is titled Protecting Your Family From Earthquakes– The Seven Steps to Earthquake Safety. Developers included the American Red Cross, Asian Pacific Fund, California Earthquake Authority, Governor's Office of Emergency Services, New America Media, Pacific Gas and Electric Company, U.S. Department of Homeland Security Federal Emergency Management Agency, and U.S. Geological

Survey. The CEA, FEMA, and others provided funding for 640,000 copies of the English-Spanish version and over 360,000 copies of the English and Asian languages version, with printing coordinated through SCEC. A multi-language media campaign in early 2007 promoted the distribution of the booklets. In September, 2007, 70,000 copies of each booklet were reprinted in order to continue distribution.

For 2008, many Roots-related efforts are underway:



- The first-ever Utah version of Putting Down Roots in Earthquake Country
- Living on Shaky Ground, an update to the well-known earthquake booklet for California’s north coast, which will include now the Seven Steps to Earthquake Safety
- The Seven Steps to an Earthquake Resilient Business, an exciting new 16-page supplement for businesses developed by a committee organized by SCEC.
- A major update of the Southern California version of Roots to include UCERF probability estimatesand ShakeOut Scenario results.

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:

- inspire responsibility for community earthquake safety and recovery;
- increase awareness, preparedness, mitigation;
- improve response and recovery planning;
- reduce losses in future earthquakes.

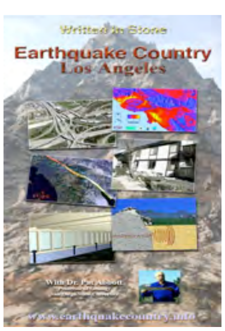
The ECA is now the primary SCEC framework for maintaining partnerships and developing new products and services for the general public.

In Summer, 2006, members of the ECA began to organize the Dare to Prepare Campaign, to achieve widespread awareness and preparedness goals 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 acknowledges that "Shift Happens," and if you "Secure Your Space" you can protect yourself, your family, and your property. If you live in earthquake country, secure your space by strapping top-heavy furniture and appliances to walls, adding latches to kitchen cabinets, and securing TVs and other heavy objects that can topple and cause serious injuries. Homes and other buildings should be retrofitted if necessary. These and other actions will greatly reduce your risk of damage or injury, and limit your need for community resources after the next earthquake. On January 9, 2007 a major press briefing was held to kickoff the Dare to Prepare campaign, including local, state, and federal government representatives, SCEC scientists, and ECA partners. A new website (www.daretoprepare.org) was announced, along with other components of the campaign:

- Movers and Shakers: leadership group of prominent Southern California elected officials, business and community leaders, and others;
- Local activities: public events throughout the region (presentations, preparedness fairs, etc.), including demonstrations of Big Shaker, a large portable earthquake simulator;
- Media campaign: television, radio, and print promotion, PSAs, on-air interviews, etc. (Fall)
- Great Southern California Shakeout, a regional public earthquake exercise planned for 2008 (see above)

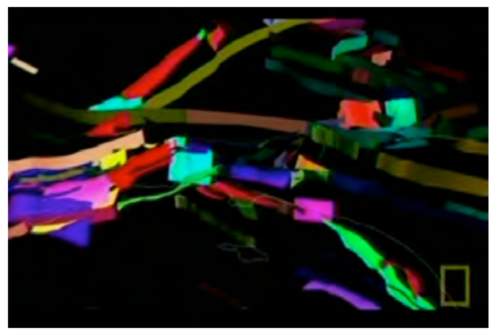
Earthquake Country Alliance Website. SCEC developed and maintains this web portal (www.earthquakecountry.info.), which provides multimedia information about living in earthquake country, answers to frequently asked questions, and descriptions of other resources and services that ECA members provide. The portal uses technology developed for the E3 project (see above). Each ECA member can suggest links to their organization's resources as answers to questions listed on the site. 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).

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's "LA3D" visualization system. In addition to conducting several focus groups with teachers and preparedness experts where the video was evaluated, SCEC is also developing curricular kits for school and community groups to accompany the video, and has added captions in both English and Spanish. These kits will be duplicated in large quantities with funding from the California Earthquake Authority. The Los Angeles Unified School District has asked SCEC to train teachers how to use these curricular kits, and may include the video in a new sixth-grade Earth science curricula soon to be adopted district wide.

Emergency Survival Program. SCEC serves on the Coordinating Council of the Los Angeles County-led Emergency Surival 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 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 also, 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 ("LA3D" animations) and in other venues to communicate earthquake hazards and encourage preparedness. These products, including the SCEC Terashake simulations, Puente Hills earthquake simulation, and Community Fault Model (CFM), 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. Each earthquake simulation is not just a scientific hypothesis, but a visualization of a potential real earthquake that could cause extensive damage and loss of life beyond what has been experienced in southern California previously. SCEC CME visualizations help the public understand how the shaking they may experience will be very intense, and how long it will last. These visualizations were featured extensively in the National Geographic Channel documentary "Killer Quake," which presented SCEC Terashake and Puente Hills animations, along with SCEC VDO fault movies.

C. 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. a lesson plan, an evaluation instrument, a website) 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.

1. SCEC Experiential Learning and Career Advancement programs

Undergraduate Internships. SCEC has provided internships to over 220 students since 1994. SCEC interns are typically paid a stipend of $5000 over the summer with support from the NSF REU program. SCEC offers two summer internship programs, SCEC/SURE, and SCEC/USEIT. These programs are the principal SCEC 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 *http://www.scec.org/internships*.

The SCEC Summer Undergraduate Research Experience (SCEC/SURE) has supported students to work one-on-one as student interns with SCEC scientists since 1994. SCEC/SURE has supported students to work on numerous issues related to 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. Summer interns interact in a collaborative, team-oriented, interdisciplinary research environment and are mentored by some of the nation's most forward-thinking earthquake and computer scientists. Research activities are structured around "Grand Challenges" in earthquake information technology. Each summer the interns build upon the foundation laid by previous sessions as they design and engineer increasingly sophisticated visualization tools.

ACCESS. Our USEIT and CME experience has identified a "weak link" in CI-related career pathways: the transition from discipline-oriented undergraduate degree programs to problem-oriented graduate studies in earthquake system science. We are addressing 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 (CI) development. Its overarching goal is to prepare a diverse, CI-savvy workforce for solving the fundamental problems of system science. Three programmatic elements have been developed to achieve this goal: (1) 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. (2) 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. (3) The ACCESS Forum, a new working group managed under the SCEC CEO program to promote CI careers in earthquake system science.

2. 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).

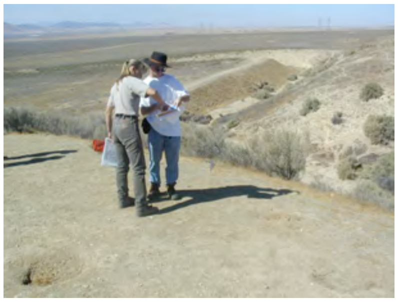
ShakeZone Earthquake Exhibit (Fingerprints Youth Museum, Hemet, CA) Developed originally in 2001, ShakeZone was redesigned in 2006. The current version of the exhibit is based on SCEC's Putting Down Roots in Earthquake Country handbook. Major partners involved in the exhibit redesign included Scripps Institution of Oceanography and Birch Aquarium at Scripps. With funding from the United Way and other donors ShakeZone will be expanded in 2009 to include a section on Earthquake Engineering.

Living on the Edge Exhibit (San Bernardino County Museum, Redlands, CA) 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

Hall of Geological Wonders (San Bernardino County, Redlands, CA) Due to be completed in mid-2009 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. We are devoting a large space to the story of Southern California's landscape, it's 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.

Other Museum Partnerships. SCEC continues to foster new and nurture ongoing relationships with several museums. Some institutions have only requested copies of Roots for distribution in an earthquake exhibit, and others have requested professional development activities for their staff or local educators. Museums have also called upon SCEC to participate in educator open houses or special professional development seminars. Other museum partners includes: Discovery Science Center, Santa Ana; Griffith Observatory, Los Angeles; KidSpace Youth Museum, Pasadena; and several others.

Earthquake Information (California State University (CSULA), Los Angeles, CA) Due to be completed in fall 2008, 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.



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 with additional information and directions to the trail). BLM has agreed to maintain the site and print the brochure into the foreseeable future. (*www.scec.org/wallacecreek*)

3. 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 wherever possible contributes to the community through participation on outreach committees, 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 a connection 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 USC. In 2003 SCEC began a partnership with the SIO 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 (grades 5–8) age girls 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. SCEC participates in national conferences to promote innovative earthquake education in all states. Earthquake related content comprises the bulk of the six grade earth science curriculum in California. SCEC has a dual responsibility to communicate the science and the preparedness and one of the best venues for this effort are the statewide science educator conferences.

USC Science Education Collaborative. Since 2003, SCEC has greatly increased engagement with the inner-city neighborhoods around USC to form various partnerships in order to improve science education and increase earthquake awareness in the local community. One of these partnerships is with USC's Joint Education Project (JEP), which sends USC students into local schools to teach eight one-hour lessons pertaining to what they are learning in their classes. SCEC, in partnership with the USC department of Earth Sciences, now provides educational resources to JEP students in several earth-science courses, and trains the students how to use the resources in their lessons. SCEC has also partnered with JEP, USC Mission Science, USC Sea Grants and the Jet Propulsion Laboratory (JPL) to create hands-on workshops for teachers at schools in the neighborhoods surrounding USC.

4. Development of Educational Products

Earthquake Country - Los Angeles Video Kit. The video was produced by Dr. Pat Abbott of SDSU. 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's "LA3D" visualization system. In addition to conducting several focus groups with teachers and preparedness experts where the video was evaluated, SCEC developed an educator kit for school and community groups. The kit is currently being used in several schools in Los Angeles County, in an earth science education course at Cal Poly Pomona, and is part of educational programming at two museums.

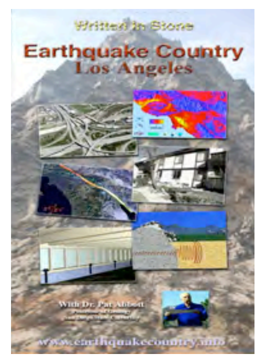


Plate Tectonics Kit. Debuting in fall 2008, this educational product makes plate tectonics activities more accessible for science educators. SCEC developed a user-friendly version of the This Dynamic Earth map used by many in a jigsaw-puzzle activity to learn about plate tectonics, hot spots, and other topics. Feedback from educators indicated that the activity would be used more often if they had maps that had the plate boundaries on the back so that the puzzle could be cut more easily. In addition to designing the new map SCEC has also 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, and through 2007 with the latest Terashake animations. Our "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 National Science Teachers Association annual meeting. Also, a supplement module to an earth science textbook (being developed by a publisher) will lead students through analysis of earthquakes using Terashake animations.

Use of SCEC Community Modeling Environment (CME) Products in Higher education. SCEC faculty (and many others) are using CME animations in there undergraduate and graduate courses. Many graduate students have been supported by the CME project and have key in the development of many CFM products. However, the major impact of the CME and related activities however has been in the SCEC Undergraduate Studies in Earthquake Information Technology (USEIT) program, which has developed LA3D and now SCEC-VDO to visualize the SCEC CFM, earthquakes, and other features. This has resulted in a very useful tool but more importantly involved students from computer science, engineering, economics, film, and many other majors in earth science applications of advanced computer science. Several have changed their career paths and are pursuing graduate degrees with SCEC.

V. State of SCEC, 2008

A. Welcome to the 2008 Annual Meeting!

This is SCEC's 18th Annual Meeting and the second community-wide gathering under the five-year SCEC3 program. The agenda features some very interesting presentations by keynote speakers, planning sessions for all the major working groups, an outstanding set of science posters, and a variety of IT demonstrations, education & outreach activities, and social gatherings. Five workshops and a student field trip are scheduled on the weekend before the meeting, and a major workshop on the Salton Trough Seismic Project will begin immediately afterwards.

The richness of the week's activities indicates how well the Center is working. SCEC has grown into one of the largest collaborations in geoscience, a fact reflected in the rising participation in our annual collaboration meeting (Figure 1): 453 people have pre-registered this year (compared to 446 last year), and 252 poster abstracts have been submitted. This will be the first annual meeting for 139 of this year's pre-registrants, so we can look forward to seeing many new faces!

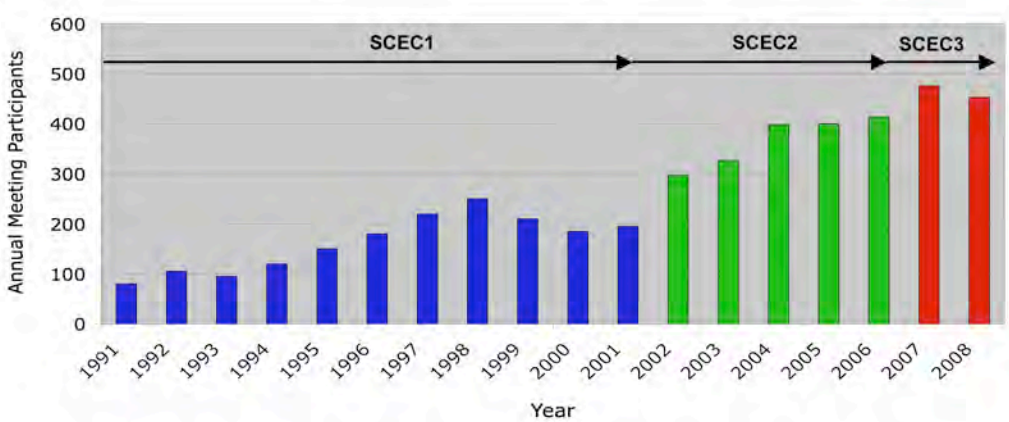


Figure 1. Registrants at SCEC Annual Meetings, 1991-2008. Number for 2008 (453) is pre-registrants.

B. Goals of the Meeting

The agenda for the Annual Meeting developed by Greg Beroza and the Planning Committee is designed to achieve three goals. The first is to share our individual scientific results and plans with our many SCEC collaborators; for this reason, the agenda includes lots of poster-viewing time and informal sessions around the pool. The second is to mark our progress toward the priority objectives of the SCEC3 Science Plan, which are summarized in the 19 bullet points of Table 1. Each year, we try to assess our achievements in the SCEC Annual Report, and we would like to report on your scientific contributions, as well as incorporate your ideas for new research into the 2009 SCEC Science Plan.

Obtaining community input to the SCEC planning process is the third major goal of the meeting. A draft of the 2009 Science Plan has been prepared by the Planning Committee and included in this meeting volume. A comprehensive set of working group sessions has been organized to promote detailed discussions of the plan.

We will also be soliciting community input on our priorities for connecting SCEC activities with EarthScope, NEES, the Petascale Computing Initiative, CIG, GEON, and other NSF and USGS programs. A particularly interesting opportunity is the Salton Trough Seismic Project, sponsored by EarthScope and led by John Hole, Joann Stock, and Gary Fuis. This large-scale active seismic experiment, scheduled for 2009-2010, will be the subject of the follow-on workshop, and we encourage your participation.

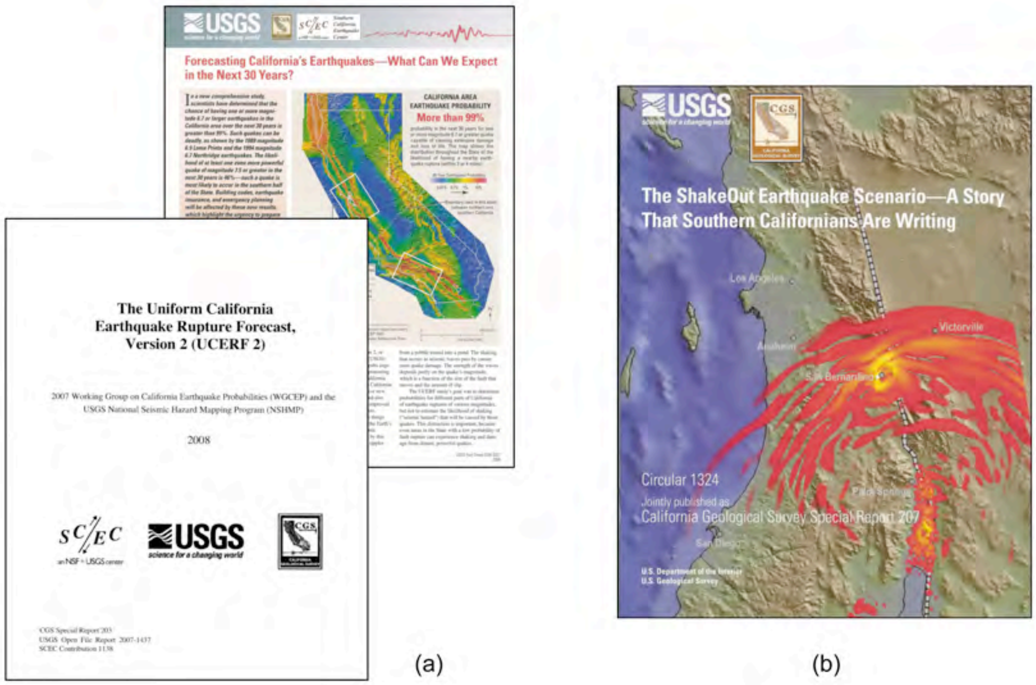
Table 1. Priority Science Objectives for SCEC3

1. Improve the unified structural representation and employ it to develop system-level models for earthquake 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.

C. Highlights of SCEC Achievements

This has been a banner year for new products in seismic hazard analysis and risk assessment (Figure 2). Last April, the 2007 Working Group on California Earthquake Probabilities (WGCEP 2007), led by Ned Field, released the Uniform California Earthquake Rupture Forecast (UCERF), providing the state with its first comprehensive time-dependent forecast model. The 28-month UCERF study was the product of a very successful partnership among SCEC, the USGS, and the California Geological Survey (CGS), sponsored in part by the California Earthquake Authority (CEA). In its final report, WGCEP (2007) has identified a number of directions for research that could substantially improve time-dependent earthquake forecasting, and their recommendations will be fodder for interesting planning discussions throughout the Annual Meeting.

Another set of studies, conducted by SCEC's PetaSHA collaboration in high-performance computing, delivered simulations of a large scenario earthquake on the southern San Andreas fault. One of these simulations, by Rob Graves and his colleagues, was selected to be the basis for the Great Southern California ShakeOut (Figure 2b). The ShakeOut exercises, scheduled for mid-November, 2008, are being organized by Lucy Jones of the USGS as part of the Multi-Hazard Demonstration Project and will include the largest earthquake drill in U.S. history. The plans for ShakeOut will be a major topic at this Annual Meeting.



(a) (b)

Figure 2. (a) The WGCEP (2007) final report and fact sheet, presenting the Uniform California Earthquake Rupture Forecast (UCERF). (b) USGS Circular 1324, describing the ShakeOut Scenario. The cover shows a snapshot of the M7.8 ShakeOut scenario earthquake on the southern San Andreas fault, simulated by Rob Graves and visualized by Geoff Ely.

Many other projects, large and small, logged significant progress during the past year, and you will be able to view these achievements in the hundreds of posters on display at the meeting. To take one example, the Collaboratory for the Study of Earthquake Predictability (CSEP) became operational in September, 2007, and updated versions of its testing-center software have been released quarterly ever since. As Danijel Schorlemmer will be describe, CSEP is now running earthquake prediction experiments in California, New Zealand, Italy, and, most recently, Japan.

D. 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 47 participating institutions (Table 2). SCEC is one of the largest collaborations in geoscience, involving more than 650 scientists and other experts in active SCEC projects. A key measure of SCEC involvement—registrants at our Annual Meetings—is shown for the entire history of the Center in Figure 1.

Table 2. SCEC Institutions (September 1, 2008)

Core Institutions (16)	Participating Institutions (47)
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; 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); 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); Institute of Geological and Nuclear Sciences (New Zealand); Jet Propulsion Laboratory; Los Alamos National Laboratory; Lawrence Livermore National Laboratory; National Chung Cheng University (Taiwan); National Taiwan University (Taiwan); National Central University (Taiwan); Ohio State University; Oregon State University; Perdue University; Rensselaer Polytechnic University; Texas A&M University; University of Arizona; UC, Berkeley; UC, Davis; UC, Irvine; University of British Columbia (Canada); University of Colorado; University of Massachusetts; University of Minnesota; University of Missouri-Columbia; University of North Carolina; University of Oklahoma; University of Oregon; University of Utah; University of Western Ontario (Canada); University of Wisconsin; URS Corporation; Utah State University; Woods Hole Oceanographic Institution

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. During the past year, Ralph Archuleta replaced Doug Burbank as the Board member from UCSB. The complete Board of Directors is listed on page ii of the meeting volume.

Advisory Council. The Center's external Advisory Council (AC) 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 2007 report follows my report in the meeting volume.

We thank Dr. Chris Rojahn, who is rotating off the AC this year, and we welcome Drs. Mary Lou Zoback and John Filson as new AC members. Dr. Zoback, who is Vice President for Earthquake Risk Applications at RMS Inc., succeeds Dr. Sean Solomon as AC chair, and we thank her for her leadership of this important council.

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 Architec-ture & Dynamics (LAD), Earthquake Forecasting & Predictabilty (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.

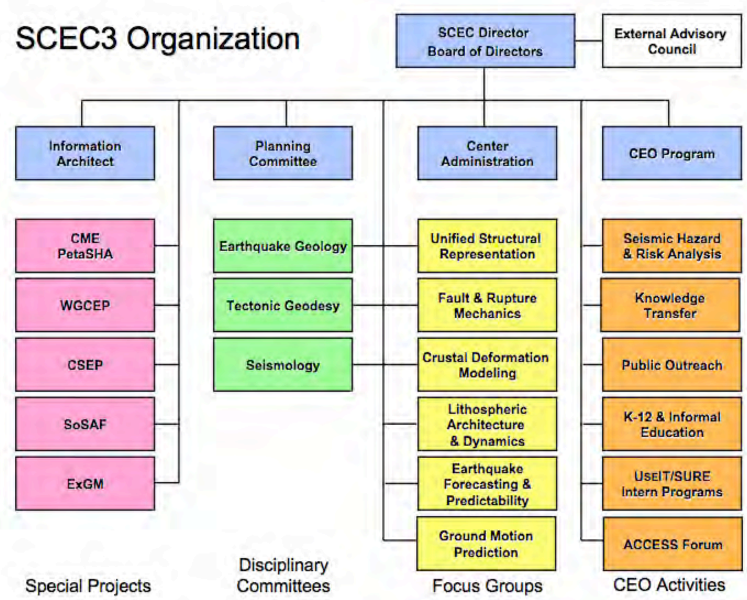


Figure 3. The SCEC3 organization chart, showing the disciplinary committees (green), focus groups (yellow), special projects (pink), CEO activities (orange), management offices (blue), and the external advisory council (white).

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 (Table 3). The PC has the responsibility for formulating the Center's science plan, conducting proposal reviews, and recommending projects to the Board for SCEC support. The working group leaders and co-leaders are a truly exceptional group of scientists working for the benefit of the SCEC community; please use the opportunity of the Annual Meeting to communicate your thoughts about the SCEC3 Science Plan to them.

Table 3. SCEC3 Working Group Leadership

Disciplinary Committees	
Geology	Mike Oskin* James Dolan
Seismology	Egill Hauksson* Jamie Steidl
Geodesy	Jessica Murray* Rowena Lohman
Focus Groups	
Structural Representation	John Shaw* Jeroen Tromp
Fault & Rupture Mechanics	Judi Chester* Ruth Harris
Crustal Deformation Modeling	Liz Hearn* Tom Parsons
Lithospheric Architecture & Dynamics	Paul Davis* Gene Humphreys
Earthquake Forecasting & Predictability	Terry Tullis* Bernard Minster
Ground Motions	Robert Graves* Steve Day
Seismic Hazard & Risk Analysis	Paul Somerville* Nico Luco
Special Project Groups	
CME/PetaSHA Project	Phil Maechling*
WG on Calif. Earthquake Probabilities	Ned Field*
Collaboratory for Study of Equake Predictability	Tom Jordan Danijel Schorlemmer*
Southern San Andreas Fault Project	Ken Hudnut*
Extreme Ground Motion	Tom Hanks*

* *Planning Committee members*

E. Center Budget and Project Funding

The 2008 base funding for the Center was $2,700K from the National Science Foundation and $1,100K from the U.S. Geological Survey. The base funding of $3,800K was augmented with $45K from the Keck Foundation for CSEP, $100K from the GPS royalty funds for GPS activities, $240K from the USGS for SoSAFE, and $255K from PG&E/DOE for the Extreme Ground Motion project. The total funding available was $4,440K.

The base budget approved by the Board of Directors for this year allocated $3,315K for science activities managed by the SCEC Planning Committee; $405K (including $25K for intern programs) for communication, education, and outreach activities, managed by the CEO Associate Director, Mark Benthien; $140K for information technology, managed by Information Architect, Phil Maechling; $280K for administration and $170K for meetings, managed by the Associate Director for Administration, John McRaney; and $130K for the Director's reserve account.

The structuring of the SCEC program for 2008 began with the working-group discussions at our last Annual Meeting in September, 2007. An RFP was issued in October, 2007, and 209 proposals (165 projects, considering collaborations) requesting a total of $6,320K were submitted in November, 2007. 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 14-15, 2008, 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 3-4, 2008. The Board voted unanimously to accept the PC's recommendations, pending a final review of the program by the Center Director, which was completed on February 26, 2008.

F. 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 has erected and maintained 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. In 2007, ECA organized the *Dare to Prepare* campaign, marking the 150th anniversary of the Ft. Tejon earthquake. It encouraged Southern Californians to “talk about our faults,” to understand that "Shift Happens," and to "Secure Your Space" in order to protect yourself, your family, and your property (see *www.daretoprepare.org*).

In the past year, the major focus of the ECA and the SCEC/CEO programs has been the organization of the Great Southern California ShakeOut, a week of special events featuring the largest earthquake drill in U.S. history. At 10 a.m. on November 13, 2008, millions of southern Californians will “Drop, Cover, and Hold On” to practice what to do when a major earthquake happens. ShakeOut is based on a potential 7.8 magnitude earthquake on the southern San Andreas fault. Dr. Lucy Jones of the USGS has led a group of over 300 scientists, engineers, and others to study the likely consequences of this scenario (see Figure 2b). The ShakeOut exercises will be a dramatic call to action for preparedness (see *www.ShakeOut.org*). All SCEC members are encouraged to participate. On November 12-14, the City of Los Angeles and the Earthquakes and Megacities Initiative will host an International Earthquake Conference, bringing together international experts to discuss policy, planning, and preparedness (see *www.iec.lacity.org*).

Putting Down Roots in Earthquake Country continues to be the principal SCEC vehicle for providing earthquake science, mitigation, and preparedness information to the public. The updated 2007 edition of the handbook is available for download at *www.earthquakecountry.info/roots*, and free copies can be ordered from the Center. In 2008, several *Roots*-related efforts are underway:

- A Utah version of *Putting Down Roots in Earthquake Country*
- *Living on Shaky Ground,* an update to the well-known earthquake booklet for California's north coast, which will include now the *Seven Steps to Earthquake Safety*
- *The Seven Steps to an Earthquake Resilient Business,* an new 16-page supplement developed for businesses by a SCEC-organized committee of experts.
- A major update of the Southern California version of *Roots* to include UCERF probability estimates and ShakeOut scenario results.

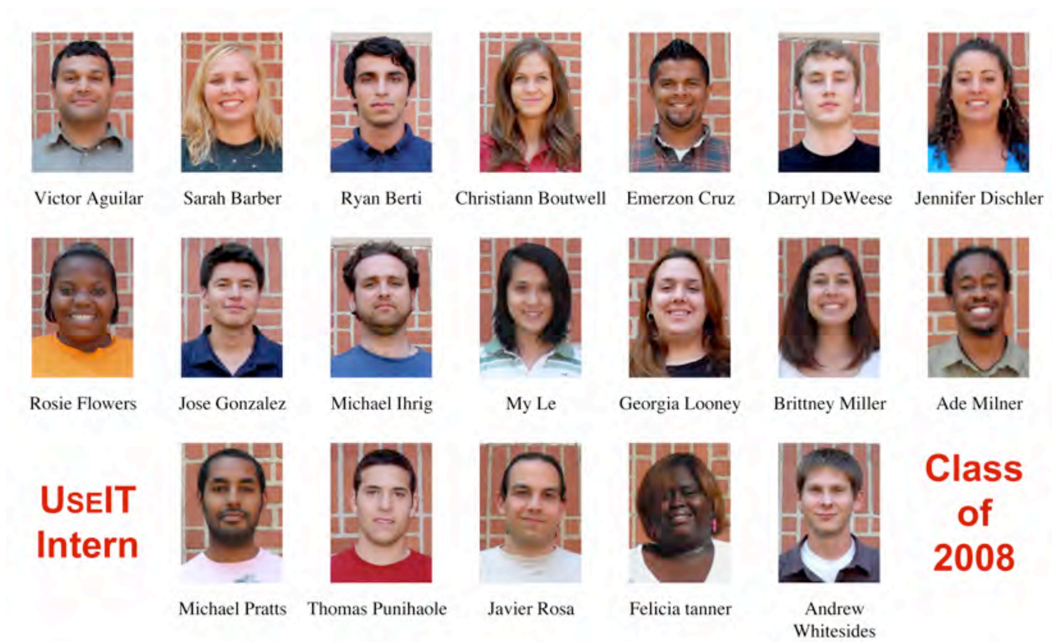


Figure 4. The 19 students from around the country who participated in the 2008 UseIT summer intern program. Many will be attending the Annual Meeting, and they will present posters, demos, and animations, as well as a film about the 2008 UseIT program.

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 *Roots*. 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).

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 current project is a partnership with EarthScope to host a San Andreas fault workshop for park and museum interpreters in Spring 2009.

Last winter, Dr. Robert de Groot took over SCEC's Office for Experiential Learning and Career Development from Sue Perry. The 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). It also promotes diversity in the scientific workforce and the professional development of early-career scientists. Many of the summer interns will be attending the meeting, and I hope you'll have the opportunity to check out the posters and other presentations of their work.

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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. Please do not hesitate to contact me personally if you have questions or comments about our activities, accomplishments, and plans. Enjoy Palm Springs!

VI. Report of the Advisory Council

Southern California Earthquake Center
September 2008 Meeting

A. Introduction

The Advisory Council of the Southern California Earthquake Center (SCEC) met during the 2008 SCEC Annual Meeting, held in Palm Springs, California, during 7-10 September 2008. The principal meeting of the Advisory Council was during the evening of 9 September; an earlier session was held prior to the start of the Annual Meeting on 7 September to outline areas of focus. The Council chair summarized the principal council findings and recommendations in an oral report delivered during the closing session of the Annual Meeting on the morning of 10 September.

On 5 September the SCEC Director circulated to the Advisory Council a report summarizing how SCEC had responded to Advisory Council recommendations from the previous year and raised a number of new and continuing issues warranting Council attention. Those issues included:

- a formal evaluation of the Center's Communication, Education, and Outreach (CEO) Program;
- feedback on the Collaboratory for the Study of Earthquake Predictability, particularly on engaging NASA in a workshop and on sustainable funding
- advice on initiatives in large-scale earthquake simulation and ground motion prediction;
- documenting SCEC3 earthquake system science accomplishments
- leadership development within SCEC and the SCEC4 planning process.

After a few general remarks below, we discuss the issues raised by the Director in his 5 September mailing; we also comment on a number of recurring topics and make several recommendations on some additional issues raised by the AC at this meeting. At our September 7 evening meeting with SCEC leadership, John McRaney raised concerns about the need to develop sustainable funding for the continually expanding Annual Meeting. Unfortunately we did not have time to discuss this topic, but we would welcome any relevant data prior to the next annual meeting and the Advisory Council would be glad to comment.

B. Some General Impressions

First of all, this has been a banner year for SCEC with the release of two major products – and congratulations are in order. In April of 2008 the Uniform California Earthquake Rupture Forecast, the first-ever, statewide time-dependent assessment of earthquake likelihood was released. This report was requested and partially funded by the California Earthquake Authority. A collaboration of SCEC, the USGS, and the California Geological Survey (Working Group on California Earthquake Probabilities), this project, under the superb leadership of Ned Field, USGS, involved more than 100 earthquake scientists who participated in workshops and contributed data.

In June of 2008, SCEC and the USGS released the ShakeOut Earthquake Scenario, a USGS Open-File report. This 400 page publication of the initial results of a large cooperative project, led masterfully by Lucy Jones' (USGS), examined the implications of a major earthquake in southern California. Its results will be used as the basis of an emergency response and preparedness exercise, the Great Southern California ShakeOut, in November 2008. Members of the southern California community will use the ShakeOut Scenario to plan and execute this exercise. The resulting community input and feedback will then be utilized to refine the assessment of the physical, social and economic consequences of a major earthquake in southern California and will lead to a formal publication in early 2009.

Since members of the Advisory Council are not also members of SCEC, the Annual Meeting provides an important opportunity for Council members to assess the community's annual progress on the Center's goals and programs. The 2008 meeting and associated workshops proved again to be impressive demonstrations of the energy and enthusiasm of the SCEC community. The 139 registrants who were attending their first SCEC Annual Meeting (30% of the 460+ total registrants), including many students and interns, provided heartening evidence of the center's growing participation and its compelling mission. The Advisory Council particularly applauds SCEC's continually strengthening of partnerships with the earthquake engineering community. It is heartening to see their ranks grow at each meeting.

The Advisory Council also lauds the entire SCEC membership for their persistently selfless spirit which produced the landmark reports mentioned above, and which continues to enable considerable progress in developing communal, system-level models that are advancing the goals of both fundamental and applied earthquake science. The structure of the 2008 meeting allowed for ample discussion of issues, lively interactions at the many poster presentations of new science, and was punctuated by a series of well-chosen overview talks, most featuring early-career scientists who exemplify the new generation of SCEC leaders.

Finally, the Advisory Council would like to acknowledge the tremendous effort in the past year by Tran Huynh, SCEC's Project Planning Coordinator. Special thanks to Tran for her always cheerful and indefatigable assistance in producing the UCERF report, and for organizing this year's Annual Meeting, which came off flawlessly.

Before moving to our recommendations on specific topics, the Advisory Council noted several issues for the leadership to be mindful of:

- We urge SCEC3 to maintain focus and avoid getting spread too thin
- With the SCEC3 goals in mind, we endorse strong and active efforts to move the SCEC community towards progress in goals not yet realized
- We also urge SCEC to begin now to explore new, creative funding opportunities for this highly visible and successful regionally focused program—perhaps considering some kind of industrial associates program or seeking funding from utilities and other infrastructure ownership groups.

C. Evaluation of the CEO Program

In his 2007 and 2008 requests of the Advisory Council to provide guidance on evaluating SCEC's CEO program, the Director posed the following specific questions:

- Are the basic elements of the CEO program – formal and informal education, public outreach, knowledge transfer – in appropriate balance?
- Is there any "right now" advice that might enhance the prospects for ShakeOut success?
- What is the best way to capitalize on the connections and "bounce" from the ShakeOut exercise—after involving close to 5 million Southern Californians--what should be next? Could you please comment on SCEC's plan to convene a 1-2 day workshop in January or February of 2009 to leverage gains of the ShakeOut exercise.and develop a strategy for next 2-3 years.
- Is SCEC's premier effort in public outreach appropriately organized through the Earthquake Country Alliance? In particular, is the current organization of the Earthquake Country Alliance appropriate for outreach to the full spectrum of NGO's?
- Would it be appropriate and feasible for a member or members of the AC to lead a formal review of the CEO program?
- Regarding a research program within CEO that was proposed by the Advisory Council in 2007 – which aspects of CEO might be worthy targets for proposals submitted to NSF/SBE Directorate or other funding organizations, including foundations, and what partnerships would be most effective in extending SCEC expertise in the social science?

As noted in last year's report, the Advisory Council knows of no other organization that has accomplished more in the area of communication, education, and outreach, nor done so as effectively and as informed by knowledge from the social and behavioral sciences, than SCEC. Existing CEO activities have focused on what works best to motivate people to prepare and mitigate for events that they really don't believe will actually happen, and, if they did, they think will affect others and not themselves. The Earthquake Country Alliance has functioned extremely successfully in bringing together a diverse group of stakeholders, well outside of the traditional earth science academic environment.

The Advisory Council would like to particularly acknowledge Mark Benthien for his exemplary and visionary leadership of this program, and to thank every member of his staff, each of which are functioning at an extraordinarily high level. The visibility and success of the Shakeout event, with several months remaining to the exercise, is really unparalleled.

Regarding the request for "right now" advice that might enhance the prospects for ShakeOut success, the Advisory Council reported at the Annual Meeting that just as the SCEC community is asking southern Californian residents and government officials to modify their behavior as part of the ShakeOut exercise, we strongly encouraged the SCEC scientific community embrace the exercise and do the same. It is an excellent opportunity for the focus groups to come up with well-coordinated post-quake response plans and to involve their institutions as well.

1. Specific Recommendations for CEO Program Review

Following up on the Advisory Council's 2007 recommendations for a formal review of the scope and impact of the CEO program, SCEC leadership requested specific input and advice for this review. The desire to define future directions for CEO and to take advantage of and build upon ShakeOut's success, makes a review especially timely.

The Advisory Council recommends a two phase review:

- A **Phase 1 review** to evaluate the impact and effectiveness of the SCEC's outreach and education program. This review should fulfill the evaluation requirements of SCEC's two principal funders, the USGS and NSF and should:
  - Produce a report that will serve as an important supporting document for the SCEC4 proposal
  - Be informed by examples of previous NSF or USGS reviews and the expected elements, if available
  - Be based on CEO staff presentations, as well as overviews, summaries and data compiled by the CEO staff.
  - Be carried out by an independent external panel, populated in consultation with the two primary funding agencies.

- A **Phase 2 review** that would be much more forward-looking, focused on exploring new CEO activities and directions and the means to sustain and expand the program funding. This review should:
  - Be informed by a range of disciplines, including
    - Social and behavioral science
    - Marketing and advertising
    - Public health
  - Identify new opportunities and directions for SCEC CEO, including specific plans and follow-up activities to leverage and build on the success of the ShakeOut.
  - Include a component based on CEO staff presentations, as well as overviews, summaries and data compiled by the CEO staff.
  - Be carried out by an interdisciplinary external review panel consisting of specialists in the above fields, not all members of which need to have specific earthquake hazard experience or background. One or more of the Advisory Council members may be involved in the phase 2 review panel, serving as a liason to the panel and/or in helping SCEC select the panel members.
  - Recommend possible additional social and behavioral research activities and programs focused on building on and extending the impact of SCEC's CEO program. These could be carried out by SCEC CEO alone or in partnership with others.
    - One example of such a research program could address the daunting challenge of motivating and empowering underserved communities to take preparedness and mitigation actions when they lack the financial resources to address everyday needs. A network of NGO's in southern California already serves these communities daily and is trusted by them (e.g. Meals on Wheels, Senior Day Health programs, etc.). Research could involve inventoring existing NGO's in southern California and the communities they serve and evaluating the capacity of the NGOs (and the resources they would need) to take a more substantive role in

earthquake preparedness and post earthquake response. This research could help determine if the Earthquake Country Alliance's organization (or some other) is the most effective means to engage these NGO's.

- Provide advice on potential non-earth science funding sources for both new CEO research programs as well the overall CEO program.

In preparation for the Phase 2 review, the Advisory Council endorses SCEC's CEO Office's plan to convene a workshop to investigate post-ShakeOut activities and spinoffs and develop a strategy for the CEO office over the next 2-3 years. This workshop should proceed very soon after the ShakeOut exercise in November, before the momentum is lost. The proposed January or February 2009 timeframe seems ideal.

D. Feedback on CSEP

The Collaboratory for the Study of Earthquake Predictability (CSEP) is in a stage of rapid development. As a SCEC special project in its third year of support from the Keck Foundation, but must also be looking to the future, in 2010, when the Keck one-time funding runs out.

In his 5 September letter to the Advisory Council, the SCEC Director asked:

- Given the tricky problems in dealing with space-based earthquake prediction, should SCEC plan a joint workshop with NASA on earthquake predictability? If yes, how might it be configured?
- Does the AC believe that involvement in CSEP would be attractive to the private sector, and that pursuing their financial and other commitment would be worthwhile?

It is the Advisory Council view that CSEP's approach to earthquake predictability is appropriately rigorous, and a direction likely to engender broad community support—as evidenced by the continued expansion to other geographic areas. We applaud CSEP for its tremendous progress in the past year, in both meeting software release milestones and firming up international participation.

The success of CSEP (and its prospects for sustainable funding) will depend, largely, on whether there are interesting outcomes to the collaboratory's activities—will all prediction methodologies fail rigorous tests or will at least one algorithm shows promise? It is unlikely that another year or two of operation will be sufficient to decide this question.

With regard to developing future funding for CSEP, the Advisory Council recommends that:

- The primary focus for CSEP in the coming year should be domestic, getting the U.S.-based program and product delivery in order – this will be a requirement in seeking any U.S. government funding.
- CSEP should continue to monitor scientific progress in earthquake prediction in other countries; however, it should avoid the appearance of validation or confirmation of earthquake predictions in foreign countries. Entanglement in issues involving public safety in foreign countries could be a huge distraction of personnel and resources.

- Private industry funding could be explored in a workshop involving potential users from the insurance/reinsurance industry and soliciting input on which products and timeframes would be of most interest to this community.

With regard to a possible joint workshop with NASA:

- As part of its recommended focus on domestic prediction issues, the Advisory Council endorses a joint SCEC-NASA workshop to explore potential guidelines for engaging space-based earthquake forecasting techniques in CSEP's rigorous and independent testing environment. Many of the space-based prediction techniques have involved retrospective predictions and indentification precursory anomalies after an earthquake occurred. We recommend that the workshop have a very sharp focus around the issue of developing guidelines defining "baselines" for datasets other than seismicity and an objective set of rules for prospective prediction (analogous to the seismicity algorithms).

E. Advice on Initiatives in Earthquake Simulation and Ground Motion Prediction

Another special project area within SCEC that is now undergoing rapid growth is large-scale earthquake simulation and ground motion prediction.

It is the view of the Advisory Council that physics-based simulations and coupled hazard assessments represent a valuable integration of much of the knowledge and new understanding gained from SCEC's earthquake system science approach. These simulations are gaining more acceptance in the engineering design community, particularly as an important alternative to the use of a limited set of 'real' earthquake recordings and as a means to explore ground motions expected at a site for various scenarios and conditions. The simulations are also being used as a means to provide theoretical confirmation and physical insights into the commonly-used empirical ground-motion prediction equations that form the backbone of probabilistic seismic hazard analysis. We agree that this remains a critical direction for SCEC.

The Advisory Council recommends:

- a strong focus on understanding those aspects of ground motion prediction that have significant engineering impact
- a strong connection between simulation and empirical validation with existing data – what aspects of simulation-based predictions can be validated with ground-motion data, and what aspects are currently untestable? Are there alternative ways to test such aspects?
- less emphasis on exploring computational challenges--such as whether deterministic modeling can be extended from 1 to 3 Hz- expending a great deal of effort on the computational challenges of extending deterministic simulations from 1 to 3 Hz does not seem warranted because: (i) this will only bring a modest increase to the frequency range available via deterministic simulation, with a large frequency range of engineering interest remaining above the 3 Hz limit; (ii) existing methodologies of joining deterministic to stochastic simulations above the deterministic frequency limit will still continue to be required (and appear to be a sound and useful approach). The exploration of the computational challenges in marginally extending the frequency range of

deterministic simulations, while technologically interesting, could thus expend considerable resources with little payback in practical terms.

- Work more closely with the Fault and Rupture Mechanics focus group and attempt to include or evaluate some of the more elaborate physical modeling they are developing. For example, how much complexity of fault geometry is needed to accurately simulate strong ground motions for engineering applications? Does off-fault damage affect strong ground motions, and if so how should it be included?
- Considering a code validation effort, similar to CSEP and conducted jointly with leaders in the earthquake engineering community, that could be critical in establishing user acceptance of simulated ground motions as input to engineering designs.
- Comprehensive documentation of the sensitivity of simulation-based ground motions to the input parameters (and their interactions), with investigation of the extent to which each input parameter can be determined and constrained by data

The final recommendation stems from comments made at the 2008 Annual Meeting by Rob Graves, URS. He reported that in his analysis of ShakeOut simulations he found the rather disturbing result that just a 15% change in average rupture speed can change the peak ground motions by factors of 2 to 3. He then asked if these results were realistic and if the seismological community could confidentially specify median values and uncertainties for rupture speed and other key parameters influencing ground motion. The AC found these statements very significant, as should the SCEC community. They point to the need for a continued focus on understanding the sensitivity of simulations to input source conditions, particularly as the interest in using such techniques in engineering practice continues to widen.

F. Other Feedback

1. Leadership Development within SCEC

The Advisory Council was extremely impressed with the diversity and youth within the SCEC community and particularly within the new membership on the Planning Committee. Rotation within this leadership group is healthy, and provides more opportunities for young scientists to have a chance to lead. We urge SCEC senior leadership to remain diligent to the need for mentoring and development to guarantee the success of these young scientists, many of whom are in their first real scientific leadership role.

The Advisory Council was pleased to hear that a succession plan is in place for Tom Jordan’s stated desire to step down from SCEC leadership in 2010. The vision, energy and savvy Tom has brought to SCEC will be a difficult act to follow and while there appears to be an excellent succession plan in place, perhaps there should be some backup plan as well.

2. The Vital Role of SCEC Workshops and Increasing Awareness of Their Outcomes

SCEC is filling a tremendous need for the community by facilitating easy-to-convene topical workshops in a very short time frame—as evidenced by the requests for many more such workshops in the coming year. The Advisory Council noted that while many SCEC members were aware of recent workshops in a related area, in general they were not very aware of the workshop outcomes if they did not personally attend.

The Advisory Council recommends:

- Continued SCEC-wide promotion of workshop opportunities, this part of the process seems to be working well.
- Convenors be required to prepare a brief workshop summary for posting on the SCEC website shortly (within 30 days?) after the meeting, with email notification to the SCEC community containing a link to the summary.

3. Evaluating SCEC Progress and Documenting SCEC Accomplishments

The Advisory Council was pleased to learn last year that the SCEC Planning Committee will be tracking progress toward the achievement of Center objectives. We look forward in the coming year to receiving synthesis of the results of this tracking and the status of progress on the various goals.

Documenting the accomplishments of the earthquake system science done by the SCEC community is challenging—both in determining the appropriate medium for such interdisciplinary work and in capturing the full impact of the contributions. Despite these challenges, the Advisory Council continues to believe that creating a monograph of synthesis papers covering topical and disciplinary contributions by SCEC will be a critical part of the Center's legacy, not just within the earth sciences—but in the broader scientific community.

The Advisory Council strongly recommends that:

- SCEC begin soon to produce an accomplishment document for SCEC3. We believe that the synthesis required to produce such a document will be essential to the SCEC4 planning--- and such a report will be an important supporting document for the SCEC4 proposal.
- Venues and formats outside of traditional publication medium should be explored-- however, independent and stringent peer review must be assured.

4. Science Planning Discussions at the Annual Meeting

At this year's Annual Meeting, various members of the Advisory Council observed a wide variability in format and level of interaction in the individual Focus Group's science planning session. This variability took many different forms:

- How much previous science was presented
- How the discussion was facilitated, and in particular, how much the Group leaders spoke versus audience participation
- Uneven success in engaging younger SCEC members in the discussions, we wonder if it might be helpful to encourage some kind of caucus by the grad students possibly lead by a very recent PhD.
- And a logistical issue, attempts at discussion focused on small type, ponderous sentences shown in Powerpoint were generally not as successful as short key bullet items put up to stimulate discussion

The Advisory Council recommends that the Planning Committee work harder in the future to stimulate more interactive discussion engaging a broad segment of the audience.

G. SCEC4 Planning

SCEC3 will mark 20 years of investment in a focused attack on a comples scientific problem with a unique interdisciplinary, system-level approach. Both the funders and the broader Earth Science community will expect products and deliverables commensurate with such an investment. Now, halfway through SCEC3, it is time to refocus on achieving SCEC3 goals with a sense of urgency, rather than slipping into a feeling of complacency that SCEC could go on forever

SCEC4 presents an exciting opportunity to build upon a number of major scientific products and contributions of SCEC3 as well as the huge outreach and preparedness success of ShakeOut. A compelling case for SCEC4 must be based on demonstrating the impact of SCEC's interdisciplinary approach focused on building system-level community models – a demonstration that these models and new understanding are changing the way earthquake scientists and engineers solve problems and approach their research.

The Shakeout exercise is an outstanding example of a "wall to wall" activity within SCEC, grounded in science that is likely to change the behavior of both residents and government officials in southern California. We believe that this work should be thoroughly documented as a national exemplar of interdisciplinary research.

Creating the earthquake rupture scenario for ShakeOut required drawing a line in the sand, and using the best understanding at the time. However, new data and understanding (largely as a result of SOSAFE) have already raised important scientific questions about the validity of the selected rupture scenario—is one 7.8 earthquake more likely than 3 events in a short time period, e.g., a M7.4.M7.2, and a M7.3 in 10 years? Is 13 m peak slip likely, or do the new LIDAR data suggest smaller offsets per event? Also, the most appropriate rupture velocity and even the sense of directivity remain unconstrained.

Both the ShakeOut scenario and the Uniform California Earthquake Rupture Forecast exercises demonstrated the value of having to make judgments based on the best available information at the time. Both identified significant gaps where future research is required and focused attention on the key parameters that influence results.

The Advisory Council recommends a strong emphasis on synthesis and completing planned predictive models/platforms before the end of SCEC3, even with incomplete knowledge. In doing so, the researchers will learn what critical data or observations are needed and which parameters actually have little effect on model outputs—defining future research. This focus on synthesis will enable SCEC to write a strong accomplishment document as well as a strong SCEC4 proposal

The Advisory Council also urges SCEC to think broadly about how to both measure and improve the impact of the Center's efforts. We recommend you begin immediately to develop a process to document impact in both scientific and outreach arenas. Finally, we (continue to) recommend that you initiate a speakers program to further disseminate the results of the earthquake system-science approach.

H. Final Comments

It is the current sense of the Advisory Council that the researchers and senior leadership of SCEC is doing an outstanding job, and the many individuals now leading committees and focus groups constitute a broadly diverse, extremely able, and committed group. The Advisory Council applauds SCEC's continued role in catalyzing and supporting related projects such as the new NSF Margins/EarthScope Salton Trough seismic experiment. Support for these kinds of activities are essential to growing the community of scientists who are engaged in earthquake science and to leverage the knowledge and understanding developed in SCEC.

The Advisory Council is pleased to continue to provide assistance to SCEC in its efforts to formulate and accomplish the center's major goals. At any time the Council welcomes comments, criticism, and advice from the seismological community, including individuals and groups both inside and outside SCEC membership, on how best to provide that assistance.

One cautionary comment falling into the category of being a victim of one's own success--we heard from some participants that it is becoming increasingly hard to maintain the intimacy and level of participation as the number of Annual Meeting participants gets larger. As noted above, we felt that the discussion in some of the science planning sessions was somewhat tentative or inhibited by the large number of people. We have no specific suggestions about how or whether the meeting size should possibly be constrained, but it is an important aspect to consider if SCEC continues to grow.

Finally, the Advisory Council welcomes new members John Filson and Anne Meltzer and looks forward to working with SCEC leadership assist in SCEC4 planning and to help ensure that the products and progress of the center in the SCEC3 era continue to be commensurate with agency and community investment.

5 November 2008

SCEC Advisory Council

Mary Lou Zoback, Risk Management Solutions-RMS (Chair)*

Gail Atkinson, University of Western Ontario*

Lloyd S. Cluff, Pacific Gas and Electric Company

John Filson, USGS (Retired)*

Jeffrey T. Freymueller, University of Alaska*

Mariagiovanna Guatteri, Swiss Reinsurance America Corporation

Anne Meltzer, Lehigh University

Dennis Miletti, University of Colorado, Boulder*

Kate C. Miller, University of Texas at El Paso*

Jack P. Moehle, Pacific Earthquake Engineering Research Center (PEER)**

Chris Rojahn, Applied Technology Council

John Rudnicki, Northwestern University*

Ellis M. Stanley, Sr., City of Los Angeles Emergency Preparedness Department

*Attended at least part of the 2008 Annual Meeting and Advisory Council sessions

** Represented by Yousef Bozorgnia, PEER

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 2008 was sent to the NSF and USGS program officers in the spring of 2008.

Table VII.1 2008 Budget Breakdown by Major Categories

Total Funding (NSF and USGS):	$3,800,000
Management	280,000
CEO Program	380,000
Annual, AC, Board, and PC Meetings	170,000
Information Architect	140,000
Director's Reserve Fund	130,000
SCEC Summer Intern Program	25,000
Budgets for Disciplinary and Focus Group Activities: (including workshops)	$ 2,675,000
SoSAFE Supplement (from USGS)	240,000

VIII. Report on Subawards and Monitoring

The process to determine funding for 2008 began with discussions at the SCEC annual meeting in Palm Springs in September, 2007. An RFP was issued in October, 2007 and 158 (including collaborations) proposals were submitted in November, 2007. Proposals were then sorted and sent out for review in mid-December, 2007. 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 14-15, 2008 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 2008 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 3-4, 2008. 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 2008 was \$3.800M. The board approved \$280K for administration; \$380K for the communications, education, and outreach program; \$170K for workshops and meetings; and \$140K for the information technology program. We also received \$25,000 from NSF for the summer undergraduate intern program.

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 2008 are shown in the table below for both the USGS and NSF components of SCEC funding.

Table VIII.1 SCEC Subcontracts for 2008

USGS Funds

AIR Worldwide	$25,000
Appalachian State University	$25,000
Berkeley Geochron Center	$35,000
Cal State, San Bernardino	$15,000
California Institute of Technology	$311,000
LANL	$15,000
LLNL	$80,000
MMI Engineering	$22,000
San Diego State University	$10,000
Spa Risk, LLC	$30,000
University of British Columbia	$18,000
University of California, Davis	$39,000
University of California, Irvine	$20,000
University of Cincinnati	$20,000
University of Colorado	$10,000
University of Nevada, Reno	$102,000
University of Oregon	$25,000
Western Ontario	$10,000
Total USGS	**$812,000**

NSF Funds

Arizona	$91,000
Berkeley	$35,000
Boston University	$10,000
Brown	$50,000
Cal State, Fullerton	$12,000
Case Western	$25,000
Columbia	$30,000
Harvard	$215,000
Indiana University	$21,000
Massachusetts	$15,000
MIT	$86,000
Oregon	$25,000
RPI	$30,000
Princeton	$27,000
Stanford	$63,000
Texas A&M	$52,000
UCLA	$150,000
UCR	$95,000
UCSB	$267,000
UCSC	$57,000
UCSD	$136,000
URS	$20,000
UTEP	$16,000
Wisconsin	$35,000
Wyoming	$24,000
Total NSF	**$1,587,000**

Report on 2008 SCEC Cost Sharing

The University of Southern California contributes substantial cost sharing for the administration of SCEC. In 2008, USC provided $366,916 for SCEC administration costs, waived $585,270 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 2007

1. USC annually provides $366,916 in cost-sharing for SCEC management (Direct Costs).

Institution	Amount	Purpose
USC	$292,508	Salary Support of Jordan, McRaney, Huynh
	$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
	$13,908	Telecommunications
	$366,916	Total

2. USC waives overhead on subcontracts. There are 43 subcontracts in 2008.

$929,000	Amount Subject to Overhead
0.63	USC Overhead Rate
$585,270	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	4	7	20	13	6
Black	1	0	0	1	6
White	19	88	53	105	28
Native American	0	1	2	0	1
No Information	39	33	112	107	49
Ethnicity					
Latino	1	4	13	3	5
Not Latino	25	93	92	129	39
No information	35	27	69	86	45
Withheld	1	5	13	8	1
Gender					
Female	11	22	44	41	38
Male	23	92	90	128	24
Withheld/No Info	28	15	53	57	28
Citizenship					
US	29	90	64	113	56
Other	2	9	52	33	1
No information	31	21	60	67	32
Resident	0	9	6	11	1
Withheld	0	0	5	2	0
Disability Status					
None	13	71	53	87	10
No information	49	56	134	135	78
Hearing	0	1	0	14	1
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 international members of our Advisory Council. Garry Rogers (retired in 2008) of Geological Survey of Canada, Sydney and 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 sixth ACES workshop was held in May, 2008 in Cairns, Australia. Participants from Australia, China, Japan, Taiwan, and Canada attended.

3. ETH/Zurich. Stefan Wiemar and Martin Mai 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 is 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 2008 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 the Evison Symposium in New Zealand in February, 2008, and earthquake forecasting meetings in Zurich in June, 2008, and Rome in October, 2008.

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, 2007 and October, 2008.

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XII. SCEC2009 RFP and Research Goals

2009 PROGRAM ANNOUNCEMENT
FOR THE SOUTHERN CALIFORNIA EARTHQUAKE CENTER

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 third year of the SCEC3 research program.

II. Guidelines for Proposal Submission

A. Due Date: Friday, November 7, 2008, 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 "2009 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, 2009.
- ***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.
- ***2008 Annual Report:*** Scientists funded by SCEC in 2008 must submit a report of their progress by 5 pm February 28, 2009. 2009 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.

- ***Labeling the Submitted PDF Proposal:*** PI's must follow the proposal naming convention. Investigators must label their proposals with their last name followed by 2009, e.g., Archuleta2009.pdf. If there is more than one proposal, then the file would be labeled as: Archuleta2009_1.pdf (for the 1st proposal) and Archuleta2009_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 only be for travel)

F. Collaboration. Collaborative proposals with investigators from the USGS are encouraged. USGS employees should submit their internal requests for support through USGS channels. Collaborative proposals involving multiple investigators and/or institutions are strongly encouraged; these must 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 ten 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 2009 and February 2010 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, 2008, 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

- 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.
- 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
- 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.
- 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.
- 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.
- Recommendations of the planning committees will be combined into an annual spending plan and forwarded to the SCEC Board of Directors for approval.
- Final selection of research projects will be made by the Center Director, in consultation with the Board of Directors.
- The review process should be completed and applicants notified by the end of February, 2009.

VI. Coordination of Research Between SCEC and USGS-EHRP

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.

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. Sue Hough, EHRP coordinator for Southern California, or other SCEC and EHRP staff to discuss opportunities for coordinated research.

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.

The EHRP web page, http://erp-web.er.usgs.gov/, 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 early 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.

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) in fault zones, 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 rupture representations consistent with observations and realistic dynamic rupture models of earthquakes.

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 earthquake simulations and verify simulation methodologies

B5. Improve our understanding of nonlinear 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 Peta-scale computing resources in post-earthquake response for evaluation of crustal stress changes along faults as well as short term prediction of potentially damaging ground motion patterns along 'newly stressed' faults; 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

Objectives: The objectives of the Seismology group are to support the SCEC mission to gather data on earthquakes in Southern California, and use the seismic networks as research tools to integrate the data into physics-based models that improve our understanding of earthquake phenomena. Proposals to enhance the seismic networks as research tools and foster innovations in network deployments, data collection, and data processing are encouraged, especially where they include collaboration with network operators in Southern California and provide community products that support one or more of the numbered goals in **A**, **B**, **C** or **D**.

Important SCEC resources are the Southern California Earthquake Data Center (SCEDC) whose continued operation is essential to deciphering Southern California earthquakes as well as crustal and fault structure, the network of SCEC funded borehole instruments to record high quality reference ground motions, and the pool of portable instruments that is operated in support of targeted deployments or aftershock response.

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

- Enhancement and continued operation of the SCEDC and other existing SCEC facilities. In particular, the near real-time availability of earthquake data from SCEDC and enhanced automated access are important for ongoing SCEC research activities. In support of tomographic, state of stress, earthquake predictability, and other seismicity studies, enhance the availability and usefulness of data products, such as waveforms, catalogs of earthquake parameters, arrival time and polarity information, and signal-to-noise measures as well as moment tensors and first motion mechanisms (A6, A7).
- Enhancements in the real-time processing of network data to improve the estimation of source parameters in relation to known and unknown faults (A3, A4, A10). Other activities could be testing of the performance of new early-warning algorithms, the determination of high precision real-time earthquake locations, or developing finite source algorithms for use in the real-time processing environment (D).
- Experiments that investigate the near-fault crustal properties as well as develop constraints on crustal structure and state of stress are also the goals of other SCEC groups (A7, A10, C). Develop innovative and practical strategies for densification of seismic instrumentation, including borehole instrumentation, along major fault zones in Southern California to measure fault zone properties and capture near-field motions for

constraining kinematic and dynamic simulations of earthquakes (B1, B2, B3, B4, B5). 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) are encouraged. Collaborations with EarthScope and other network operators to develop innovative new methods to search for unusual signals using combined seismic, GPS, and borehole strainmeter data (A5, A6) are also encouraged. Other possible strategies (often started with SCEC seed funds) include the design of future passive and active experiments such as dense array measurements of basin structure and large earthquake properties, OBS deployments, and deep basement borehole studies.

2. Tectonic Geodesy

Objective: The broad objective of the geodesy group is to foster the availability of the variety of geodetic data collected in Southern California and the 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).

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

- Develop reliable means for detecting, assessing, and interpreting transient deformation signals (A5).
  - Participate in a "blind test" exercise being undertaken to stimulate progress on this topic. Proposals focusing on all aspects of this effort including generation of test data, design of metrics for assessment, and development of detection algorithms are encouraged.
  - Investigate processes underlying detected signals and/or their seismic hazard implications.
- Refine or extend estimates of interseismic crustal motion (A1, A2, A3, C):
  - Identify possible trade-offs in regional slip rate models, conduct quantitative comparison of such models, and/or develop new models.
  - Quantify uncertainties (especially those relating to model uncertainty) in rate estimates.
- Improve and expand geodetic data products in support of a range of applications (A1, A2, A3, A5, B1, D):
  - Reprocess the full southern California GPS data set using consistent, state-of-the art methodology.
  - Advance InSAR processing and data combination strategies.
  - 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. Design of methods for assessing the utility of such combinations for interpreting tectonic or nontectonic signals is encouraged.

- Improve vertical velocity estimates through, for example, the combined use of multiple data types or improvements in data processing strategies.
- Conduct a systematic assessment of existing geodetic observations throughout Southern California in order to identify locations for which further data collection is necessary to discriminate among regional deformation models, refine slip rate estimates, conduct future earthquake response and postseismic investigations, or for other applications related to SCEC goals.
- Increase the usability of high-rate GPS observations by developing community accessible tools for using these data. Such tools can address different goals including immediate response to major earthquakes (for which rapid availability of solutions is a priority) or detailed deformation analysis (for which the highest accuracy solutions are needed). Assessment of the required accuracy for specific problems of interest to SCEC is also encouraged.

Studies should utilize data from the Plate Boundary Observatory wherever possible, and proposals for additional data collection should explicitly motivate how they complement existing coverage.

3. Earthquake Geology

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.

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).

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 (oskin@geology.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 below. 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.

- ***Community Velocity Model:*** Improve the current SCEC CVM-H model, with emphasis on more accurate representations of Vp, Vs, density structure, basin shapes, and 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.
- ***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.
- ***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. 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.

Proposed studies should aim to:

- 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).
- 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).
- 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).
- 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).
- 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).
- 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).
- 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).
- 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)

The CDM group focuses on deformation occurring within the earthquake cycle, at time scales linking dynamic rupture (minutes) to secular deformation (thousands of years). We are interested in proposals to (1) develop, or facilitate the development of, models of southern California fault systems based on the SCEC USR and (2) develop other models which contribute to the larger goal of understanding stress transfer and the evolving distribution of earthquake probabilities within active fault systems. Items (1) and (2) should contribute to our ultimate goal of developing physics-based seismic hazard assessments (SHA) for southern California faults. We also seek proposals for modeling to optimize the design of GPS networks. Collaborative research with other SCEC focus areas is encouraged. More specifically, we invite proposals to:

• Develop kinematic or dynamic models of the southern California crust, incorporating SCEC USR products (e.g., the CFM and the CVM). C, A3, A11.

• Investigate how assumed rheologies affect modeled stress transfer among Southern California faults. Assess effects of aseismic fault creep (including transient slip events), inelastic upper crust, poroelasticity, and heterogeneous material properties on the seismic cycle and stress transfer. A7, A10, A11.

• Investigate combination of, and communication between regional and fine scale models. Develop techniques for simultaneous or sequential integration of broader-scale block (or other) modeling with more detailed (finite element meshes or other) models of complex fault structures to study fault slip issues and augment earthquake forecasts. A3, A10, A11.

• Investigate how to represent multi-scale fault complexity in deformation models, and how to quantify model sensitivity to spatial heterogeneity of structure. Use such models to help geologists discover what to look for, and where to look, to find evidence of how slip and deformation are distributed at fault intersections. A10, A11.

• Investigate connections between geodetic and geologic slip rates. Investigate factors that might make fault slip rates vary over different time scales. Use geodetic data to develop California fault slip rates and test models used by the Working Group on California Earthquake Probabilities 2007 and National Seismic Hazard Map Program 2007 forecast models for kinematic consistency. Augment the database through joint consideration of geologically- and geodetically-determined slip rates and identify fault slip rates that are dependent on observation period/methods. A1, A2.

• Develop models and methods to guide permanent, campaign, and post-event GPS site deployments, with an emphasis on precomputing and web-based platforms for data and model sharing. D.

• Develop comprehensive earthquake simulators to unify driving and initial-condition stresses and time-dependent stress interactions, with geologic, geodetic, and paleoseismic observations. Characterize the statistical parameters of stress heterogeneity on faults and in the crust, and the extent to which such heterogeneity influences simulator results. A3, A6, A10.

• Evaluate sensitivity and use of deformation and triggering models in earthquake forecasting. For example, explore plausible range of seismic release scenarios consistent with deformation observations, or assess how different modeling approaches (or assumptions) affect estimates of hazard-forecast parameters. A6.

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, with the provision that they focus on seismicity and deformation data. 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. 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 will include developing and/or refining physics-based simulation methodologies, with particular emphasis on high frequency (1-10 Hz) approaches (B3) and the incorporation of non-linear models of soil response (B2, B4, B5). Source characterization plays a vital role in ground motion prediction and research is needed to develop more realistic implementations of dynamic or dynamically-compatible kinematic representations of fault rupture that are used in the simulations. 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). Verification (comparison against theoretical predictions) and validation (comparison against observations) of the simulation methodologies will continue 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 (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). In addition, 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 SSC Building 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

- 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.
- 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.
- Develop ground motion parameters (or intensity measures), whether scalars or vectors, that enhance the prediction of structural response and risk.
- Investigate bounds on the variability of ground motions for a given earthquake scenario.

Ground Motion Time History Simulation

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

- *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.
- *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.
- *SSC Buildings.* Participate with PEER investigators in the analysis of SSC reference buildings using simulated broadband ground motion time histories.
- *Earthquake Scenarios.* Perform detailed assessments of the results of scenarios such as the ShakeOut exercise, as they relate to the relationship between ground motion characteristics and building response and damage.

Risk analysis

- Develop improved site/facility-specific and portfolio/regional risk analysis (or loss estimation) techniques and tools, and incorporate them into the OpenRisk software.
- Use risk analysis software to identify earthquake source and ground motion characteristics that control damage estimates.

Other Topics

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. These may include investigation of the relationship between input ground motion characteristics and local soil response, liquefaction, lateral spreading, local soil failure, and landslides.

VIII. Special Projects and Initiatives

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

1. Networks as Research Tools
2. Southern San Andreas Fault Evaluation (SoSAFE) project
3. Working Group on California Earthquake Probabilities (WGCEP)
4. Next Generation Attenuation Project, Hybrid Phase (NGA-H)
5. End-to-End (“Rupture-to-Rafters”) Simulation
6. Collaboratory for the Study of Earthquake Predictability (CSEP)
7. National Partnerships through EarthScope
8. Extreme Ground Motions (EXGM)

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

10. Advancement of Cyberinfrastructure Careers through Earthquake System Science (ACCESS)

1) Networks as Research Tools

SCEC encourages proposals that enhance the use of seismic and geodetic networks as research tools. The goal of such research is to promote innovations in network deployments and data integration that will provide new information on earthquake phenomena. Projects in this category are meant to be complementary to ANSS, IRIS, EarthScope, and UNAVCO. The Earthquake Early Warning Demonstration Project is an example of such an activity.

2) 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.' Most work to be funded is expected to involve paleoseismic and geological fault slip rate studies.

The second year of SoSAFE is expected to again be funded at $240K by USGS. Targeted research by each of several selected self-organized multi-investigator teams will be supported to rapidly advance SCEC research towards meeting objective A1. We encourage investigator teams to propose jointly in response to the RFP. Each team will address one significant portion of the fault system, and all teams will agree to collaboratively review one another’s progress. We welcome requests for joint infrastructure resources, for example geochronology support. That is, an investigator may ask for dating support (e.g., to date 6 radiocarbon samples). Requests for dating shall be coordinated with Earthquake Geology.

Other SCEC objectives will also be advanced through the research funded by SoSAFE, such as A2, A10, and B1. For example, interaction between SoSAFE and the scenario rupture modeling activity will continue beyond the ShakeOut, as we discuss whether or not additional radiocarbon dating could 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. Use of novel methods for estimating slip rates from geodetic data would also potentially be supported within the upcoming year. Slip rate studies will continue to be encouraged, and for these it is understood that support may be awarded to study offset features that may be older than the 2000 yrs. stated in objective A1, perhaps as old as 60,000 yrs. in some cases. It is expected that much support will go towards improved dating (e.g., radiocarbon and OSL) of earthquakes within the past 2000 yrs., however, so that event correlations and coefficient of variation in recurrence intervals may be further refined.

We will also discuss 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.

3) Working Group on California Earthquake Probabilities (WGCEP)

The ongoing WGCEP is developing a time-dependent, statewide earthquake-rupture forecast that uses “best available science”. This model, called the Uniform California Earthquake Rupture Forecast (UCERF), will have the endorsement of SCEC, USGS, and CGS. The California Earthquake Authority, which holds about two-thirds of all homeowners earthquake insurance policies throughout the state, is interested in using the model to set insurance rates. Development of this model is tightly coordinated with the USGS National Seismic Hazard Mapping Program. For example, the time-independent component of UCERF 2 was used in the 2007 USGS/CGS California hazard map. We are deploying the model in an adaptable, extensible framework where modifications can be made as warranted by scientific developments, the collection of new data, or following the occurrence of significant earthquakes (subject to the review process). Our implementation strategy is to add more advanced capabilities only after achieving more modest goals.

The following are examples of SCEC activities that could make direct contributions to WGCEP goals:

- Extend our UCERF, which gives the magnitude, average rake, and rupture surface of all possible earthquakes throughout the state, to include different viable slip time histories for each of these ruptures (A).
- Develop models that give fault-to-fault rupture probabilities as a function of fault separation, difference in strike, and styles of faulting (A9).
- Refine estimates of observed earthquake rates and their uncertainties, both statewide and as a function of space. This could include associating historic events with known faults (A4 and C).
- Further refinement of fault models including geometries, seismogenic depths, and aseismicity parameters (C).
- Develop self-consistent, Elastic-Rebound-Theory motivated renewal models
- Development of deformation models that give improved slip- and stressing-rates on known faults, as well as off-fault deformation rates elsewhere (A3).
- Further constrain viable magnitude-area relationships, especially with respect to how they are being used in this project (A4). Important here is the question of the down-dip extent of rupture (lower seismogenic depth).
- Resolve interpretation of UCERF2's "Empirical" model (which implies a statewide stress shadow).
- Develop moment-balanced rupture models that predict a long-term rate of earthquakes that is consistent with the historical record (e.g., no discrepancy near magnitude 6.5) (A6). In so doing, also relax segmentation and include fault-to-fault ruptures.
- Develop methodologies for computing time-dependent earthquake probabilities in our model. These methodologies could include approaches that invoke elastic-rebound-theory motivated renewal models, earthquake triggering effects that include aftershock statistics, or physics-based earthquake simulations (A6).

- Develop easily computable hazard or loss metrics that can be used to evaluate and perhaps trim logic-tree branch weights (B6, C).
- Develop a community-standard hazard-to-loss interface (i.e., that can be used by anyone from academics, government officials, and consulting companies) (B6, C).

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).

4) 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.

5) 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.

6) 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:

- 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;

- Constructing community-endorsed standards for testing and evaluating probability-based and alarm-based predictions;
- Developing hardware facilities and software support to allow individual researchers and groups to participate in prediction experiments;
- 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;
- Intensifying the collaboration between the US and Japan through international projects, and initiating joint efforts with China;
- 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
- 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.

7) 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.

8) 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. 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 sensibly constant and so much less than the frictional strength of rocks at mid-crustal depths.

This project is sponsored by DOE. The main SCEC discipline and focus groups that will work on this project are 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.

9) 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.

10) Advancement of Cyberinfrastructure Careers through Earthquake System Science (ACCESS)

Project goal: Provide students with research experiences in earthquake system science to advance their careers and creative participation in cyberinfrastructure (CI) development.

Three programmatic elements:

- ACCESS-U: One-term undergraduate internships to support CI-related senior thesis research in the SCEC Collaboratory
- ACCESS-G: One-year graduate internships to support CI-related master thesis research in the SCEC Collaboratory
- ACCESS Forum: a new CEO working group to promote CI careers in earthquake system science

IX. SCEC Communication, Education and Outreach

SCEC is a community of over 600 scientists, students, and staff from 56 institutions, in partnership with many other science, engineering, education, and government organizations worldwide. To facilitate applications of the knowledge and scientific products developed by this large community, 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. Many of 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. To support the involvement of as many others as possible, budgets for proposed projects should be on the order of $2,000 to $7,000. 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.

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 failure process 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:

(1) 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.
(2) 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.
(3) Combine the laboratory, field-based, and theoretical results into effective friction laws 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.

(4) 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 dS/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 S0 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 sixfold:

(1) 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.
(2) 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.
(3) 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.
(4) Constrain the evolving architecture of the seismogenic zone and its boundary conditions by understanding the architecture and dynamics of the lithosphere involved in the plateboundary deformation.

(5) Broaden the understanding of fault systems in general by comparing SCEC results with integrative studies of other fault systems around the world.
(6) 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:

(1) 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.
(2) Investigate stress-mediated fault interactions and earthquake triggering and incorporate the findings into time-dependent forecasts for Southern California.
(3) Establish a controlled environment for the rigorous registration and evaluation of earthquake predictability experiments that includes intercomparisons to evaluate prediction skill.
(4) 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 dynamically consistent 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:

(1) 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.
(2) 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.
(3) 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.
(4) 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.